Augmenting Communication Technologies with Non-Primary Sensory Modalities

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The research in Chapter 3 was a group project. The author of this thesis built the hardware used in the experiments and designed the study with the cited colleagues below, lead by his supervisor, Dr. Jon Bird. The preliminary results were published at Augmented Human 2014 (Appendix I.1) and Advances in Computer Entertainment Technology (ACE) 2014 (Appendix I.2):

Pradana, G.A., Cheok, A.D., Inami, M., Tewell, J. and Choi, Y., 2014, March. Emotional priming of mobile text messages with ring-shaped wearable device using color lighting and tactile expressions. In Proceedings of the 5th Augmented Human International Conference (pp. 14). ACM.

Choi, Y., Tewell, J., Morisawa, Y., Pradana, G.A. and Cheok, A.D., 2014, November. Ring* U: a wearable system for intimate communication using tactile lighting expressions. In Proceedings of the 11th Conference on Advances in Computer Entertainment Technology (pp. 63). ACM.

The research in Chapter 5, 6, and 7 has been published in CHI 2017 (Appendix I.3; I.4):

Tewell, J., Bird, J. and Buchanan, G.R., 2017, May. The heat is on: a temperature display for conveying affective feedback. In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (pp. 1756-1767). ACM.

Tewell, J., Bird, J. and Buchanan, G.R., 2017, May. Heat-Nav: using temperature changes as navigation cues. In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (pp. 1131-1135). ACM.

Abstract

Humans combine their senses to enhance the world around them. While computers have evolved to reflect these sensory demands, only the *primary* senses of vision and audition (and to an extent, touch) are used in modern communication. This thesis investigated how additional information, such as emotion and navigational assistance, might be communicated using technology-based implementations of sensory displays that output the *non-primary* modalities of smell, vibrotactile touch, and thermo-touch. This thesis explored using a portable atomiser sprayer to deliver emotional information via smell to mobile phone users, a ring-shaped device worn on the finger to display emotional information using vibration and colours, and an array of thermoelectric coolers worn on the arm to create temperature sensations. Additionally, this thesis explored two methods of signalling temperature using the thermal implementation, and finally, used it in a controlled study to augment the perceived emotion of text messages using temperature.

There were challenges with using some of these implementations to display information. Smells produced with the scent technology were ambiguous and highly cognitive, and poor delivery to the user produced undesirable cross-adaption effects when smells lingered and mixed in the environment. The device used to communicate vibrotactile and colour lighting cues neutralized emotions in text messages. Furthermore, temperature pattern discrimination using the thermal implementation was difficult due to non-linear interaction effects that occurred on the skin's surface, as well as latency resulting from the thermal neurological pathway and the technology used to heat and cool the skin.

However, the thermal implementation enabled more accurate user discrimination between thermal signals than what a single stimulator design provided. Furthermore, the utility of continuous thermal feedback, in the context of spatial navigation, was demonstrated, which improved user performance compared to when the user was not presented with any thermal information. Finally, temperature was demonstrated to elicit arousal reactions across subjects using the thermal implementation, and could augment the arousal of text messages, especially when the content of the message was strongly neutral. However, no similar statistical significance was observed with valence, demonstrating the complex implications of using thermal cues to convey emotional information.

Chapter 1

Introduction

Humans combine their senses to enhance the world around them. "These senses enhance each other in various ways, adding synergies or further information dimensions" (Blattner and Dannenberg, 1992, pg. xvii). Blattner and Dannenberg give several examples of this synergy. Artists use dance movements and music and combine them into an entertaining, sensual experience. Scientists combine graphics and animation to aid in data visualisation. Music and sound effects combine with film to communicate information difficult to verbalise with actors. Dramas use chorus and musicians to provide a setting with plot.

Computers have evolved to reflect these sensory demands. What began as expensive and specialised devices, lacking the analogues of human senses needed to gather information from the real world, modern computers used in everyday life are now multimedia systems capable of presenting visual, audio, and (to an extent) tactile output from content sources, like the internet. Blattner and Dannenberg (1992) argue that the addition of all sensory modalities will be necessary for these systems to fully understand and communicate with human beings. Multimedia systems should therefore strive to facilitate communication with all human senses.

Within the recent decade, a human-computer interaction (HCI) field has emerged referred to as *multi-sensory communication* (Tanikawa and Hirose, 2008). This sub-field of HCI seeks to create *implementations* of multimodal, computer-mediated, interactive systems using the human senses of taste, smell, touch, vision, and audition, to investigate better understandings of their effectiveness for communication. Furthermore, significant literature from psychophysics, psychology, and physiology, have strengthen the positions that smell (Halpern, 1987; Schab, 1991; Chu and Downes, 2000; Gottfried *et al.*, 2004; Herz, 2004; Gould and Martin, 2001), and touch (Eisenberger *et al.*, 2003; Singer *et al.*, 2004; Williams and Bargh, 2008; IJzerman and Semin, 2009; Zhong and Leonardelli, 2008) could be leveraged for communicating information in such interactions.

The primary contribution of this thesis investigated how additional information, such as emotion and navigational assistance, might be communicated through technology-based implementations of sensory displays that output smell and touch (both vibrotactile and temperature) feedback. This thesis will describe how simple, off-the-shelf technologies can present these *non-primary* senses to users. Particularly, this thesis explored portable atomiser sprayers to deliver smells to mobile phone users (Chapter 2), jewellery worn on the finger capable simulating hugging using vibration and colours (Chapter 3), and an array of thermoelectric coolers (TECs) worn on the arm to create temperature sensations (Chapter 4). Additionally, this thesis explored two methods of signalling temperature using the temperature array device (Chapter 5 and Chapter 6), and finally, conducted a controlled study using temperature as an information display to augment the perceived emotion of text messages (Chapter 7).

1.1 Motivation

Human communication can be broadly defined as 'the physical signals whereby one individual can influence the behaviour of another' (Cheery, 1957). Blattner and Dannenberg (1992) argue that people can communicate information better through multiple channels: humans use gestures and eye gaze, for instance, to complement speech. In face-face encounters, non-verbal cues, such as facial expressions, bodily posture, and proximity to others, are used to communicate information difficult to verbalise and to let the speaker acknowledge information, such as happiness, surprise, and annoyance at what is being said (Argyle, 1969). When this feedback is lacking, communication can be embarrassing or misunderstood, and complete removal of feedback can impair the speaker's ability to persuade others (Argyle, 1969), reduce expression of social-emotional material (Short *et al.*, 1976), and can decrease attitudes, mood, and reactions of the conversers and their interactions.

Human communication can be facilitated by computers. E-mail is a popular means of communication done with computers, along with desktop publishing software, which helps users organise information in documents and presentations, and translation tools, which allow humans to communicate in their different languages. Blattner and Dannenberg (1992) argue that as computational power increases, it will become more important for people to have excellent communication with computers to fulfil these tasks and more. Communication should consequently consider the limitations of both humans and machines. Computers can exchange information rapidly, but they lack a deep understanding of human-human communication. "People" on the other hand "require abstractions to formulate and express their thoughts" (Blattner and Dannenberg, 1992, pg. xxii). "In the long term, integration of different *modalities* to the computer interface can help the user achieve a natural style of interaction approaching the richness of human-human communication" (Rudnicky and Hauptmann, 1992, pg. 147).

A modality is "the sense of which information is perceived, that is, the sensor modality" (Blattner and Dannenberg, 1992, pg. xxiv). This thesis refers to two types of modalities. 'Primary modalities', like audio and vision, are used in everyday, digital communication. For example, technologies, such as Skype, allow for teleconferencing using video and audio channels to approximate real-life, face-to-face conversations. 'Non-primary' modalities, on the other hand, encompass the more niche' touch senses, like vibration and temperature, and senses not used in modern, digital communication, such as smell.

Human experiences are multimodal and can be perceived by more than one modality or a combination of them. Perceptual integration occurs at the neural level, which has the consequence of information from different senses combining to form multimodal representations (O'Hare, 1991). O'Hare argued that this allows for a rich source of information, as information from one sense can often *augment* information from another. Furthermore, responses from multimodal events can be faster and more accurate than those from unimodal events and can even enhance user performance (Spence and Driver, 2004). An example is the verbal commentary of modern satellite navigational systems, which is designed to augment instead of disrupt the driver's visual channel.

Weiser (1991) stated the challenge with current (predominantly visual and audio) multimedia devices is that they turn computer displays into the focus of attention, rather than allowing them to fade into the background. Multimodal displays may therefore, reduce distractions by freeing visual and auditory channels. As an example, tactile displays can support visual and audio information while filling gaps when necessary, solving issues of intrusive demands on a user's visual and audio attention (Gemperle *et al.*, 2001). In addition vibrotactile communication can even substitute these primary modalities for users with visual, auditory, or vestibular impairments, and to assist in spatial navigation in unfamiliar environments (Green et al., 2011).

Mediums are carriers of information (Blattner and Dannenberg, 1992) and can be described by the richness of salient information, like emotion and intent, which can be conducted from the communicator to the receiver. Salient information can be influenced by the number and resolution of sensory modalities provided by a communication medium (Steuer 1992; Zeltzer 1992), as well as the range and intensity of stimuli that can be detected (Heeter, 1992). Such findings suggest that information exchange is highly dependent on the senses provided by a medium of communication.

However, some mediums may lack channels for effective communication of information, such as emails, instant messenger chats, and SMS messages, which do not contain non-verbal cues needed to communicate information as effectively as face-face interactions (Short *et al.*, 1976). Some methods have been developed to approximate nonverbal cues in these mediums, for instance, paralinguistic utterances, such as 'like', and 'uh' can signal turn taking, deictic gestures such as 'liking' and 'poking' on Facebook can draw attention to one's self (Schandorf, 2013), and typographic images like emoji and emoticons can express emotions and humor in absence of facial expressions. However, emoticons have severe limitations in the scope of emotions that they can transmit in that they are only good for communicating positive emotions and are used mainly amongst only friends (Derks *et al.*, 2008). Furthermore there is potential for miscommunication using emojis, due to different standards of rendering them across multiple platforms (Miller *et al*., 2016). In contrast, face-face encounters are highly socially engaging due to the ability of the receiver to perceive the speaker using all senses, such as touching one another to communicate power (Henley, 1977), status (Henley, 1973), and emotion (Fisher *et al.*, 1976) and using smell to alter, and even invert, positive perceptions of others (Baron, 1981).

'Non-primary' senses of touch and smell have not been widely considered for use in communication technologies. On the other hand, they have been used to enhance the human experience. The Sensorama motorcycle ride stimulation is a classic example which pumped odours of motor exhaust, as well as pleasant smells such as flowers, into riders' noses (Heilig, 1992; Rheingold, 1991). Sensurround used vibration in seats to simulate in-movie events, like earthquakes, in theatres (Chamberlain, 2008). Other systems have used sophisticated hydraulic motion platforms to create false inertia forces in amusement park rides (Showscan, 1991), while video game controllers use simpler and cheaper hardware which can be mass-produced to provide force feedback from videogames. It is possible in the future that other mass-produced technologies may incorporate the senses of smell and more sophisticated forms of touch to enhance experiences in daily communication as well.

On the other hand, touch and smell have been extensively researched in the domains of psychophysics (Blake and Sekuler, 2006; Dalton, 2002; Kenshalo *et al.*, 1961; Stevens *et al.*, 1974; Pertovarra and Kojo, 1985; Gibson, 1966; Kenshalo, 1972), psychology (Schab, 1991; Herz, 2004; Hollins and Risner, 2000; Summers *et al.*, 1994; Gunther *et al.*, 2002; Craig, *et al.*, 1996), and physiology (Freeman, 1991; Kauer, 1991; Levine and Shefner, 2000). These domains have provided HCI research with a solid foundation towards understanding how these non-primary modalities could be utilized to provide controllable feedback design parameters, such as understanding the human limits of what can be perceived, safety considerations (like upper and lower thermal thresholds), and latency, or how long it takes for the body to perceive a change has occurred. These parameters could then be incorporated into communication technologies to expand and enrich information for use in interaction with other humans. For instance, when sending a text message, communicators could also send an accompanying smell over the internet, 'poke' their friend or partner by using a vibration, or alert them using temperature. Thus, by adding these additional, non-primary senses of touch and smell to human communication networks, it might be possible to extend the bandwidth of information which can be decoded and interpreted in human-human communication.

This emerging HCI field of 'multi-sensory communication' (Tanikawa and Hirose, 2008), has so far investigated technology-based implementations of smell and touch displays. This field has also explored examples of information that can be conveyed with these senses, such as emotion. Though implementations have been novel, most research has not thoroughly measured the effectiveness of them for use in communication, and it is unclear what the best method is for building technologies which can accurately send smell and touch stimuli to recipients. For instance, smell relies on the usage of chemicals to transmit its characteristics, and it is unclear how to combine its basic components to achieve any response from users which could be useful to communicate with. Cutaneous touch is complex and made up of several dimensions, such as pressure and temperature, each of which combine to achieve meaningful, tactile perceptions. In addition, there are numerous difficulties with applying temperature directly to the skin, as there are latency issues (the time it takes to perceive changes) and non-linear interactions, which can undermine temperature's usefulness as a communication channel.

Therefore, this thesis took an exploratory approach to discover how to send kinds of smell, vibrotactile, and temperature stimuli, to users. First, this thesis will document the construction of prototypes to facilitate the rapid testing of their effectiveness for presenting these senses to participants. From Chapter 2 to Chapter 4, this thesis will discuss how affordable technologies, such as off-the-shelf electronics kits, micro-controllers, and 3D printing, were combined with prototyping techniques to create devices capable of presenting these non-primary sensory modalities to users in a variety of novel ways, as well as exploring any pre-existing technology available on the market: dispersing of scents to users' faces using an attachable phone accessory (Chapter 2), transmitting 'poking' and 'hugging' expressions using a wearable ring device worn on the finger along with additional, coloured lighting expressions (Chapter 3), and warming and cooling the arm using an array of thermal stimulators (Chapter 4). Second, controlled lab studies examined the effect of stimuli on participants' behaviour and reactions using quantitative data. Chapters 2, 3, and 7 examined the affective reactions of subjects using the developed implementations. Chapter 5 investigated the perception of thermo-spatial patterns using the thermal display and signalling temperature to the user discretely. Finally, Chapter 6 demonstrated the ability of using temperature cues from the thermal display to guide user navigation.

1.2 Research Questions

To examine the effect of using implementations of multi-sensory technology on participants' behaviour and their affective reactions in communication, this thesis aimed to address the following research questions:

RQ1: Can a mobile smell display augment the perceived emotional content of SMS text messages?

RQ2: Can a wearable ring device augment the perceived emotional content of SMS text messages with tactile and colour feedback?

RQ3: Can a wearable array of thermal stimulators be constructed to provide information using temperature?

RQ4: What are the benefits of using an array of thermal stimulators over a single stimulator design?

RQ5: Can continuous feedback provide reliable information from a thermal display?

RQ6: Can a wearable array of thermal stimulators augment the emotional content of social media messages?

Main RQ: Can additional information, such as emotions and navigation assistance, be communicated through different implementations of sensory displays that use smell and touch?

1.3 Thesis Outline

Chapter 2, *Augmenting Text Messages with a Mobile, Olfactory Display*, will explore augmenting text messages using olfactory scents sent from a portable, smell-atomising spray device. A literature review on perception of smell will be introduced to acquaint the reader with the difficulties with labelling smells, the human limits of smell detection, and how smell could be used to present information, like emotion (Section 2.1). A small section on physiology (Section 2.2) will illustrate the complicated olfactory pathway from scent detection in the nose to the brain. A HCI perspective using smell will also discussed, as well as some historically significant commercial attempts using scents (Section 2.3). This chapter will present one of these devices (Section 2.5) for usage in a later study. The chapter then will then examine how well human subjects could consistently rate the perceived emotion of text messages and smells in two pilot studies (Section 2.4). Finally, this chapter will conclude with a main study (Section 2.6), which combined the scents and messages together to observe if smell could augment the emotion of the text messages. The outcome of the study showed that smell exerted a strong interaction effect on the messages, and accurate delivery was difficult with prolonged use due to the lingering of the smells in the air.

Chapter 3, *Augmenting Text Messages with a Wearable, Multimodal, Ring Device* will examine if using tactile cues and colour lighting effects emitted from a ring device can augment the perceived emotion of text messages. The chapter will begin with a discussion of relevant literature in perception and physiology to discover appropriate parameters for presenting vibrotactile feedback on the skin: frequency, duration, rhythm, waveform, and body location (Section 3.1 and 3.2). A literature review on haptics in HCI will be discussed, mainly focusing on TCONs, or structured vibrotactile feedback, and research of haptic feedback in affective computing (Section 3.3). The development of the ring device, Ring*U, will be documented (Section 3.4), which is a wearable, ring–shaped device that can communicate small haptic gestures over the internet as well as coloured lighting expressions using an LED. Several pilot studies assessed using the Ring*U and were used to select appropriate TCON and colour feedback stimuli (Section 3.5). The main study at the end of this chapter then examined if combining the different TCON vibrotactile patterns with text messages, along with colour lighting effects, could augment emotion in the text messages (Section 3.6). The outcome of this study, however, revealed that the Ring*U effectively neutralised the emotion in the text messages. The preliminary results of this chapter's study were published in a paper for Augmented Human 2014 (Appendix I.1) and the design of the technology used in this chapter was also published in Advances in Computing Entertainment 2014 (Appendix I.2).

Chapter 4, *Thermal Array Display: a System Description*, will discuss the development of a thermal haptic display device for exploring user discrimination of thermo-spatial patterns on the arm. The chapter begins by reviewing literature in thermal perception (Section 4.1) and the physiology of the cutaneous sense of temperature (Section 4.2) to identify key parameters and safety considerations: thresholds, location of stimulation, rate of change, direction, magnitude, age, gender, touch temperature, re-adaptation, psychological zero points, latency, and discrimination. These parameters, and the designs of previous implementations of thermal displays (Section 4.3), were used to facilitate the design of a temperature display prototype, the 'Thermal Array Display' (Section 4.4).

Chapter 5, *Discrete Signalling of Temperature Feedback*, will look at various methods of signalling temperature sensations to users using a method called *discrete signalling*, which involves resetting the skin to a neutral temperature each time a new cue is presented to the subject, as is done throughout studies in HCI. This chapter will first examine the application of discriminating thermo-spatial patterns, which are patterns of hot and cold temperatures applied simultaneously to the skin, a poorly understood area in HCI (Section 5.1). A pilot study, however, will demonstrate the difficulty of human discrimination of these thermal-spatial patterns. This chapter will then turn its attention to examining different methods of conveying thermal states on the skin (Section 5.2). Three methods of signalling temperature states will be explored: Single, where only one stimulator is used, Amplification, where all three stimulators are used and set to the same temperature value, and Quantification, where all thermal states are signalled by the number of active stimulators turned on in the array. The outcome will reveal that the Amplification method resulted in the best detection and lowest error rates, compared to the other two methods. This study was featured in a paper published at CHI 2017 (Appendix I.3).

Chapter 6, *Providing Information Using Continuous Thermal Feedback*, will alternatively explore the plausibility of providing continuous thermal feedback, which does not require resetting temperature to neutral each time a new signal is sent to the user, to guide user behaviour. Though this thesis is not the first to suggest continuous thermal feedback (Section 6.1), it is the first to test this approach in robust studies where subjects completed a navigational task by relying on using thermal cues to guide themselves in a 2D maze (Section 6.2 - 6.4). The outcome of the study reveals that the subjects could rely on the thermal feedback to guide them, and that they could complete the navigational tasks with less moves and in less time than the control condition with no feedback, despite the issues of latency with temperature perception. This study was published as a note at CHI 2017 (Appendix I.4).

Chapter 7, *Augmenting Text Messages with the Thermal Array Display*, will examine if using the Thermal Array Display can augment the perceived emotion of text messages. The chapter will first provide a literature review of temperature research, which examined affective responses of thermal stimuli (Section 7.1). The chapter will then proceed to explore a more rigorous literature review of HCI work which has addressed how users rate temperature, such rating thermal stimuli on scales of valence and arousal, as well as data obtained from qualitative sources such as interviews. Most importantly, HCI work which has used temperature to augment media, like images, music, and movies, will be deeply discussed. The chapter then will propose a study to examine if thermal cues can augment the emotion of text messages. Pilot studies showed that users could reliably rate the content of the text messages according to valence and arousal, that they could reliably rate the arousal of temperatures, but had mixed reactions to ratings of temperature according to valence (Section 7.2). The results of the main study (Section 7.3), which combined the messages and temperatures into pairs of trials, demonstrated that users could reliably rate the trials according to arousal, and that warm temperatures were sensed as more arousing than cool temperatures. However, the message content surprisingly dominated over the valence of the temperatures, regardless of whether the temperature was warm or cool. The chapter concludes with a discussion of why temperature had no effect on valence and contrasts this finding with previous work done in the field. The studies in this chapter were published as part of the paper presented at CHI 2017 (Appendix I.3).

Chapter 8, *Discussion and Conclusion*, summarises the research contributions in this thesis and reiterates and answers the research questions posed in this chapter. Finally, the limitations of the research that was undertaken in this thesis will be discussed and future work in this area of multi-sensory communication is proposed.

Table 1.1 summarises the seven chapters that constitute the body of this thesis and their experiments, which were performed to answer the research questions. The first two chapters contain exploratory studies framed around testing implementations of smell and TCON/colour displays. Chapter 4 focuses on the construction of an implementation of a thermal display. Chapters 5 - 7 examines this implementation with regards to signalling temperature and using temperature to provide different kinds of information, like navigation and emotion. Each chapter will have its own literature review relevant to the aims of the implementation/modality and/or previous work in HCI. The purpose and contributions of each topic and its respective chapter are listed in the right most column in Table 1.1.

Topic	Chapter	• Purpose ✓Contributions
Assessing a Mobile, Olfactory Display	Chapter 2	• Find appropriate smell and message stimuli • Test smell/message pairs using Scentee ✓ Smell was ambiguous and highly cognitive ✓ Implementation caused smells to linger and mix within the environment, creating interaction effects
Assessing a Wearable, Multimodal, Ring Device	Chapter 3	• Find appropriate TCON and colour stimuli • Test emotional ratings of TCON/colour/messages using Ring*U ✓ Implementation neutralised the emotional content of the messages.
Constructing Thermal Implementation	Chapter 4	• Constructing an array-based thermal display that can present patterns of temperatures ✓ Implementation was created that can be safety worn on the arm
Testing Discrete Thermal Signalling	Chapter 5	• Test discrimination of thermo-spatial patterns • Test signalling of temperature states with three methods ✓ Users could not discriminate thermo-spatial patterns ✓ Using more than one stimulator resulted in better perception of thermal states.
Testing Continuous Thermal Signalling	Chapter 6	• Test effectiveness of continuous temperature feedback • Continuous feedback can be used to guide behaviour, despite temperature's latency
Thermal Signalling of Emotions	Chapter 7	• Test emotional ratings of temperature/message stimuli pairs ✓ Temperature from the TAD can significantly influence arousal ✓ Warm temperatures arouse message content, cool temperatures calm message content ✓ Message valence dominates over temperature from the TAD

Table 1.1: Summary of all experiments, their purposes, and their contributions, in this thesis.

Chapter 2

Augmenting Text Messages with a Mobile, Olfactory Display

This thesis first focused on the use of a chemical sense for communicating information: *olfaction,* or simply, smell. Significant research in smell perception and psychology have argued that smell possesses an intimate link with emotion and memories (Schab, 1991; Chu and Downes, 2000; Gottfried *et al.*, 2004; Herz, 2004; Herz 2007; Seo *et al*. 2009), as both smell and emotion are fused within the limbic system of the brain (Goldstein, 2010). This supported this chapter's aim of using sensory cues for providing information, in this case emotion, in order to augment the emotional content of text messages.

This chapter examined the usage of smell to investigate the research question: *Can a mobile smell display augment the perceived emotional content of SMS text messages?* While work in the field of HCI has examined using smells to provoke emotional reactions from subjects, no substantial work has investigated if smell can augment the emotional content of text messages from social media. A smell-based language could therefore, be used in communication channels to replicate, for example, the usage of emoticons to convey emotional intent. More specifically, the sense of smell could be used to *augment* these communication channels in a way that may support, or increase, the emotional content of digital media, such as text messages.

This chapter first provides a quick summary of smell perception and hedonics (Section 2.1), to tie together smell within the aims of communicating emotion. Section 2.2 provides a review of how the body detects and discriminates different smells. Section 2.3 then summarises the usage of smell in prior HCI research. Two pilot studies (Section 2.4) found appropriate smell and message stimuli which subjects were asked to emotional rate. Rather than building new technology, this thesis evaluated a pre-existing commercial device (Section 2.5), to assess the viability of using smell to augment communication. The remaining main study (Section 2.6) then observed how subjects emotionally rated the text messages while smelling the scents together in pairs using the commercial device. An analysis of the results and a discussion is then provided in the remainder of this chapter.

2.1 Olfactory Perception

The earliest efforts in the study of olfactory perception attempted to classify odours based on pre-conceived, primary odour qualities, such as the lists proposed by Linnaeus (Cain, 1978) and Zwaardmaker (1895) in the 18th century. Henning (1916) proposed an *odour prism* classification scheme, like Newton's colour circle. In his classification were six primary odours: Flowery, Putrid, Fruity, Spicy, Burnt, and Resinous. Amoore (1964) was the first smell researcher to create a scheme based on the physicochemical properties of smell stimuli and suggested that there existed specialized odour receptors for each of these primary odours, of which combinations could create all the possibilities of smell.

There were issues with devising such schemes, however. Without experimentation, early classifications were heavily biased, as they were mostly subjective and introspective from the researcher's point of view. To sidestep the problem of subjectivity bias, *Multidimensional Scaling* was proposed (Schiffman, 1974), which used numerical ratings instead of descriptor (language) terms to rate odours instead of identifying them. After smells were rated, they were then arranged into an *odour place* on a two-dimensional model so that the distances reflected the similarities between the tested odours. In this model, the horizontal axis denotes pleasantness (valence) and the vertical axis denotes 'sharpness', or the spiciness of the smell.

In addition to classification of smell, there were also the challenges of accurately identifying odours. While humans can discriminate as many as 100,000 different odours (Firestein, 2001), they can only detect the substance the odour is associated with at chance levels (Engen and Pfaffmann, 1960). However, identification improves if participants are made aware of the substances' names before the experiment (Desor and Beauchamp, 1974), but doing so consequently alters the perception of the odour if the name is presented after the stimulus (Cain, 1980). Giving odours different labels also was demonstrated to affect their perception, such as labelling an onion smell as pizza instead of body odour (Herz, 2003).

Another issue often encountered in experiments with smell perception is that odour sensitivity decreases with prolonged exposure to smell (Blake and Sekuler, 2006). This is known as *odour adaptation*, which was believed to be mainly caused by how the brain encodes smell rather than due to the individual smell receptors in the nose (Engen, 1982). Furthermore, smell sensitivity can decrease by much as 30% due to odour adaptation (Cain, 1978) and the recovery time can be highly variable, from a few minutes to up to an hour depending on the original strength of the odour (Berglund *et al*., 1971).

There are also *cross-adaptation effects* to consider in olfaction experiments. These occur when odours interact with different odours in the air after being inhaled, such as deodorants (Blake and Sekuler, 2006). These effects can be wildly unpredictable, due to the way encoding of smells happens after they have been detected by smell receptors. For example, some odours have been demonstrated to have asymmetrical interaction effects in that one odour may influence another but not the other way around (Cain and Engen, 1969). *Mixture suppression* (Derby *et al.*, 1985; Jinks and Laing, 1999) can result in non-additive behaviour, such that two odorants of similar intensity may not yield a mixture that is perceived to be twice as strong. If odours are highly different, however, they may not produce interaction effects at all (Moncrieff, 1956).

Smell sensitivity is another parameter that should be carefully controlled in studies. This can be measured by the *recognition threshold*, or the concentration at which an odour's quality can be recognized (Dalton, 2002). Sensitivity can change with training or induced exposure to odorants (Wang *et al.*, 1993). Excessive or repeated exposure to smells also decreases neural sensitivity to the odour (Dalton, 2000).

Sensitivity can change throughout the day (Stone and Pryor, 1967), and has been demonstrated to decrease with age (Cain and Gent, 1991; Schiffman, 1997). It is also dependent on gender (Koelega and Köster, 1974).

Smell is also dependant on the time duration of initial exposure (Blake and Sekuler, 2006) and the concentration of the odour, which also impacts latency. Moderate size responses can take up to a second to detect, whereas trivial concentrations can take up to 30 seconds or more (Gesteland, 1978).

Though the discussion of smell perception so far has been limited to the scope of identification, accuracy, and sensitivity, smell also has a wide range of consequences on human behaviour and emotion once the smell has been thoroughly decoded in the brain. This is due to implications that arise due to how the olfactory pathway is intertwined within the limbic system of the brain, as will be discussed more deeply in Section 3.2.

Simple and primitive urges, such as sex and aggression, can be influenced heavily by smell. The most famous example of this is the use of pheromones in mammals. *Signalling pheromones* can affect social behaviours such as aggression and an infant's interaction with their parent (Halpern, 1987). Scents can affect a female's ability to attract males (Holden, 1996) and is used by mammals to identify gender (Wallace, 1977; Doty *et al*. 1982). Scents given off from the urine of male rats can induce females to be more receptive to sexual advances, and the scent of female hamster vaginal secretions can likewise attract males as well (O-Connell and Meredith, 1984).

In humans, smell can moderate consumer behaviour and be used to prevent accidents. Businesses are known to employ tactics with smell to appeal to consumers. For example, bakeries often vent their aromas onto the street to lure in customers (Winter, 1976), and automobile manufacturers embed scents into the fabric of new car interiors (Hakim, 2003) to attract potential buyers after giving the automobiles a test drive. Another example of using odour to modify behaviour is the odour of bleach, which is often used as an agent in toxic, odourless substances to ward off people from ingesting them (De Wijk and Cain, 1994).

Emotion, and its link to memory, is perhaps one of the most studied aspects of odour perception. Odour can induce arousal, an important component of emotion (Gould and Martin, 2001). Smell can evoke forgotten memories (Schab, 1991; Chu and Downes, 2000) and is especially potent if the smell played a role in the original event itself (Gottfried *et al.*, 2004). Olfactory cues create stronger, more emotional, and more vivid experiences than stimuli of different modalities (Herz, 2004). Herz (2007) further argued that the ability to experience and express emotion grew directly from the part of the brain that processed smell. "Without a sense of smell, our ability to know ourselves and others is obscured, our emotional world becomes deadened or disturbed, our ability to enjoy food is lost, our health may decline, and our sexual desire...is severely weakened." Smell is "...tied to our emotions, our memories, our behaviours, and our health. Scents influence our social relationships and family ties, and they fuel our passions for people and food" (pg. 10).

The connection between smell and emotion can be further evidenced by observing smell-disabled patients, or anosmics. Seo *et al*. (2009) observed elderly women who suffered from olfactory loss due to age. They found that subjects with severe anosmia exhibited higher levels of depression, less cognitive ability, and a decreased quality of life than subjects with a normal sense of smell or moderate anosmia.

Experiments with human subjects have revealed that subjects can rate odours along emotional scales and relate them to past experiences. Willander and Larsson's (2006) subjects were asked to relate odour, verbal, and visual information to autobiographical events. Olfactory information was found to trigger memories better than verbal or visual information, in that the memories from odours were more nostalgic. In a study by Alaoui-Ismaïli *et al*. (1997), subjects inhaled five odorants while their autonomic nervous system (ANS) responses were recorded. The ANS results showed that pleasantly rated smells evoked happiness and surprise, while unpleasant smells triggered disgust and anger. In another study by Bensafi *et al*., (2002), 12 subjects inhaled six odorants and were asked to rate them on dimensions of intensity, pleasantness, arousal, and familiarity. Pleasant smells correlated with heart rate variation, while arousal correlated with skin conductance and intensity ratings. Distel *et al*., (1999) had subjects of different ethnicities rate 18 odorants on scales of strength, pleasantness, and familiarity. A positive correlation was found between intensity, familiarity, and pleasantness, suggesting that intensity depends not just on odour concentration, but also past experiences as well. These findings suggest smell can be rated emotionally by human subjects, which makes the modality useful to explore as an information channel.

This section reviewed the perceptual aspects of the sense of smell. It discussed how odours could be classified and examined issues pertaining to the accuracy and sensitivity of smell. There are complicated interaction effects to consider if smells are combined before and after being inhaled and the delay of their perception (latency) caused by the duration of initial exposure to the smell and its concertation, all of which may need to be compensated for in a controlled study. Finally, the behavioural and emotional responses from smell were examined, which supported the notion of using smell to augment emotion for communication.

The next section will provide a summary of the olfactory pathway in the body. Issues pertaining to what has been discussed so far will be examined at the physiological level to understand their occurrences. Most importantly, the pathway in the brain will be closely examined to reveal the intimate links between smell and emotion, which further supports using smell as a means of displaying information that can augment human emotion.

2.2 Olfactory Physiology

The sense of smell is triggered by *olfactory sensory neurons*, or simply, smell receptors, in the olfactory epithelium at the top of the nasal cavity, as shown in Figure 2.1. Smell receptors are genuine neurons, and thus perform the job of both sensing smells as well as transmitting them to the brain. Humans have millions of such smell receptors (Levine and Shefner, 2000) and most can respond to several odours (Kauer, 1991; Sicard and Holley, 1984). Hundreds of receptors types have been classified (Baraniga, 1991; Buck and Axel, 1991), combinations of which can produce up to 10,000 possible odours (Johnston, 1992). Smell receptors have short life spans, lasting about five to eight weeks before being replaced (Graziadei, 1973; Moulton, 1974), which may contribute towards changing sensitivity to odours over time (Ahlström *et al.*, 1986).

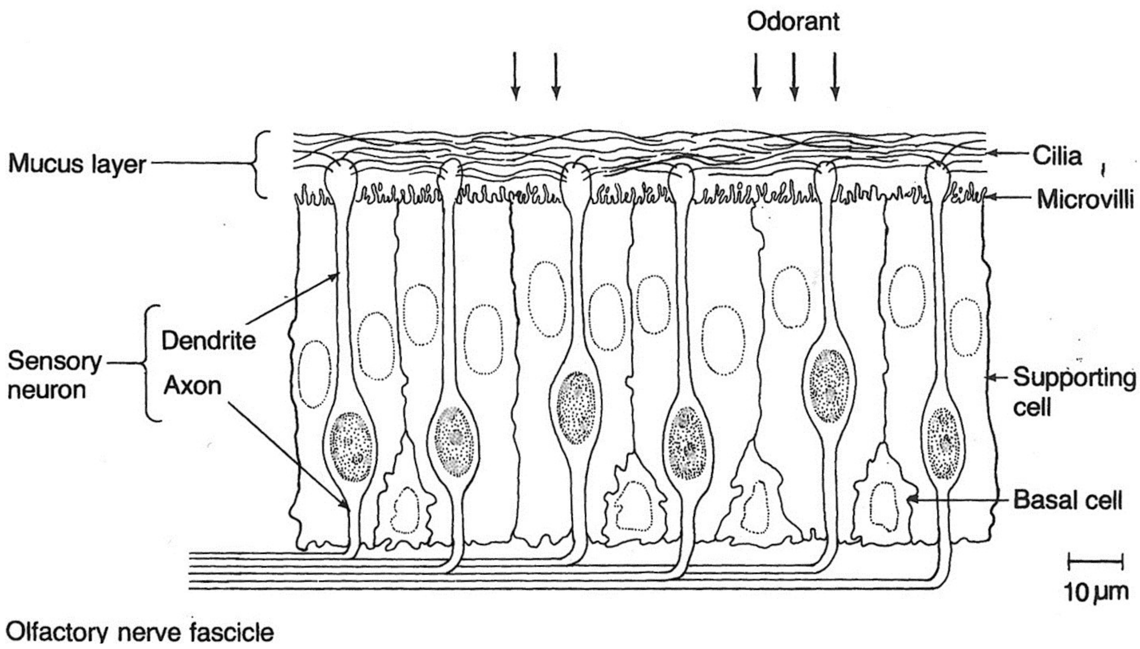


Figure 2.1: Cross-section of the olfactory epithelium (image from Lancet, 1986).

Smell receptors depend on *polarisation* to generate signals to the brain. When odorant particles flow into the nasal cavity through the nostrils, they interact with the smell receptors' tips, or cilia, which bind with the smell molecules absorbed into the mucus layer (Cometto-Muniz and Cain, 1990). The surface of the cilia is made up of unique shaped groves which capture the odour molecules in a *lock and key* binding process (Amoore, 1970). When binding occurs, ion channels in the cells of the cilia open in a state of depolarization, where they lose their negative charge, resulting in a generator potential (not to be confused with an action potential, which is the summation of many graded potentials) (Lancet, 1986).

Once a stimulus is detected, the receptor's neuron synapses in a region known as the glomeruli, a part of the olfactory bulb in the brain (Goldstein, 2010). Within this region, the axons projecting from the olfactory epithelium connect to second order neurons within the glomeruli in a 1000 to one mapping (Blake and Sekuler, 2006). The glomeruli provides a sensory map which the brain uses to identify which receptors were activated by the inhaled compounds (Uchida *et al.*, 2000). Signals from the glomeruli are then sent to the primary olfactory cortex, and subsequently, the secondary olfactory cortex below the anterior temporal lobe (Goldstein, 2010).

One unique aspect of smell compared to other senses is that it is pre-processed in the limbic areas, the oldest part of the brain responsible for emotion, before reaching the neocortex for encoding. Once in the limbic system, neurons project into a variety of its areas, such as the amygdala and the prepiriform cortex. The prepiriform cortex is involved with perceiving complex odours made up of more than one molecule (Wilson and Stevenson, 2006), and its neurons can learn over time to tell the difference between the odours (Wilson, 2003). From here, signals travel onward to the thalamus and then finally, to the neocortex for decoding.

A number of studies using functional magnetic resonance imaging (fMRI) have measured brain activity in the limbic system when odours are inhaled. Gottfried *et al.* (2002) asked subjects to view faces paired with pleasant, neutral, and unpleasant odours and found that all odours activated the posterior piriform cortex: a brain region that mediates emotional processing, providing evidence for the close coupling of olfactory and emotional systems in the brain. Bensafi *et al.* (2007)'s subjects smelled both real and 'imagined' odours that were pleasant and unpleasant. The authors found that imagined odours induced similar activity as real odorants, and that unpleasant odour stimuli induced greater activity than pleasant odours in the left frontal piriform cortex. De Araujo *et al.* (2005) showed that activations in the anterior cingulate cortex and medial orbitofrontal cortex were correlated with user ratings of pleasantness. Further studies have shown that an odour's valence, and not the type of odour, associates with activity within the piriform cortex (Zelano *et al.*, 2007), whereas the amygdala region activates with odour intensity (Anderson *et al.*, 2003). Within the piriform cortex, pleasant odours activate the medial orbitofrontal cortex, and unpleasant smells are correlated with activity in the left and right lateral orbitofrontal cortex (Rolls *et al.* 2003a), providing evidence of a hedonic map of the sense of smell in the brain.

There are a variety of theories as to how the brain decodes odour signals. The mainstream belief is that the spatial pattern of neutral fibre activity determines the odour quality (Freeman, 1991; Kauer, 1991). In this model, all neurons in the olfactory bulb contribute toward the encoding of each smell, and there are no neurons that specialize in certain scents. These patterns of receptor activity are called the *odour recognition profile* (Malnic *et al.*, 1999). Therefore, each odorant results in unique firing patterns across the receptors.

This section reviewed the olfactory pathway from receptors in nasal cavity to the limbic system in the brain. Receptors produce generator potentials when scent molecules bind to their cilia. Signals are sent from the receptors to the olfactory bulb and limbic areas in the brain for decoding. The prevailing belief behind this process is that each smell generates a specific odour recognition profile response in the brain which is used to identify the scent.

This chapter now will turn its attention to reviewing relevant literature in HCI and other applicable areas where smell has been applied to communication. Surprisingly, the HCI literature in this area is sparse, but has roots in early commercial applications. Though such commercial pursuits did not contribute significant studies, they are worthy to examine as examples of how scents could be delivered to users. In addition, studies that experimented with delivering smell to subjects, particularly those that attempted to communicate emotion using smell, will be thoroughly reviewed.

2.3 Literature Review

Significant interest in utilizing smell for commercial applications began in the middle of the last century. The Smell-O-Vision (Time Magazine, 1959) was one of the earliest and most famous of these attempts to commercialize smell to augment other media like moving pictures. More recently, 'iSmell' (How Stuff Works, 2001) was a conceptual prototype that emitted a scent when users browsed the internet or checked email. 'Trisenx' (How Stuff Works, 2001) was fully programmable PC accessory which allowed users to create their own scents for games and movies. 'Multi-Aroma-Shooter' (Ando, 2013) was a video editor interface which could synchronize up to six different scents with video imagery. 'oPhone' (Bereznak, 2014) allowed users to tag photos with an 'aroma note' using a proprietary smartphone app. However, no significant studies were performed to evaluate any of these technologies, and none were commercially successful.

One of the earliest attempts in HCI research to support communication using smell was *Feather, Scent, and Shaker* (Strong and Gaver, 1996). The system consisted of several prototypes, one of which utilised scent to enable feelings of intimacy and sociality between close friends and lovers. The system consisted of a tangible object, a picture frame, which the person away from home manipulated. This action activated a heating element underneath a metal bowl containing a vaporising, essential oil in their house that their partner would then be able to smell. When the oil scent filled the home, it indicated to their partner inside the home that the sender (the user manipulating the picture frame) was thinking of them. However, no study was carried out to demonstrate whether this system was effective at conveying the desired feeling of companionship.

Kaye (2001) proposed a number of prototypes for situations in which smell could be used as a source of information. 'In Stink' implemented a spice rack that served as an input device in the kitchen. When the user moved one of the jars in the rack, it signalled to a system of airbrushes in another household which then sprayed the content's scent of the jar that had been moved. 'Dollar and Scents' tracked the price movements of the stock market and mapped asset gains and losses as minty and lemon smells, respectively. 'Honey I'm Home' used smell to convey a feeling of presence between partners. It used a smooth, box-shaped device which one partner rested his or her hand onto that signalled a scent device on their partner's desk. 'Scents Reminder' mapped smell to calendar events which reminded users of upcoming appointments. Despite the novelty of these devices, however, no significant studies were carried out to indicate their usefulness, though Kaye noted that pleasant smells could combine to produce unpleasant smells if they lingered too long and even gave users headaches.

Olfoto was one of the first serious attempts in HCI that analysed the effectiveness of a smell-based interaction system (Brewster *et al.*, 2006). The system consisted of a photo viewer which tagged photos with certain scents that users could then browse and search with. Smells were dispersed using a cube-shaped device that featured RFID tags on the bottom side. Users tagged the photos by moving the cube over the album's RFID reader when the photo or group of photos was selected in the viewer. To evaluate their system, the authors examined how well users could recall photos tagged with smell compared with tagging photos with text after a two week period had elapsed. The results revealed that subjects performed better using the text tagging condition than the smell condition: successful recalls with smell were correct only about 52% of the time. The study therefore revealed some difficulties with using scents for interaction. First, the smell intensity of the chemicals became diluted due their overuse over the course of the study. Second, about half of the smells tested were considered by subjects to be 'too synthetic', and could not be consistently labelled for tagging in early testing. Consequently, the authors admitted more work needed to be done to find more appropriate smells for research. Lastly, subjects reported that smell tagging was cognitively demanding and caused fatigue, which may have played a significant factor in their poor performance.

Sound Perfume (Choi *et al.*, 2011) and Light Perfume (Choi, *et al.*, 2013) were both wearable accessories which examined the effect of smell in face-face encounters. Sound Perfume was a pair of glasses outfitted with speakers, which were used to pulse fragrances emitted using heat generated within the glasses. Light perfume provided a similar concept consisting of an arm-worn bangle using RGB LED colours and scents that were also emitted using a heating circuit. Both systems were designed for use between friends and partners: Sound Perfume could reproduce the sounds and fragrances of initial encounters when friends met each other again, and Light Perfume could detect gestures and sense environmental sounds which the system would then map to colour effects and fragrances in face-face encounters. Only the Sound Perfume system was evaluated in a study, but mainly the technical aspects of the system and not how effective Sound Perfume was for communication. Four people participated in their study which asked them to perform tasks with Sound Perfume, such as setting up their profiles, meeting people, and conversing with them while wearing the glasses. While some users commented on the interesting novelty of the device, many found it confusing to set up as it manually required entering the MAC addresses of both their glasses and their partner's phone, to facilitate the connection for conversation.

Another wearable scent display was 'Essence' (Amores and Maes, 2017), which took the form of a necklace. The device used a piezo-electric motor and a tank which dispersed scents towards the face when worn around the neck and could be refilled with different scents. The aim of the technology was to examine the plausibility of using smell in variety of different areas: to enhance learning and cognitive performance, to aid in sleep and memory consolidation, to trigger and enhance emotional responses and moods in social interactions, and to enhance immersion to "augment digital experiences…" and create "a more complete sensual experience" (pg. 31). A preliminary evaluation of the system over the course of 3 days in both indoor and outdoor environments was conducted using four subjects, who were asked to carry out their normal lives while wearing the necklace, which released a scent every 20 seconds. Users rated the device favourably on scales of ease of use, satisfaction, and comfort, though some subjects remarked that the scents were too strong and indicated a desire to control the parameters of intensity and duration between the sprays.

Obrist *et al.* (2014) explored collecting subjects' memories of past experiences with odours and used them to facilitate the design of smell displays. Subjects were asked to think of their past experiences with smell and to describe the experiences in detail. The subjects were then asked to give a title to their 'stories' and to indicate their valences. Based on these stories, the authors explored how smell technologies can be designed by matching the smell stories with technologies, as well as having expert HCI researchers brainstorm their own ideas in parallel but independently of the subjects. The authors found most stories were rated positivity, and that they took place in a context with familiar people and places in the subject's lives, like their friend's home or public spaces. Suggestions for technology included the ability to share smells with family and friends, to support decision making, regulating mood, awareness of body smells, and to combine smell with everyday objects. On the other hand, the HCI researchers came up with different ideas for technologies, such as performance regulation, autonomous smell agents, smell alerts, and telling stories. This revealed a gap between how users and researchers think about the design of smell displays and what they might be used for in everyday life.

Some work has created technology capable of mixing scents together to create more complex odours that the user could specify. Sugimoto *et al.* (2010), for example, developed an 'olfaction printer' from a standard ink jet printer that pulsed small amounts of scent chemicals into the air. Their device allowed for quick delivery of scents with minimal latency, and the smell could be dissipated into the environment after a few seconds. The 'printed' scents could then be synchronized with visual stimuli such as a cooking show. However, unlike a real printer, there are no primary scents like colours that the scent printer could easily hold, so the range of scents which could be loaded into the device was extremely limited. Nevertheless, the authors conducted several studies that experimented synchronising the pulsing of the scents as the users' took a breath, as well as during the users' respiration. The authors also experimented with presenting patterns of odours by switching the odours on and off in a sequence. The authors found it was difficult to synchronise the odour with breath cycles, as respiration timing varied greatly between individuals. The authors also noted that "presenting two kinds of scents in one breath is not suited for switches of scents" (pg. 307).

There have also been attempts to create tele-olfactory systems using chemical-based olfactory displays, such as the one presented by Nakamoto *et al.* (2008). In their system, participants could choose remote objects to smell in real time, which were synchronized with streaming videos of the objects. This system was achieved by creating an odour recognition system which could send the smell and visual information over the internet to the receiver. The objects were then reconstructed by the olfactory display and the visual monitor. The olfactory display was comprised of an array of solenoid valves which could blend various odour components to recreate the smell. However, the experiment was only performed on just apples and oranges, as the recognition system, or classifier, required extensive training to recognize even just a few odours.

A downside with the work discussed thus far is that they required chemicals to mix and spray toward the user, which resulted in non-portable and bulky instruments. An investigation into 'digital' smell revealed that it may be possible to stimulate the brain or olfactory bulb directly, such as in experiments conducted where olfactory 'hallucination' symptoms were induced like those produced by synaesthesia. In one experiment, the frontal lobes of children with epilepsy were stimulated electrically with nodes (Kumar *et al.*, 2012). In the study, 69% of the child subjects reported smelling something when the stimulation was applied, however, 81% of these reported smells were perceived as unpleasant. While this research direction was promising, it is highly speculative to suggest that it could be leveraged for interactive purposes, as there have been no significant studies which have indicated such stimulation methods could be used for digital smell perception. As such, digital smell is not yet viable as a methodology to stimulate olfaction.

This section reviewed a variety of work in olfactory delivery systems. Commercial applications were discussed, though none have gained significant market attention. Little work has been carried out in HCI: work has mainly examined the technical issues with using smell in interactions but has not thoroughly investigated if smell could be useful to communicate information like emotion. Tele-olfactory delivery systems were described, though the reproduction of smell remotely is difficult. Lastly, digital stimulation of the sense of smell through electro-magnetic stimulation methods were explored, though no significant work had demonstrated that this could reliably control smell.

After consideration of the alternative means of delivering smell, this thesis decided to focus its attention on the chemical use of smell to investigate if smell could communicate emotional content on its own. Several pilot studies are proposed: first to examine if users could consistently rate the emotions of smells alone (Section 2.4.1), and then to study if subjects could agree on the perceived emotional content of text messages alone (Section 2.4.2). These studies were also conducted to select smell and message stimuli so that the effect of smell on text messages could be studied further in the main experiment (Section 2.6). No technology for emitting smell was developed for the smell pilot study in Section 2.4.1: this eliminated the additional challenge of testing a smell display implementation and allowed for testing different kinds of smells quickly with human subjects.

2.4 Pilot Studies

As discussed in Sections 2.1 and 2.2, there exists a link with human olfaction and processing of emotion. Thus, it may be possible to use smell to augment information, like emotion, in human communication. Some studies have mapped other stimuli modalities to certain emotions by asking subjects to rate their excitement (arousal) and their pleasure (valence), when they were presented with images (Lang *et al.*, 1999) and texts (Bradley and Lang, 1999). A question therefore remains as to how smell could be used to augment a user's perceived valence and arousal of text messages. For example, would subjects rate a pleasant smell, like honey, and a pleasant text message more pleasantly or less pleasantly than if they had perceived the message without the smell of honey?

To address this question, first, two pilot studies were carried out with 20 participants at different times. The first pilot study assessed how consistently the 20 participants could associate specific smells with certain emotions selected on a computer display in the lab. The second study, using the same 20 participants, instructed them to associate the content of text messages with certain emotions selected on their own computer display at home.

2.4.1 Pilot 1 – Smell Stimuli

The objective of the first pilot study was to assess how well participants could associate a smell with particular emotions and to identify issues with odour delivery. Participants were instructed to categorise 12 smells by selecting one of the eight emotions presented to them in the emotion wheel shown in Figure 2.4 (shown in Section 2.4.1.3). They were also instructed to select an emotion intensity (not to be confused with the intensity of the smell).

2.4.1.1 Measuring Emotion

This thesis examined how technology-based implementations of sensory displays can communicate information to users. Emotion as a form of information was selected in this chapter because of the property of emotion as an ongoing continuous process that undergoes "constant modification" which can be measured and analysed (Scherer, 2005). In this case, the information can be both the subjective-emotional content of media and the perceived emotional content of sensory stimuli presented using an implementation of a sensory display device. Thus, this thesis argues that by measuring changes in how subjects rate the media with and without the presence of sensory modalities, such as smell, the implementation's ability to send information can be assessed based on whether the perceived emotion of the media was augmented or not.

There is no general agreement in academia regarding the definition of what constitutes *emotion*. Most attempts to verify emotion empirically in studies are constrained by the ambiguity of language, as well as culture and individual differences, which "make it difficult to define central working concepts in the universal, invariant, and consensual fashion generally required by a systematic scientific approach" (Scherer, 2005, pg. 696). Zimmermann *et al.* (2003) defined emotion as the embodiment of body reactions and affective feelings, however, this is one of over a hundred such scientific definitions of emotion (Kleinginna and Kleinginna, 1981). Nevertheless, there is a strong interest in HCI research to examine how computer interfaces can communicate qualities like emotion (Brave and Nass, 2003), particularly in the area of *affective computing* (Picard, 1999).

Therefore, it is necessary to first discuss how this thesis collected the subjects' emotional perceptions so that the emotional data could be categorised and analysed empirically. This thesis took a conservative approach which looked to emotional models to examine the effect of smell on augmenting the subjects' perceived emotion of text messages. By using an emotional model, the perceived emotional content of text messages alone and in conjunction with sensory modalities, like particular smells, could be measured in order to determine the effectiveness of the implementations at changing the perceived emotional content of the text messages.

Several emotion models had been proposed in psychology. Russell's *circumplex model* (1980) is a *dimensional* method which depicts emotion as consisting of two dimensions: *valence* (pleasant vs unpleasant) and *arousal* (excited vs calm) (Russell attributed arousal to 'alertness' and valence as a pleasure–displeasure continuum). Another model was proposed by Ekman (1992) who postulated that emotion could be broken into six discrete emotions: anger, disgust, fear, joy, sad, and surprise. Many other models exist; however, Russell's circumplex model is more well-known and has advantages over Ekman's discrete model due to its utility for reporting emotion feelings, general reliability, and ease of analysis due to the use of interval scales (Scherer, 2005). Thus, this thesis decided to adopt the circumplex model.

A popular method of rating emotion with the circumplex model is the *emotion wheel*. An example of an emotion wheel, used by Gill *et al.* (2008) and overlaid with the two axis for valence and arousal, is shown in Figure 2.2. Eight emotions are mapped around the circle. These are, in clockwise order starting at the 13:00 position: Surprise, Joy, Anticipation, Acceptance, Sadness, Disgust, Anger, and Fear. In addition, a neutral emotion lies at the centre of this particular wheel implementation.

The eight emotions around the emotion wheel can be categorised by valence and arousal depending on their location within the wheel. The valence and arousal axes in Figure 2.2 intersect each other at the neutral point, which partitions the eight emotions into a 2-diminsional space with four quadrants. The four emotions on the right side of the wheel (Surprise, Joy, Acceptance, and Anticipation) are high valence, or pleasant emotions. The four emotions which lie on the left side of the wheel (Sadness, Disgust, Anger, and Fear) are low valence, or unpleasant emotions. The four emotions that lie above neutral (Anger, Fear, Surprise, and Joy) are highly arousing, or exciting emotions. The four emotions that lie below neutral (Sadness, Disgust, Acceptance, and Anticipation) are low arousal, or calm emotions. Thus, each emotion falls within one of four quadrants in the two-dimensional space, though emotions that share the same quadrant can still have markedly different valence and arousal qualities. For example, Surprise and Joy both fall in the high valence/high arousal quadrant, meaning they are both pleasant and arousing emotions, but Joy is ‘happier’ and less arousing than Surprise. The middle of the emotion wheel, the intersection point of both axes, represents the neutral state of emotion, which denotes a space that is neither pleasant nor unpleasant and neither calm nor exciting. This is similar the middle point used in Likert scales that indicates the subject is indifferent or unsure about how they feel about their response. The distance from the neutral point to the wheel circumference indicates a degree of emotional intensity, with eight different strengths.

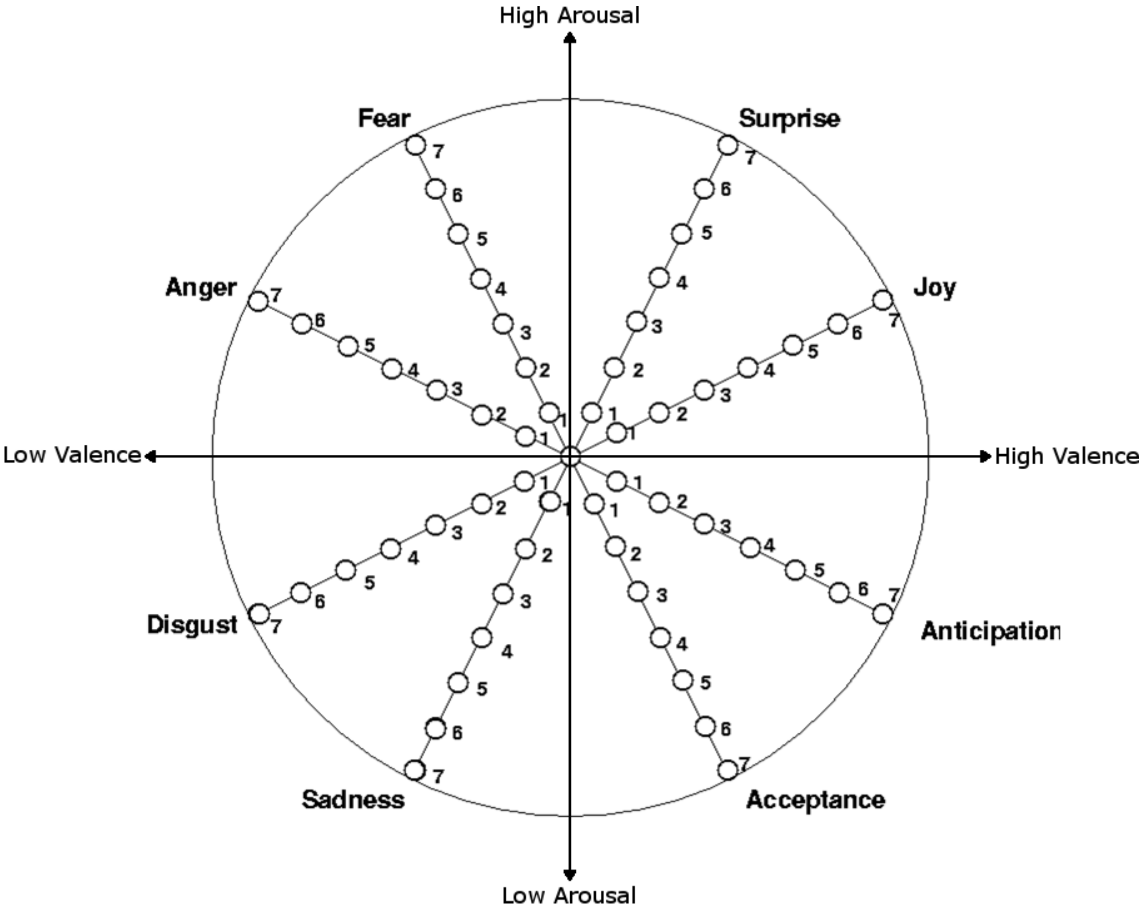


Figure 2.2: An emotion wheel implementtion overlaid with Russell’s circumplex model, depicting valence and arousal as two dimensions within a cartesian space with eight emotions: Surprise, Joy, Anticipation, Acceptance, Sadness, Disgust, Anger, and Fear. Each emotion has 8 degrees of intensity, from 0 ‘Neutral’ to 7 (image adapted from Gill et al. 2008).

A procedure used throughout this chapter (and in Chapter 3) in analysing the emotion wheel results from stimuli, will be to calculate the stimuli's *valence rating* (and arousal rating). This provides a manner of coding each emotion and its intensity rating as a single statistic in terms of either valence or arousal depending on the selected emotion's location in the wheel. Figure 2.3 shows an example of how this statistic is calculated for valence. The selected emotion and intensity gets 'flattened' to the horizontal axis so that the rating is converted to a 15-point scale from -7 to +7 (with 0 as the neutral point). The sign of the rating is determined by the location of the emotion in the wheel. Pleasant or arousing emotions are assigned a positive sign and for unpleasant/not arousing emotions, the sign becomes negative. For valence, the rating is flattened across the horizontal axis, as shown in Figure 2.3; for arousal, the ratings are flattened across the vertical axis. Once the valence and arousing ratings are created for each stimuli, further statistical testing can be performed on this data. For example, the mean valence rating is computed by averaging the calculated valence ratings for all participants, likewise the mean arousal rating is the average of all the arousal ratings across all subjects' responses to a stimulus.

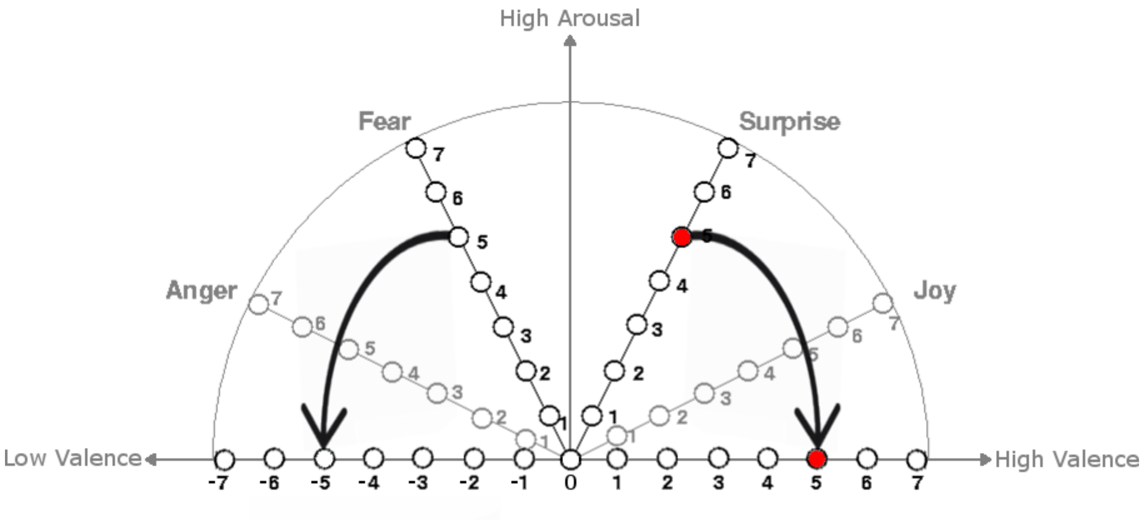


Figure 2.3: Example of 'flattening' the subject's emotion wheel rating of a stimulus to obtain the valence rating on a 15-point scale from -7 to +7. Here, the subject choose 'Surprise 5', which becomes a valence rating of +5 on the 15-point scale on the horizontal axis. Emotion ratings on the left side of the vertical axis become negative when they get flattened, and are assigned a '-' sign.

This section provided an overview of how experiment participants can report the emotion they feel is communicated with in some medium, such as text messages. Emotion is difficult to define and many definitions exist. Furthermore, there are many ways emotion can be modelled. This research adopted the circumplex model due to its reliability, understand-ability, and ease of analysing due to the use of interval scales. The emotion wheel was described as a way of obtaining ratings of stimuli in a study, and the procedure by which the emotion wheel data is analysed in this thesis was discussed. The emotion wheel is used throughout this chapter and the next as the manner of how subjects reported their emotional feelings with.

2.4.1.2 Stimuli Design

Twelve different smells were used for the smell pilot study. These are shown in Table 2.1. They were ordered from Demeter (https://demeterfragrance.com), an online perfume company, which supplied the smells as liquids in mini cologne bottles.

Smell ID	Smell Name
1	Dust
2	Pink Grapefruit
3	Baby Powder
4	Swimming Pool
5	Oud
6	Mildew

Smell ID	Smell Name
7	Fresh Hay
8	Rain
9	Dirt
10	Pure Soap
11	Earthworm
12	Honey

Table 2.1: Smell stimuli, colour coded based on hypothesised valence. Blue = pleasant, grey = neutral, and red = unpleasant.

These twelve smells were divided into three groups of four smells each in terms of valence: pleasant, unpleasant, and neutral. To choose smells for testing based on these three categories, keywords associated with positive, negative, and indifferent (neutral) words were searched for in the customer reviews on the Demeter website. For instance, Earthworm was described as ‘musty’ and ‘slimy’, which connotes negative feelings. Based on this procedure, ‘Honey’ and ‘Baby Powder’ were smells reviewed by customers as favourably pleasant scents, while fouler smells like ‘Dirt’ and ‘Earthworm’ were rated by customers as unpleasant. ‘Rain’ and ‘Dust’ were not reviewed as particularly pleasant or unpleasant, and were thus placed in the neutral group. These are colour coded in Table 2.1, with blue indicating pleasant smells (high valence), grey indicating neutral (an emotional state that is neither pleasant nor unpleasant) smells, and red indicating unpleasant smells (low valence). In this thesis, pleasant and unpleasant will refer to high valence and low valence, respectively.

2.4.1.3 Procedure

Participants were first sent a participation agreement form (Appendix H.1) to be signed in advance in accordance with the university's ethics procedures (this form was used for the main study in Section 3.6 as well). The participants had to confirm that they possessed a 'normal sense of smell', that they had no history of olfactory dysfunction, were not currently suffering from cold/flu or other temporary respiratory problems at the time, did not suffer from asthma or any form of air-born allergies, and had normal or corrected-to-normal vision. They were also notified of their right as a participant to stop the experiment at any time.

Participants were instructed to come to the lab on their scheduled days. They sat down in front of a computer terminal for the duration of the experiment. They were first asked to input their personal information, including their nationality, age, and sex, which was recorded into a database along with their responses in the study. They were then presented with on-screen instructions that described how to record their responses (Appendix G.1). At this point, they could ask the lab monitor any further questions. Otherwise, they clicked the 'OK' button, which began the test.

The participants were presented with a scent stimulus and simultaneously, the emotion wheel, which appeared on the display in front of them. At the start of each trial, participants were handed an unmarked bottle containing the trial's scent. To prevent the smells from lingering in the air if sprayed, participants were instructed to sniff the contents of each bottle as many times as they wished before marking a response. They would then rate the emotional feel of the smell, or the smell's perceived emotional content that they believed the smell was conveying to them, using the emotion wheel interface shown in Figure 2.4. Once they had made their selection on the wheel, they were instructed to click on the 'Next' button at the bottom of the screen, which would start a new trial. Smells were given in the ID order shown in Table 2.1 and were presented only once to the participants.

Before running the pilot, it was necessary to run a 'pre-test' beforehand to first assess the design of the study for any issues. This provided a more exploratory approach to designing the study, and it allowed experimenting with various methods of delivering smell stimuli. Four people volunteered to participate in the initial pre-test. The data collected is detailed in Appendix A.1.

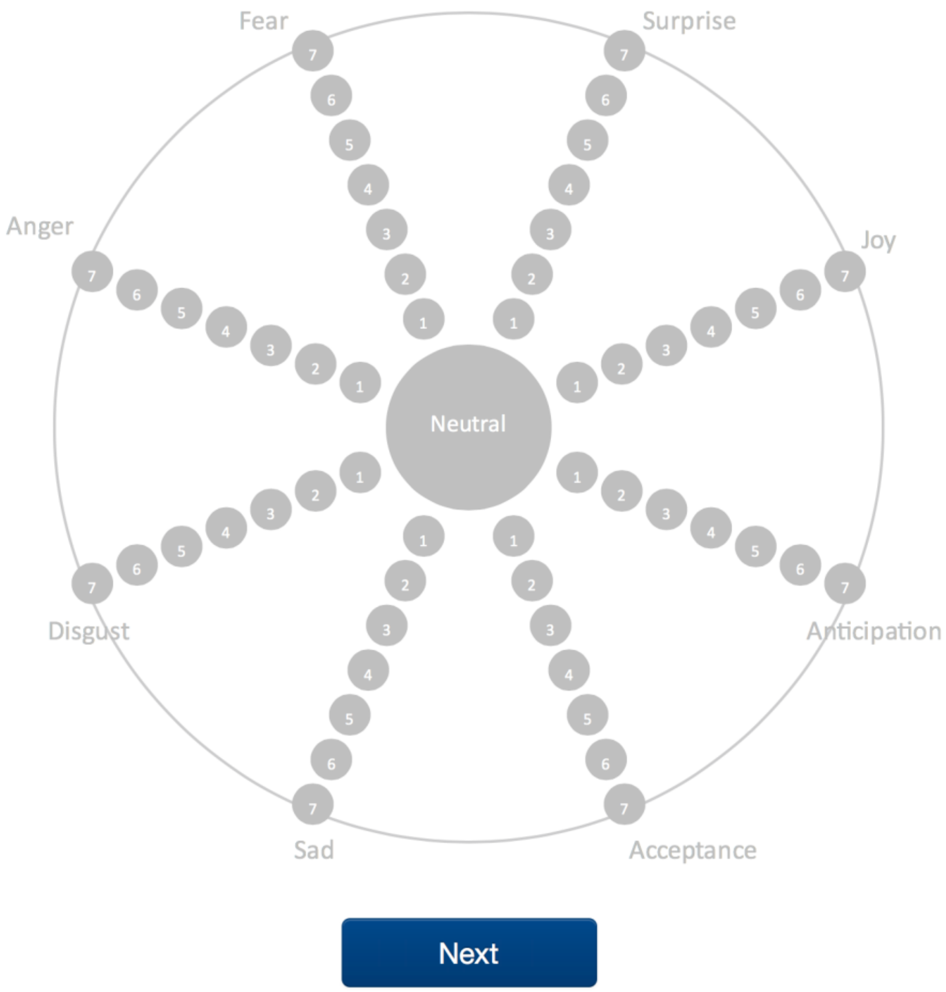


Figure 2.4: Emotion wheel interface that the subject would see on the computer terminal display in front of them.

To assist in analysing the results of the pre-test, marking criteria were introduced. If all four participants agreed on the valence of a smell, then the smell was categorised as pleasant, unpleasant, or neutral. Other smells that were rated with a mix of pleasant, neutral, and unpleasant emotions were categorized as 'ambiguous'. This meant that a least one of the four subjects disagreed with the other participants over the smell's valence. This allowed for easy assessment of whether participants were in strong agreement over the smell's valence.

Only 'Swimming Pool' was rated as a pleasant smell, and 'Rain' was the only smell consistently rated as unpleasant by all four participants. The other smell stimuli were rated ambiguous overall, with differing levels of agreement by the participants. For example, three out of four participants rated ‘Dust’, ‘Baby Powder’, ‘Oud’, and ‘Mildew’ as smells that felt unpleasant. Participants were evenly split on how ‘Honey’, ‘Earthworm’, ‘Pure Soap’, and ‘Fresh Hay’ made them feel. Only one participant rated a smell as having a neutral valence (‘Mildew’).

Because of the overall ambiguous ratings, some changes were made to the pilot study procedure. One of these changes included changing the presentation order, as there may have been possible ordering effects resulting from smells not being randomized in the pre-tests. Further changes included adding a timer in the software to log how long participants took to complete each trial. To make the perceived intensity of each scent the same, the concentrated smell solutions were diluted in different volumes of water and tested beforehand with volunteers.

Finally, the manner the smells were delivered and the number of sniffs allowed was also altered to make delivery more consistent. First, wafting smells directly from the bottle was deemed inappropriate for consistent delivery as some smells have different intensities, and users may miss odours if they did not waft the odours strong enough. Spraying odours, on the other hand, would ensure more equal disbursements of the smells as they could be delivered via small airborne droplets to ensure being inhaled by the users. Second, as mentioned in Section 2.1, excessive exposure to smell can decrease sensitivity to the odour (Dalton, 2000; Wang *et al.*, 1993). In the new procedure, the lab monitor took a more direct role in choosing the correct bottle from a pre-determined order. They then sprayed the contents in front of the participant once from pre-prepared, identical spray bottles. To disperse the scent from the environment, a box fan was turned on for ten seconds in between each trial to ventilate the smell from the room and though an open window.

The full pilot study with the modified procedure was conducted at Keio University’s Graduate School of Media Design in Japan, as was done with the pre-test. 20 participants were selected who were graduate students of mainly Japanese nationality, with a small percentage of subjects having Indonesian, Taiwanese, American, Malaysian, and Brazilian nationality. Appendix A.2 details all participant information collected, with their names omitted to maintain their anonymity. Their ages ranged from 19 - 27, with a mean age of 23.5 years (σ = 2.01 years). 12 participants were male and 8 were female. Participants were paid the equivalent of

$10 in yen for their participation. The experiment had the ethics approval of the university.

To summarize the procedure:

- 20 participants were given 12 unique smell stimuli, one at a time.
- The lab monitor sprayed the smells in front of each participant once from pre-prepared, identical spray bottles.
- The participants were instructed to rate the emotional feel of each smell by making a selection on the emotion wheel.

2.4.1.4 Results

The raw data collected can be referred in Appendix A.3. The independent variable was the smell administered. The dependent variable was the valence and arousal ratings obtained from the emotion wheel.

Smell Name	+	N	-	Mean Valence	Std Dev
Dust	6	0	14	-1	3.18
Pink Grapefruit	19	0	1	3.75	2
Baby Powder	13	0	7	1.1	3.45
Swimming Pool	11	2	7	1.3	3.73
Oud	7	1	12	-1.2	3.43
Mildew	3	1	16	-2.7	2.74
Fresh Hay	10	1	9	0.15	3.96
Rain	6	0	14	-1.3	3.71
Dirt	5	5	10	-1.25	3.08
Pure Soap	13	0	7	2.05	3.66
Earthworm	2	3	15	-2.55	2.58
Honey	11	0	9	0.8	4.06

Table 2.2: Smell Pilot Valence Results. Numbers under the '+', 'N', and '-' columns indicate the frequencies for pleasant, neutral, and unpleasant responses. The 'Mean Valence' column contains the mean valence ratings for each smell. The 'Std Dev' column shows the standard deviations of the valence ratings for each smell.

Table 2.2 shows the summarised outcome of the pilot. The '+', 'N', and '– ' columns indicate the pleasant, neutral, and unpleasant response frequencies, respectively, for each smell. For example, 6/20 (30%) of participants rated 'Dust' as a pleasant smell, 0 participants rated it as a neutral smell, and 14/20 (70%) of participants rated it as an unpleasant smell. Highlighted markings indicated frequencies where at least 13 out of the 20 subjects agreed on the valence of the smell.

Another useful metric used to quickly 'grasp' the valence results for each smell was by examining their *mean valence rating*, shown under the 'Mean Valence Rating' column in Table 2.2. The procedure for obtaining this was discussed in Section 2.4.1.1. For example, Participant 3's response to 'Honey' was Acceptance 5. 'Acceptance' is a pleasant emotion, so the participant's intensity rating of 5 became a valence rating of +5. Participant 2's response was Disgust 2, which is an unpleasant emotion, so the intensity rating became a valence rating of -2. After computing each participant's response in this manner, all 20 of the subjects' valence ratings were then averaged to give the mean valence rating for that particular smell. Mean valence ratings for the smell pilot study ranged from -2.7 to 3.75, indicating that subjects found the smells almost moderately unpleasant to moderately pleasant. Figure 2.5 below shows box plots of the valence ratings for all 12 smells.

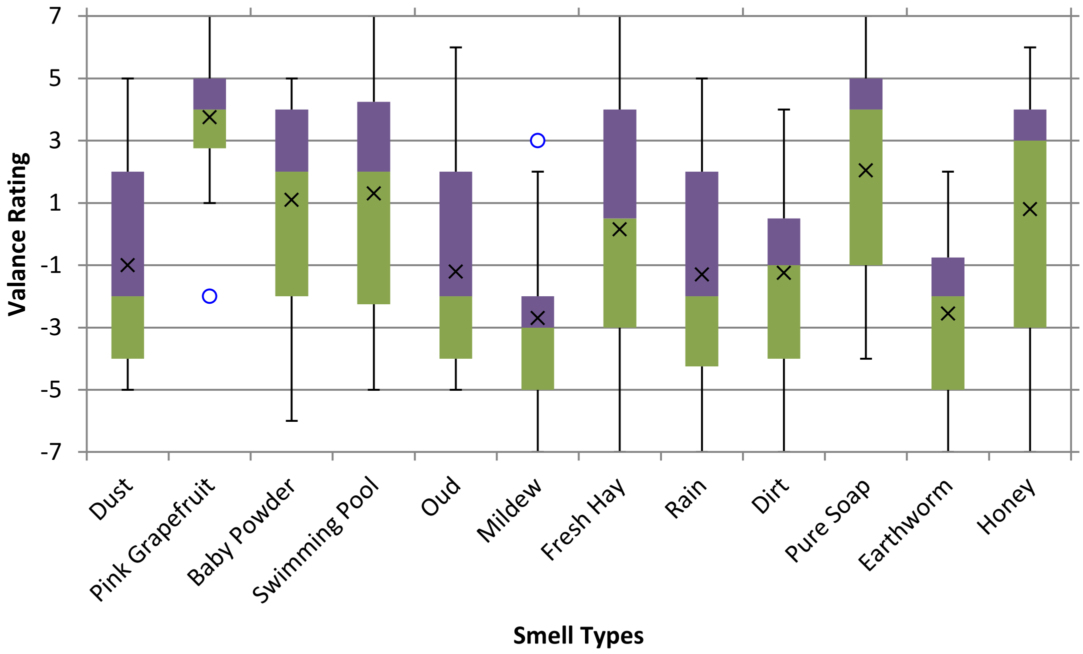


Figure 2.5: Box plots of the valence ratings of the 12 smells.

Examining both the frequencies and the mean valence ratings, as well as the boxplots in Figure 2.5, allows for insight as to which smells had the greatest and most consistent effect on how their valences were perceived. Only 'Pink Grapefruit' received a strong high valence rating. It had the highest mean valence rating of 3.75, with 95% of participants rating it as strongly pleasant. 'Baby Powder' and 'Pure Soap' tied for the second most pleasant smells in terms of frequency, as 65% of participants rated them with pleasant emotions. However, 'Pure Soap' had a higher mean valence rating of

2.05, therefore it was selected over the ‘Baby Powder’ odour as another pleasant odour to study further. ‘Mildew’ was selected by 80% of participants as an unpleasant smell and it also had the lowest mean valence rating of -2.7. ‘Earthworm’ was rated by 75% of participants as an unpleasant smell and it had the second lowest mean valence rating of -2.55. No smells produced consistently neutral ratings in terms of frequency and mean valence ratings however.

To examine if these results were statistically significant, analysis was done on the calculated valence ratings of all 12 smells, and then, on the four smells: ‘Pink Grapefruit’, ‘Baby Powder’, ‘Mildew’, and ‘Earthworm’. Figure 2.6 shows the boxplots of just the four selected pleasant and unpleasant smells selected for reference.

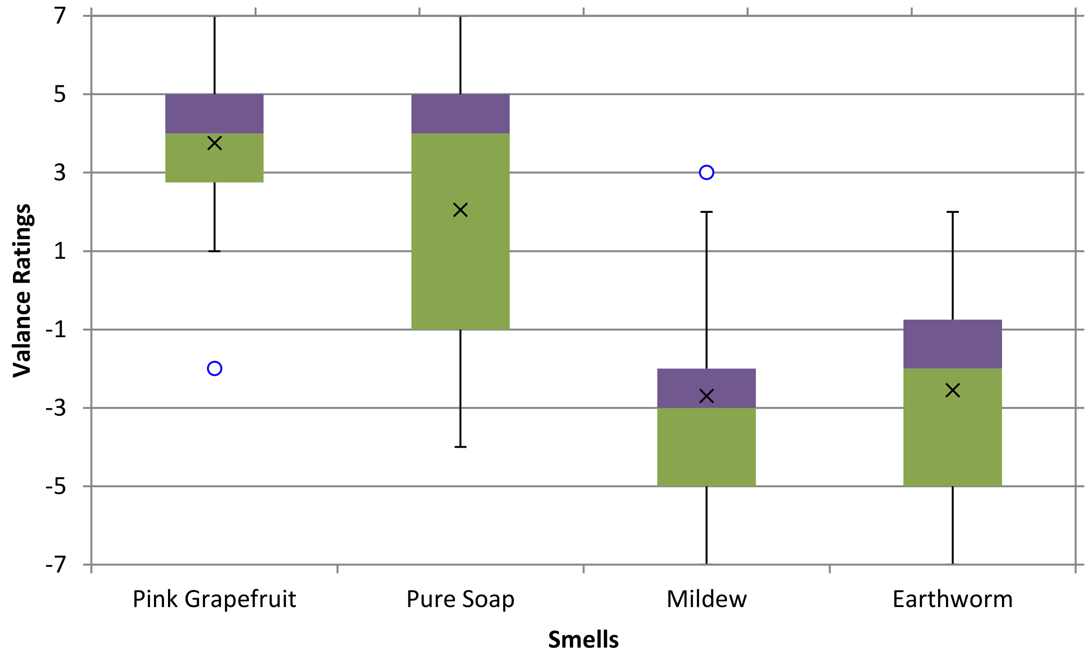


Figure 2.6: Boxplots of the pleasant smells (‘Pink Grapefruit ‘and ‘Pure Soap’) and the unpleasant smells (‘Mildew’ and ’Earthworm’).

First the data was tested for normality using a Shapiro-Wilk test. This produced $p < 0.001$ ($W = 0.94$). Thus non-parametric tests were subsequently used. A Friedman test across the 12 smell treatments valence ratings produced $p < 0.001$ ($Q = 56.06731$, $df = 11$), indicating that at least one of the treatments was statistically, significantly different amongst the other 11 smells. This was expected (as no differences would indicate the subjects emotionally perceived all the smells to be the same). Furthermore, testing the four selected smells: ‘Pink Grapefruit’, ‘Pure Soap’, ‘Mildew’, and ‘Earthworm’, using a Friedman test revealed evidence that at least one of them was also different from each other ($p < 0.001$, $Q = 27.29$, $df = 3$). Again, this was expected, and so these four smells were tested with further non-parametric tests.

Further pairwise testing using Wilcoxon signed rank tests (exact tests) was needed to determine similarity of the two pleasant smells and then, for the two unpleasant smells. Significances would mean that the two pairs of smells were rated differently. Testing the two pleasant smells produced $p = 0.05$. Testing the unpleasant smells produced $p = 0.85$. This indicated that the smells in each pair were rated similar to each other as no significant differences were found within the pairs.

Lastly the two pairs of pleasant and unpleasant smells were compared against each other for any similarity. This was prepared by combining each pair into a single treatment so that the results were two treatments of 40 rows: a pleasant smell treatment and an unpleasant smell treatment. This will be a standard procedure when comparing arbitrarily positive, neutral, and negative stimuli when there is more than one stimulus in each group, assuming there is no statistically, significant differences within each group, as was tested beforehand. Comparing the pleasant smells and unpleasant smells using an exact Wilcoxon signed rank test produced $p < 0.001$, indicating a strong, significant difference between the pleasant and unpleasant smells. As the mean valence ratings for both pleasant smells were positive and the mean valence ratings for each of the unpleasant smells were negative, the conclusion is that they are indeed, pleasant and unpleasant smell stimuli.

The outcome of the pilot study found that participants did rate smells differently in how the smells made them feel emotionally. ‘Pink Grapefruit’ and ‘Pure Soap’ were the most pleasant smells out of the 12 smells that were tested. These two smells had the highest mean valence ratings and highest frequencies associated with pleasant emotions. ‘Mildew’ and ‘Earthworm’ were given the lowest mean valence ratings in the group and had the highest frequencies associated with unpleasant emotions. Thus, they were considered the most unpleasant smells out of the 12 that were tested. No smells however, were rated to be neutral per the criteria described here.

Before moving on to the next pilot study, it should be noted that this research also attempted to examine the arousal component of these smells, that is, which smells were calm and exciting. Unfortunately, after examining the pilot data, it was determined that no smells were rated as high valence/high arousal or low valence/high arousal. Mean arousal ratings, calculated like the mean valence ratings (again refer to

Section 2.4.1.1 for how this was calculated), fell into a much tighter range of -2.25 to 0.9, indicating that the smells overall were interpreted by participants as calming. Only the 'Honey' smell was rated to be highly arousing by 65% of the subjects and was the only smell to have a positive, mean arousal rating of 0.9. Figure 2.7 shows the boxplots of the arousal ratings of the 12 smells to illustrate this.

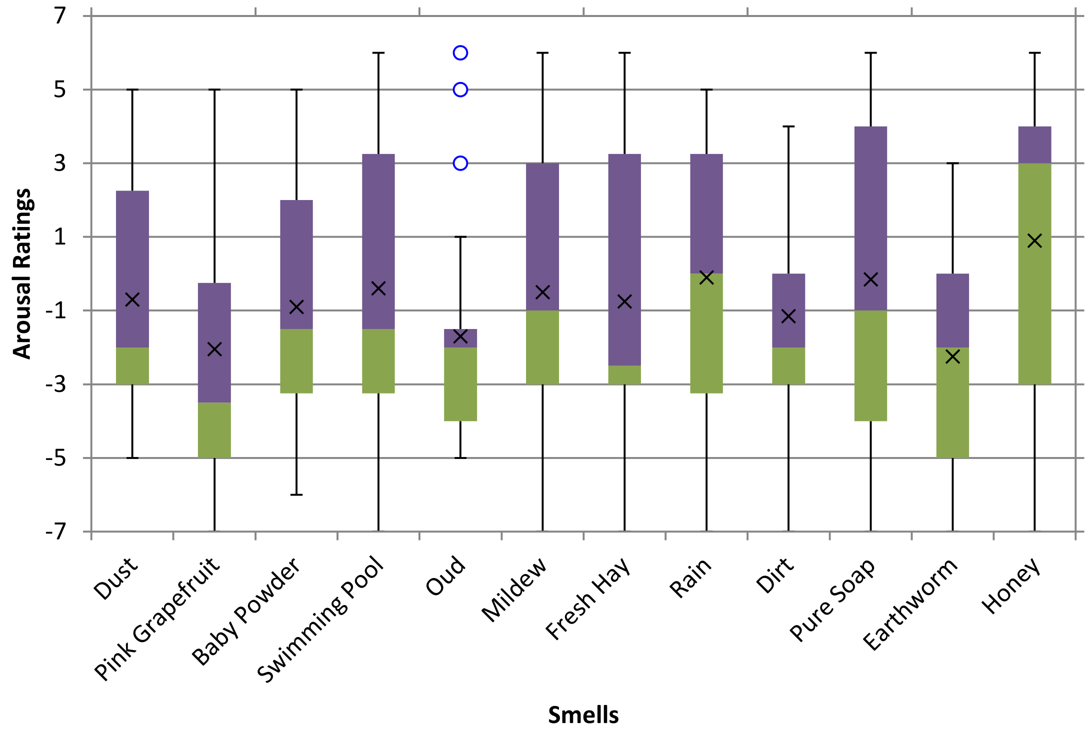


Figure 2.7: Box plots of the arousal ratings of the 12 smells.

Further statistical analysis using Friedman tests confirmed that the smells were given similar arousal ratings. A Friedman test was performed across all 12 smells, using the smells' arousal ratings. This produced p = 0.19, (Q= 14.70) indicating that there was no statistically significant difference in arousal ratings between the smell stimuli. This is evidenced by the similarity of mean arousal values for the four selected smells, as all four smells had negative mean valence ratings of -2.05 (σ = 3.79), -0.15 (σ = 4.22), -0.5 (σ = 3.86), and -2.25 (σ = 2.86) for 'Pink Grapefruit', 'Pure Soap', 'Mildew' and 'Earthworm', respectively. Thus, this thesis halted any further investigating of arousal in this chapter, and only investigated the emotional effects of valence using smell.

2.4.2 Pilot 2 - SMS Messages

There was a question as to what kind of media would be used to measure the augmentation effect of smell. Short text messages can be sufficient for detecting emotions, opinions, and other subjective information of the writer (Martinazzo *et al.* 2011). Specifically, SMS text messages were considered due to their brevity of conveying specific situations in a variety of circumstances, regardless of where the user was when reading them. Furthermore, studies have examined how human subjects emotional perceive such text messages (Tagg, 2009). These studies have also produced open source databases of text messages categorised by emotion. However, there has not been sufficient work published that has examined the use of smell in controlled studies to augment the emotional content of text messages.

To first confirm which messages would be suitable for presenting to participants with smell, a second pilot study was ran to find which messages could be consistently rated by subjects to be pleasant, unpleasant, or neutral. This would make it possible to then examine the effect of pleasant, unpleasant, and neutral smells on subjects' emotional perceptions of text messages. For example, can pleasant messages be further augmented by pleasant smells to feel even more pleasant? Or, can unpleasant smells reduce the valence of pleasant messages so that the subjects feel that the content of the message is unpleasant?

2.4.2.1 Stimuli Design

A list of 450 messages, gathered by a previous study in the UK (Tagg, 2009) was used as the basis for the SMS text message stimuli. Out of the 450 text messages used in Tagg's study, 113 messages, which can be referred to in Appendix A.4, were subsequently selected from this list that the experimenter felt were fully understandable to a Japanese reader and contained no profanity. As this study took place in a Japanese university, it was necessary to translate the messages into Japanese. A native Japanese lab colleague performed the task (Appendix A.5 contains the Japanese translations of the 113 messages from Appendix A.4) and inserted them into a database managed by Parse, a cloud-based, database backend tool. Another lab colleague programmed a web script that both randomised the order of the messages and displayed them sequentially on a webpage.

2.4.2.2 Procedure

The procedure of this study generally followed the first pilot, with some key differences. First, participants were not required to come to the lab to complete the study, except for handing in their consent form to verify that they were fluent Japanese speakers. After this, they could perform the test in their own leisure and on their own PC. They simply had to connect to the internet and login to a webpage to take the test. After logging in, they were presented with an online form where they had to register their name, age, and sex. They were then provided with written instructions on screen (Appendix G.2).

After clicking the 'OK' button, an SMS message appeared on their PC screen, with the emotion wheel appearing below. This is similar to the user interface shown in Figure 2.4 in Section 2.4.1.3. The participant then proceeded to rate the emotional feel of the text message using the emotion wheel. Once the participant selected an emotion and intensity on the wheel and were satisfied, they would click the 'Next' button. This displayed the next trial's message and would reset the emotion wheel form.

As before in the previous pilot study, a pre-test was run with three volunteer participants, who had participated in the smell pre-test. All text messages were presented in Japanese. A similar analysing strategy was re-used from the smell pre-test (see Section 2.4.1.3 for this criteria) that categorised the stimuli, this time text messages, as either pleasant, neutral, unpleasant, or ambiguous. For example, Message #1 had ratings of Joy 5, Joy 2, and Joy 1 by all three pilot participants, so it was rated as a pleasant message. The data can be referred to in Appendix A.6.

Out of the 113 messages, 63 were rated as ambiguous, 41 were rated as pleasant, and 9 were rated as unpleasant, using this criteria. No messages were consistently rated as neutral across all participants. However, Participant #2 and #3 gave neutral ratings to some of the messages. A possible concern was that the neutral circle selection in the form was not made large enough. This was therefore enlarged (it should be noted that the final smell pilot test from Section 2.4.1 used the enlarged neutral button wheel as well, shown in Figure 2.4, as both the final message and smell pilots were conducted after pre-testing had finished for both).

As there were deemed enough pleasant and unpleasant messages from the pre-test to test with, the main pilot study proceeded, using the same 20 subjects from the smell pilot (refer to Section 2.4.1.3 for details of the subjects tested). To summarise the pilot procedure:

- 20 Participants were presented with 113 SMS styled text messages, one at a time.
- They were instructed to rate the emotional feel of the text messages by making a selection on the emotion wheel.
- They were allowed to do the experiment from their own PC using an online form at their own leisure.

2.4.2.3 Results

The data collected from the text message pilot can be referred to in Appendix A.7. The scope of the analysis was limited to examining the valence of the messages. As discussed in Section 2.4.1.4, categorising stimuli by arousal was ignored as it was difficult to obtain smells which could be categorised by how well they excited subjects after inhaling them. Because of this, message arousal was also ignored from further examination. For the remainder of this chapter, only valence, or pleasantness, was examined for stimuli.

By limiting the selection criteria of the messages to only valence, the process of selection was simplified, as only 3 categories of messages needed to be found (pleasant, unpleasant, and neutral, as opposed to pleasant/excited, pleasant/calm, unpleasant/excited, unpleasant/calm, and neutral). This simplification produced many pleasant and unpleasant message candidates, based on the resulting mean valence ratings of the messages and the frequency of subjects giving pleasant, unpleasant, and neutral ratings for each of the 113 messages. In total, out the 113 SMS messages tested, 39 pleasant SMS messages were found where more than 15 participants rated them positively, and 17 unpleasant SMS messages were discovered where more than 14 participants rated them negatively.

However, selection of neutral message stimuli were still difficult to obtain using the criteria based on mean valence ratings of the messages and the frequency of subjects giving neutral ratings to the messages alone. Therefore, a new criterion was introduced to choose neutral messages. This coding criterion used was based on the difference of the frequency of subjects who rated a SMS message as pleasant and those who rated the message as unpleasant. If this (absolute) difference was less than or equal to 3 participants, the message was considered neutral. For example, 8 participants rated Message #7, 'Beerage?', as a pleasant message, whereas 6 participants categorised it as neutral, and the remaining 6 participants associated the message with one of the four remaining, unpleasant emotions. Using the criteria scheme described above, this message was therefore, considered a neutral text message, as $|8 - 6| = 2$, which is less than 3. Using this criteria for neutral message selection, 17 SMS messages were found which could be used as neutral text message stimuli.

A concern from the message pre-test, which unlike the final message pilot had participants come to the lab to complete the test, was that participants showed signs of fatigue and boredom when rating all 113 messages. Testing many text message and smell combinations in the final study would have made the experiment last too long. Therefore, it was decided to reduce the three groups of pleasant (39 messages), neutral (17 messages), and unpleasant (17 messages) message categories to 10 messages each, for a total of 30 messages for use in the main study, which will be described in Section 2.6. A criteria for reducing the message count was to use only a maximum of two text messages per group that contained an emoticon, due to them explicitly conveying emotion graphically instead of within their textual content. Figures 2.8 - 2.10 show the box plots of the valence ratings of the 10 selected messages for each of the three groups.

After categorising and selection of the messages was complete, they were statistically tested to verify that the messages were fitted well for their valence category. First, all 30 messages were tested for normality with a Shapiro-Wilk test. This produced $p < 0.001$ ($W = 0.96$). As the data was not normally distributed, non-parametric tests were used in follow up testing. Testing the valence ratings (see Section 2.4.1.1 for how this was calculated) of all 30 messages across all subjects revealed a significant difference amongst at least one treatment (message) in the dataset ($p < 0.001$, $Q = 329.82$, $df = 29$), which was expected. Friedman tests were then run on the 10 messages of each of the message groups to test whether any differences between the mean valence ratings of each message were statistically significant (or are just due to random effects). These were then with followed up with post-hoc Wilcoxon tests comparisons between the pleasant, neutral and unpleasant message groups.

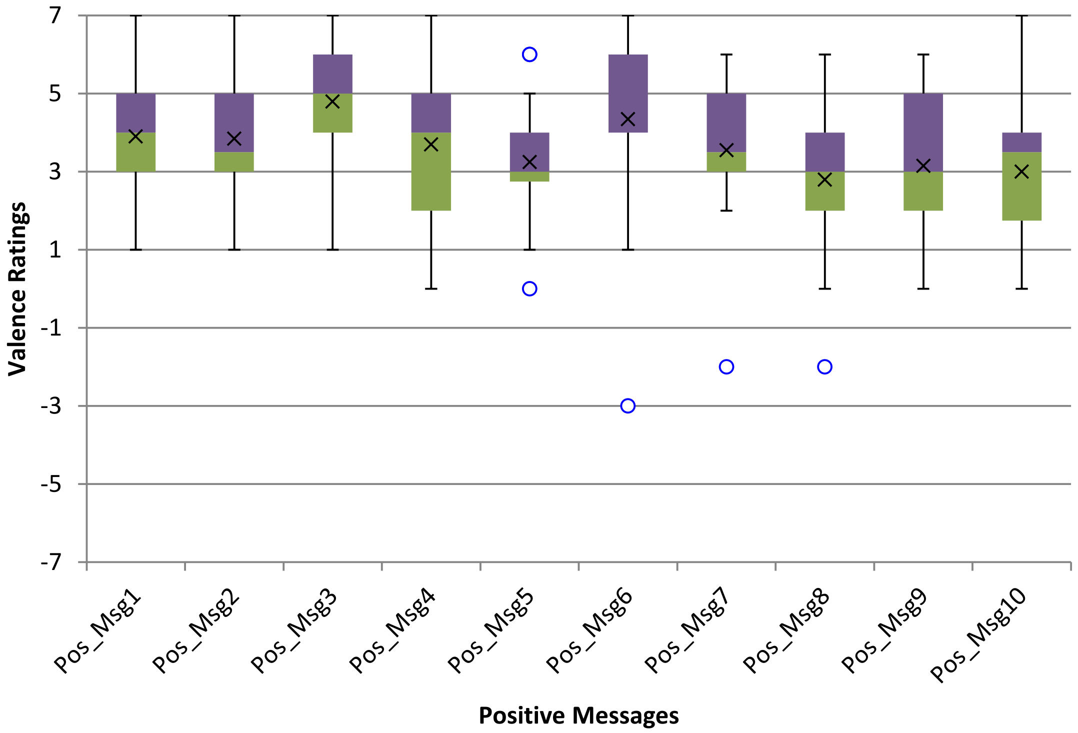


Figure 2.8: Box plots showing the valence ratings of the 10 pleasant messages.

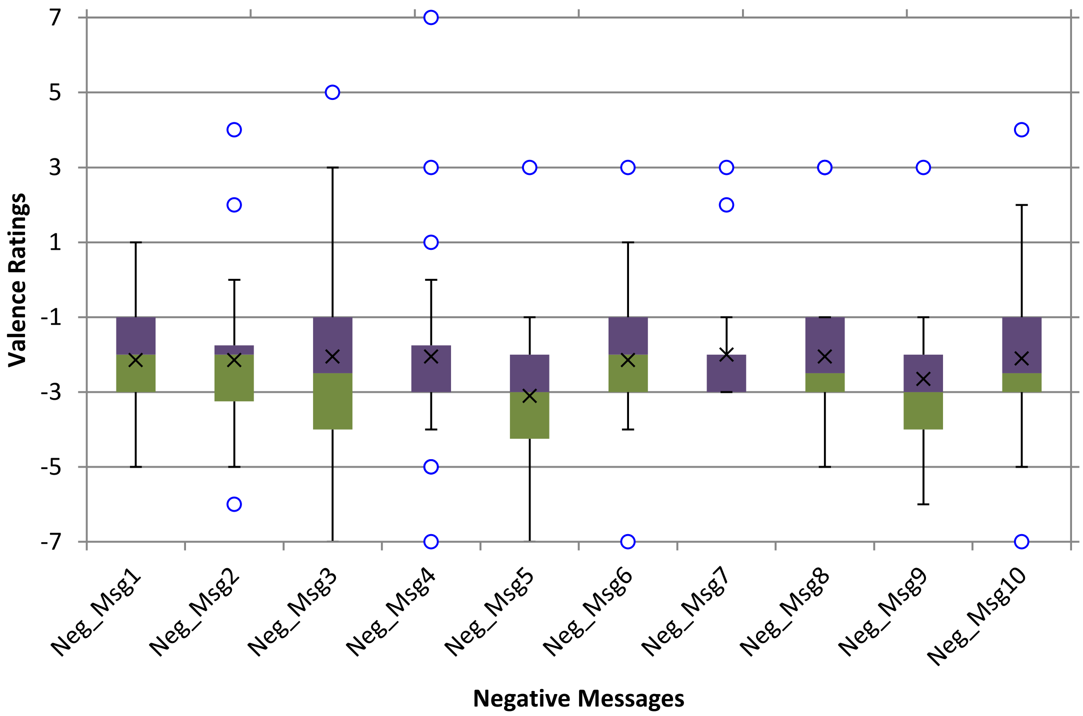


Figure 2.9: Box plots showing the valence ratings of the 10 unpleasant messages.

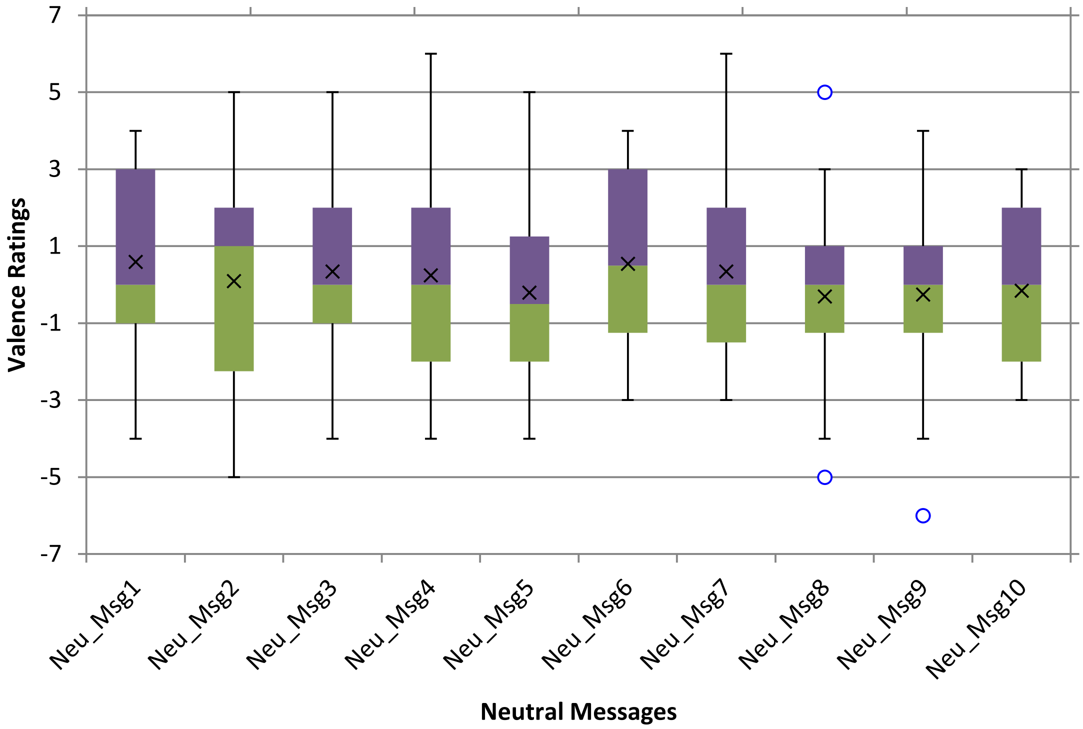


Figure 2.10: Box plots showing the valence ratings of the 10 neutral messages.

First, significant differences within the three groups was tested using Freidman tests. The testing of the neutral message group produced p = 0.99 (Q = 1.99, df = 9), with a mean valence rating of 0.13 (σ = 2.49). The testing of the unpleasant message group produced p = 0.45, (Q = 8.4, df = 9), with a mean valence rating of -2.25 (σ = 2.22). Thus, the messages were of strong similarity in how they were rated within their groups. However, a significant difference was found when testing the similarity of the 10 pleasant message ratings ($p < 0.001$, Q = 30.22, df = 9), which had a mean valence rating of 3.64 (σ = 1.89). This meant that there was a strong possibility that at least one of the 10 messages was not rated the same as the others. It may mean that this/these messages were not pleasantly rated, or that it/they were rated more pleasantly than the rest of the group.

In order to further test the validly of the three groups' categorised valences, the entire groups were tested against each other using Wilcoxon sign rank tests to find if there were differences between them. No differences would imply similarity between the groups, which would invalidate using them for further study. To prepare the data, each subjects' valence rating for all messages in each group was averaged to produce 3 columns of data, one column for each valence group (pleasant, unpleasant, and neutral). Figure 2.11 shows the boxplots of the mean valence ratings for all three message groups. These three treatments were then compared in pairwise Wilcoxon tests. Table 2.3 shows the results of the tests (all p-values reported are exact). As can be seen in this table, all pairwise test comparisons resulted in significant differences. Thus, while participants rated pleasant messages inconsistently, this group was still statistically, significantly different from the groups of neutral and unpleasant messages, and the latter two groups were found to have no significant differences in their intra-group mean valence ratings, as the p-values did not exceeded their significance levels for either group using Friedman tests.

These 30 messages were thus selected as message stimuli for the final study in Section 2.6, which examined combinations of these 30 messages and the smells selected from the smell pilot in pairs to subjects, one pair at a time, with the aim of understanding how smell could augment the perceived emotion of text messages. Before proceeding to Section 2.6, however, a new technology, the Scentee, was adopted to aid in the delivery of the scents to the participants as the smell display implementation. This will be discussed in the next section.

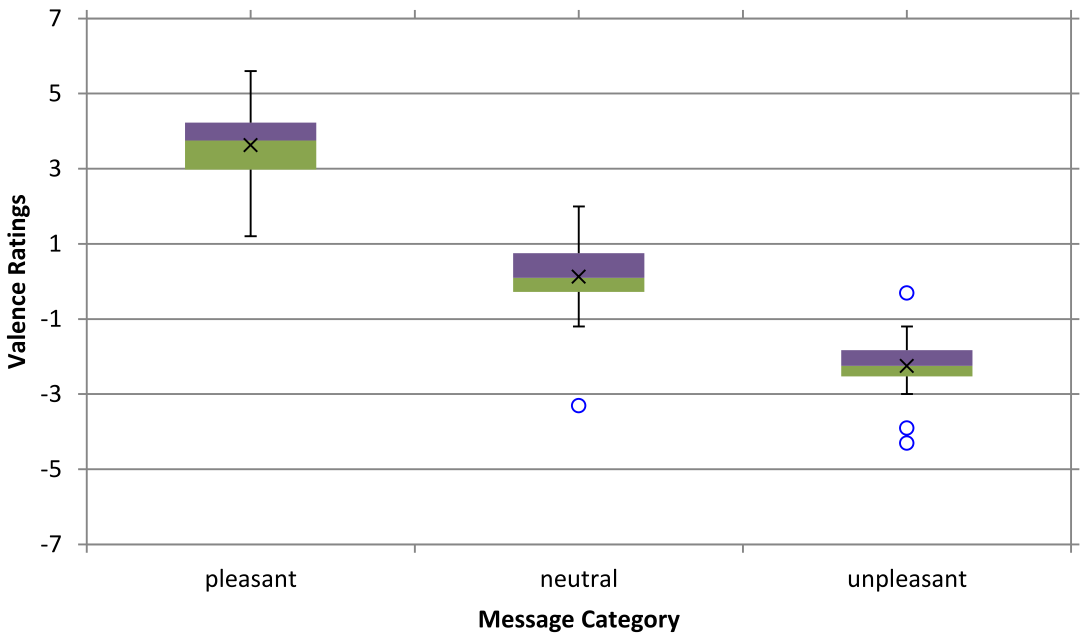


Figure 2.11: Boxplots showing mean valence ratings of the 3 message groups.

Message	VS	Message
Pleasant	$p < 0.001$	Unpleasant
Neutral	$p < 0.001$	Unpleasant
Pleasant	$p < 0.001$	Neutral

Table 2.3: Results of the Wilcoxon sign rank tests on the three pairs of message groups. All p-values are exact.

2.5 Scentee System Description

The smell pilot study detailed in Section 2.4.1 used two methods of delivering smell. In the pre-test, subjects unscrewed bottles of liquid scents and wafted the odours into their nostrils. The problem with this was that delivery was highly variable depending on their hand motions. The second method, used in the main pilot study, had the lab monitor spray the scents toward the subjects' faces. This too caused delivery to be uncontrollable as the amount sprayed could have been different depending on the pressure applied to the trigger. It also raised issues with dispersing the scents, as the distribution of the spray mist was uneven, causing the mist to collect into droplets which fell around the participant. This may had contaminated the area around the subject. This research, therefore, looked to existing commercial technologies to rectify this issue.

One commercial product, 'Scentee' (https://scentee.com), was investigated to see how effectively it could deliver scents. This device connects directly to a smartphone and can emit a single scent using ultrasonic peizo motors, which sprays the scent towards a user's face when the user holds his or her phone in front of them.

A few commercial prototype samples of Scentee were obtained for evaluation. This was made possible due to an involvement with the manufacturer of the device and Mugaritz, a Michelin star restaurant in Spain, whom was interested in developing a 'Digital Food App' for the iPhone. The app involved rotating the phone to mimic the physical motion of stirring food in a bowl. After stirring, the Scentee emitted the scent of the dish, using chemicals supplied by the restaurant's chefs. As part of the project, the manufacturer sent extra free samples of the Scentee devices which were permitted to be used for the main experiment presented in the next section (Section 2.6). The Scentee device and the Digital Food App are shown in Figure 2.12.

Figure 2.12: Digital Food App. Top Left - Mortar soup preparation. Top Right - Mortar soup as seen in the Digital Food App on the iPhone's screen. Bottom Left and Bottom Right - Mugaritz Chef Andoni Luis Aduriz demoing the Digital Food App at Madrid Fusion 2014 (images courtesy of Mugaritz [top row] and Madrid Fusion [bottom row]).

No experiments were conducted with the Digital Food App, though demoing the technology using the app helped determine the Scentee's abilities and its general reliability for use in controlled experiments. The most important feature of the Scentee was that any event in an app could be used to trigger a scent's emission. In the Digital Food App, after the user made enough rotations, the app transmitted an event notification to the device to determine when and how long to disperse the scent. The Scentee also proved to be reliable enough in that the device would always dispense the scent with the same quantity each time, providing the chemical reservoir inside the device was not dry. Though the main limitation of the Scentee was that it could hold only one chemical at a time, it was discovered that several Scentee devices could be easily swapped in and out of the phone while continuously using an app. Mugaritz provided several variations of their soup scent, which were stored in three different Scentee devices.

After careful consideration, the Scentee was deemed acceptable to be used in the main experiment to disperse scents. Though the main limitation of the technology was the number of scents that could be loaded at once, this could be bypassed by having multiple Scentee devices loaded with different smells. Another benefit was that smell quantity and duration could be highly controlled from code, as opposed to using cruder methods such as wafting and manually spraying the subject with spray bottles. The description of how the Scentee was used will be provided in the next section.

2.6 Main Experiment

For the final part of the study, the main experiment, participants were asked to rate the emotional feel of the selected SMS messages from Section 2.4.2 in pair combinations with the smells selected from Section 2.4.1 using an implementation of a smell display (Scentee). These smells, again, were 'Pink Grapefruit' and 'Pure Soap' (the pleasant smells), and 'Mildew', and 'Earthworm' (the unpleasant smells). Pure distilled water was also chosen as the neutral smell. Though the emotional perception of pure water's valence was not tested in the smell pilot, water vapour has no discernible scent as long as it has been properly purified, and therefore, should not cause an emotional reaction in subjects when smelling it in vaporised form.

This thesis looked to similar research with odour as the basis of which to design the main experiment. Dematte *et al.* (2007) investigated whether or not odour could augment people's judgements of facial attractiveness. In their study, subjects viewed different human faces on a computer display along with scales to select how attractive they felt the faces were. While viewing each face, one at a time, subjects in their study were simultaneously presented with either clean air as the neutral condition, or either a pleasant odour or an unpleasant odour. Dematte *et al.* also used two odours for both kinds of valences, which they tested beforehand to ensure both smells for the pleasant and unpleasant groups were equally rated. Their experiment consisted of 3 blocks of 40 randomised trials. A trial consisted of pairing one of the five smells with a face.

Therefore, this chapter adopted the design of Dematte *et al.*'s (2007) study as the basis for the main experiment. Participants were asked to perform 90 trials total. A trial consisted of a paired combination of one of the 5 smells and one of the 30 messages selected from Pilot 2. Like Dematte *et al.*'s experiment, a within-participants, repeated measures study was used so that every participant was able to be tested under all the conditions. Each subject performed the trials in a randomized order to reduce ordering effects. While a better method to deal with such effects is to use a counterbalancing strategy, a randomized ordering strategy was used instead as there were many conditions to test for. Participants were given two, five minute breaks, each one taking place after they completed a 30 trial block.

2.6.1 Stimuli Design

For brevity, the five scents were given labels to identify them according to their valence. Pink Grapefruit was given the label 'A+'. Pure Soap was labelled 'B+'. Mildew was given the label 'C-'. Earthworm was labelled 'D-'. Lastly, water was labelled as 'N'. The reasoning for these labels is not only to abbreviate the smell names, but to also serve as a labelling scheme for the Scentees. This will be explained in the next section (Section 2.6.2).

An added complexity of the study was the usage of two separate pleasant smells and two different unpleasant smells, as was used in Dematte *et al.*'s study (2007). To prevent consecutive trials of using the same scent and SMS message pairing, alternating sequences of the A+ and B+ smells, and likewise, the C- and D- smells, was created. Respecting these constraints, a sequence of trials, such as 'A+, C-, D-, B+, C-, A+…' was created for each participant. The text messages were then assigned to this sequence of smells, such that each text message was presented once with one of the pleasant smells, once with one of the unpleasant smells, and once with the neutral smell (water). This allowed each participant to have their own, randomised sequence of smell-message pairs, the sequence of which was presented in three blocks of 30 pairs for a total of 90 stimuli (Appendix A.8).

2.6.2 Procedure

13 people, 7 males and 6 females, none of whom had participated in any of the previous studies, participated in the main experiment. Detailed participant information can be found in Appendix A.9. Their ages ranged from 23-25, with a mean age of 23.8

years (σ = 0.7 years). As in the pilots, each subject was paid the yen equivalent of $10 for their time, and were given the same consent form to sign. Participants were instructed to come to the lab on a scheduled day. They were told the experiment would take approximately one hour to complete.

Participants were seated during the entire study in front of a desk, on top of which was an iPhone and a computer monitor. An iPhone app, developed by a lab colleague, presented the user with a text message to mimic the experience of receiving a SMS message on their phone. There was also a computer display monitor on the table used for recording the ratings on the emotion wheel, along with a button which the participant pressed to proceed to the next trial. The iPhone was placed in the same location on the table and in front of the computer monitor for each trial. The device remained on the table during all trials and the participant was instructed not to pick it up. Participants were given the instructions shown in Appendix G.3.

The order of the 90 stimuli for each subject, that is, the message and scent pairs, were randomized in a Microsoft Excel worksheet (Appendix A.10). The ordering data was then saved as a comma separated value (CSV) file for each participant, which was read by the software to determine which order to present the stimuli. During the experiment, the lab monitor would use the list to keep track of the smell order so that he could change the appropriate Scentee module and insert it into the phone.

Five Scentees, each loaded with one of the five, diluted smells chosen from the smell pilot, were labelled using the labelling criteria discussed previously in Section 2.6.1. Again, ‘Pink Grapefruit’ was given the label 'A+'. ‘Pure Soap’ was labelled 'B+'. ‘Mildew’ was given the label 'C-'. ‘Earthworm’ was labelled 'D-'. Lastly, water was labelled as 'N'. These label names were not explained to the participants and only the lab monitor knew of their meanings to keep the identities of the scents hidden (though subjects could see the labels as the Scentees were mounted to the phone). To insure there was an adequate amount of scent in each Scentee module during the trials, the lab monitor would check the contents and refill as necessary during the five-minute breaks. After a participant rated a trial stimulus, the experiment monitor switched on a box fan for 10 seconds to clear the smell from the environment. While the fan was operating, the experiment monitor swapped the Scentee to be used in the next trial. After 10 seconds, the fan was switched off and the new Scentee was attached to the iPhone, which was placed in front of the participant to begin the next trial.

Finally, after a participant clicked on the next button on the computer display, the Scentee would spray its contents once for a duration of one second in front of the participant and, at the same time, the text message would appear on the iPhone screen. This mimicked the experience of receiving the message along with a scent from some sender, like a friend. The participant would then indicate whether they smelled something by providing a 'yes' or 'no' answer on a popup dialog box on the computer terminal in front of them. After this, they rated the emotional feel of the text/smell pair, as per the instructions they were given, using the emotion wheel on the computer terminal. Participants were encouraged in the instructions to complete the trials as quickly as they could, but were not told they were being timed, and no time limit was given.

Several types of data were logged during the main experiment. The subjects' personal information (age and gender) was recorded. The subjects' detection response (yes or no) was recorded, as well as their ratings of each stimuli pairing, including the emotion selected and its intensity. Lastly, the time taken to rate each trial was logged. All data was saved into a Parse database for easy data retrieval afterwards.

To summarize the procedure:

- Participants came to the lab and sat down at a desk in front of an iPhone and computer display.
- For each trial, the text message appeared on the iPhone, and the scent was sprayed in front of the subject once.
- Participants were instructed to rate the emotional feel of both the message and scent by making a selection on the emotion wheel interface on the computer screen in front of them.
- After making their selection, the lab monitor prepared the next scent and ventilated the room.
- Participants received their own unique order of 90 trials, which were split into three equal size blocks, separated by five minute breaks.

2.6.3 Results

To simplify reporting the results, the data analysis is divided into three sections. First, the emotion rating data will be examined to find any interaction effects between the odours and the messages (Section 2.6.3.1). This procedure will first examine the means of the valence ratings to identify any obvious trends. The procedure will then use a series of statistical tests to find whether the smell valence or the message valence had the greater effect on the perceived emotional valence of the combined stimulus. The second section (Section 2.6.3.2) will then examine the time logs to observe how long participants took to respond to the trials. The last section (Section 2.6.3.3) will look over the Boolean data that indicated if the subjects detected a smell or not for each trial. The raw data can be referred to in Appendices A.11 – A.13. It should be noted that the emotion selection results (Section 2.6.3.1) will be analysed irrespective of whether or not subjects correctly detected a stimulus presented to them (e.g. when no detection was made or when they detected a smell when only water was presented to them).

2.6.3.1 Emotion Wheel Selections

Valence data was first obtained from the raw data ratings provided by the emotion wheel (i.e. ‘Surprise 4’, ‘Anticipation 3’, ‘Neutral 0’, etc.). As the arousal component was ignored in the pilots, it was not analysed in the main experiment either as it was not controlled in the trials.

As a first step, the mean valence rating range was calculated for all trials to gain perspective of the variability of the user responses. First, the raw data was converted into valence ratings (again refer to Section 2.4.1.1 for this procedure), which was subsequently used to calculate the mean valence ratings of all 90 trials each participant performed. This resulted in 90 mean valence ratings with a range of -2 to 3.46. On the 15-point, ‘flattened’ valence scale (refer back to Figure 2.3 for how this was done), this range indicated that subjects felt that the stimuli were slightly unpleasant at most, to moderately pleasant overall.

	Pleasant Smells			Unpleasant Smells			Neutral Smell		
Statistic	$\bar{x}$	$\tilde{x}$	σ	$\bar{x}$	$\tilde{x}$	σ	$\bar{x}$	$\tilde{x}$	σ
Pleasant Texts	0.86	0.5	3.13	1	1	2.9	0.78	0	3.26
Neutral Texts	0.86	0	3.19	1	1	3.3	0.67	0	3.28
Unpleasant Texts	0.61	0	3.15	0.6	0	3	0.02	0	3.69

Table 2.4: Means, medians and standard deviations for each smell and message group (pleasant, neutral, and unpleasant).

Next, standard descriptive statistics and box plots, including the means, medians, and standard deviations for the nine combinations of the three smell types and three message types, was computed using the valence ratings. The descriptive statistic results are shown in Table 2.4. For example, the mean cell under the 'Pleasant Smells' column and on the 'Pleasant Texts' row, 0.9, was the mean valence rating of the particular 10 trials where a pleasant text message was paired with a pleasant smell (either 'Pink Grapefruit' or 'Pure Soap'). To illustrate this table better, box plots were generated for the three smell pair groups (Figure 2.13) and three message pair groups (Figure 2.14) shown in Table 2.4.

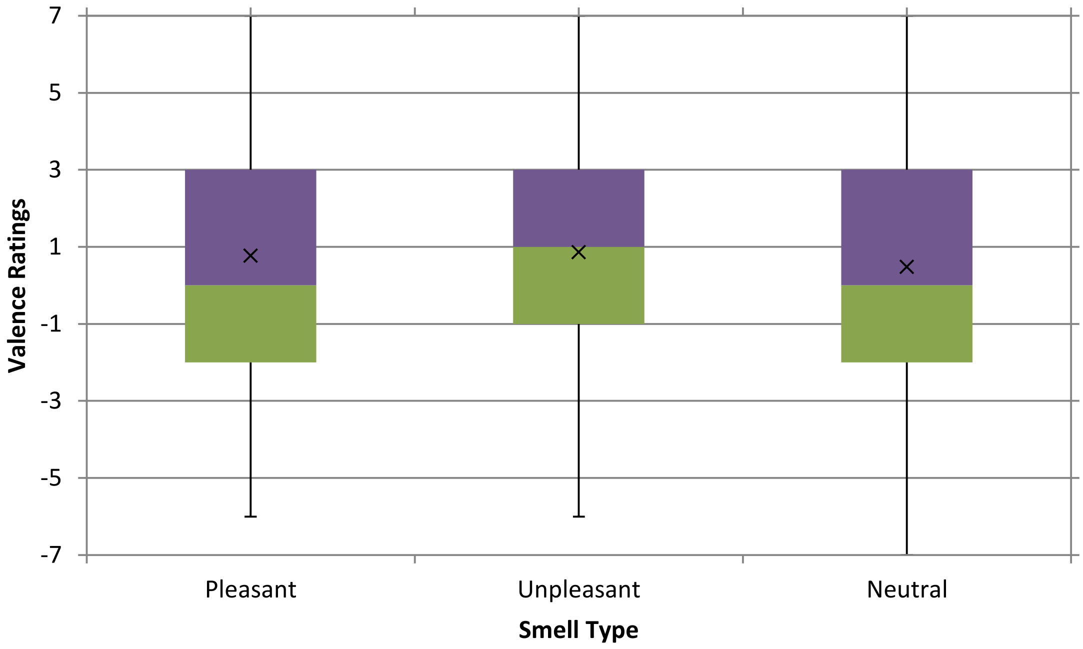


Figure 2.13: Box plots showing the smell and message pairs grouped by smell type.

From Table 3.3, and Figures 2.13 and 2.14, some generalisations were identified. At a glance, it appears that subjects rated the smells and messages the same, irrespective of their valence: means remain between 0 and 1, and whiskers extend towards the extrema of the 15 point scale (-7 and 7). This indicates that neither the smell nor message channels appeared to dominate: if they did, then the box plots would be skewed towards the valence of the smell or message type. Second, there were no negative mean valence ratings, indicating that participants tended to rate the emotional content of all the stimuli as having a positive, or pleasant valence. Mean valence ratings for pleasant messages, regardless of which scent they were paired with, did not appear to be different from each other (0.86, 1, 0.78). Third, when the message was neutral, both the pleasant and unpleasant smells appeared to have little effect on the perceived valence of the message, as both resulted in similar mean valence ratings. Fourth, when examining the mean valence ratings of smells, regardless of which message the user saw, the pleasant smells resulted in higher mean valence ratings than the neutral smells. However, the unpleasant smells surprisingly resulted in a slightly higher mean valence rating than the pleasant smells, regardless of which message was presented to users, pleasant, neutral, or unpleasant.

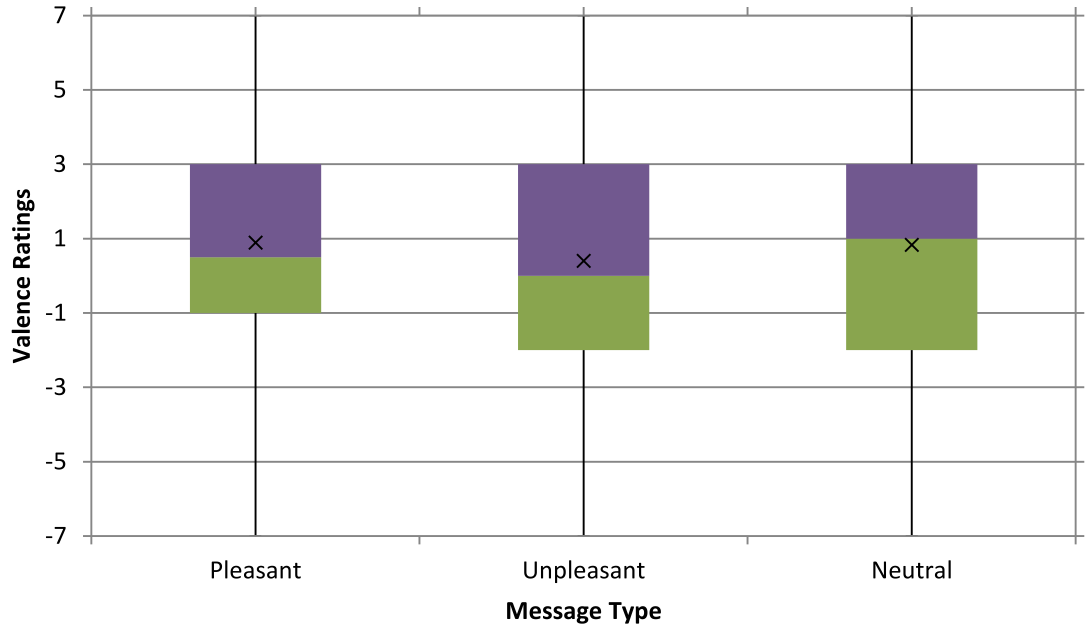


Figure 2.14: Box plots showing the smell and message pairs grouped by message type.

Summarising the data analysis up to this point, users appeared to rate the trials overall quite neutral and slightly skewed toward pleasant. Neither message nor smell had a particularly dominating effect over how subjects emotional perceived the combined stimuli. Participants rated stimuli with unpleasant scents more pleasantly than expected, and in some circumstances, were rated higher than the stimuli containing pleasant and neutral scents. To test the significance of whether or not messages or smells had no dominant effect over the combined stimuli, statistical tests were run on the valence ratings.

First, intra-group differences were tested of the pleasant, unpleasant, and neutral messages shown in Figure 2.14. The valence ratings of all subjects' responses were pre-sorted into three groups: the valence ratings of pleasant message stimuli, neutral message stimuli, and unpleasant message stimuli. As the global valence rating data was not normal (a Shapiro-Wilk test resulted in $p < 0.001$, $W = 0.98$), non-parametric tests were used. Running a Friedman test on the pleasant message group resulted in significance, ($p < 0.001$, $Q = 98.25$) as well as the neutral message group, ($p < 0.001$, $Q = 108.85$) and the unpleasant message group ($p < 0.001$, $Q = 105.2$). Message type therefore did not have a statistically significant, dominating effect over the perceived valence of the stimuli, as no significant differences would have resulted in accepting the null hypothesis that all message treatments, regardless of which smell the subject was presented with, had similar valence ratings. A naive assumption here is that the intra-group differences of the messages should be due to the presence of the smells that accompanied them.

Next, the intra-group differences of the pleasant, unpleasant, and neutral smells groups, shown in Figure 2.13, were tested for significance. The valence ratings of the entire data set were organized into three groups: the valence ratings of the pleasant smell stimuli, neutral smell stimuli, and unpleasant smell stimuli. Friedman testing on the pleasant smell group was significant ($p < 0.001$, $Q = 96.57$), as was the unpleasant smell group ($p < 0.001$, $Q = 100.31$), and the neutral smell group ($p < 0.001$, $Q = 104.32$). Smell, therefore did not appear to have a dominating effect over the messages, as illustrated in Figure 2.13: users rated the smell groups similarly, regardless of the valence of their smells.

So far whole groups of messages and smells of similar valence have been examined for domination effects, of which there appears to be none. However, there remains a question of whether smell had any augmentation effect of the perceived valence of messages: do pleasant smells cause pleasant messages to feel more pleasant or vice versa? What of unpleasant smells and the neutral smell: do they have an effect on the perceived valence of messages? To test the significance of any augmentation effects, further testing was done using Wilcoxon sign rank tests.

First, pair-wise comparisons of the two pleasant smells and two unpleasant smells were tested to find any significant differences in each pair. The pleasant and unpleasant smell boxplots are shown in Figure 2.15. Running a Wilcoxon test (p-values reported are exact) on the pleasant smells pair produced $p = 0.19$, indicating that users rated trials with the two pleasant smells similarly, regardless of the message content. Comparing the valence ratings of the unpleasant smell pair produced a $p = 0.05$; again, participants rated the two unpleasant smells similarly, regardless of message content. These results are expected, and further testing of the smell pairings proceeded.

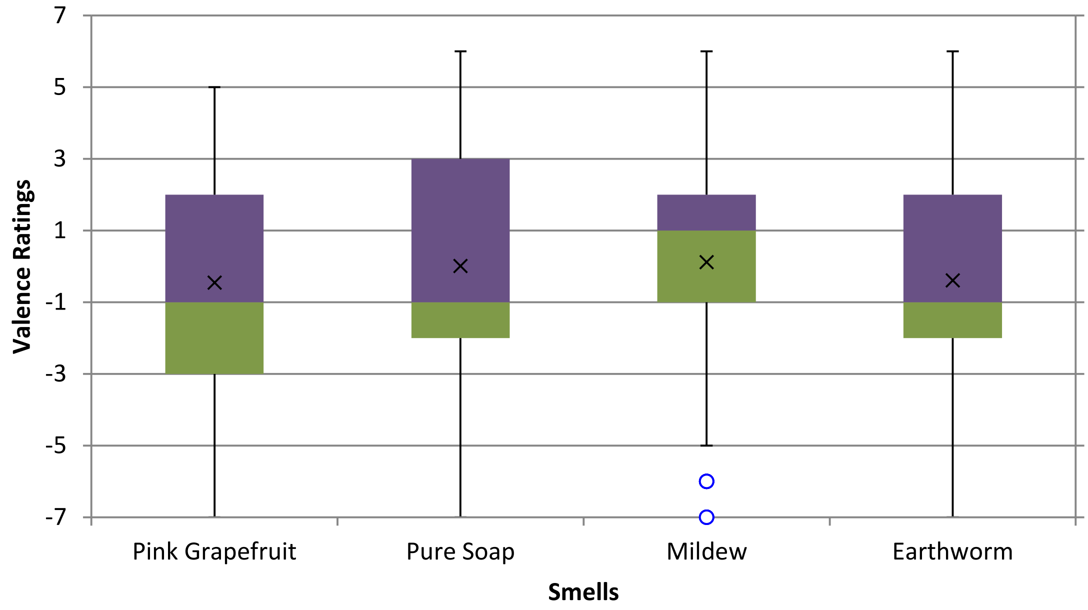


Figure 2.15: Side by side boxplots of the two pleasant smell stimuli pair ('Pink Grapefruit' and 'Pure Soap', on the left) and the two unpleasant smell stimuli pair ('Mildew and 'Earthworm', on the right).

Smell Group Valence	VS	Smell Group Valence
☺	p = 0.53	☹
😐	p = 0.05	☹
☺	p = 0.28	😐

Table 2.5: Pairwise comparisons of the three smell groups using Wilcoxon sign rank testing. The p-value results are reported under the 'VS' column and are the exact p-values. The pairwise comparisons are coloured and indicated by the smiley icons pleasant (blue, ☺), unpleasant (red, ☹), and neutral (grey, 😐).

Next, the pleasant smell stimuli pair, the unpleasant smell stimuli pair, and the neutral smell stimuli were compared against each other in pairwise comparisons with Wilcoxon tests (refer back to Figure 2.13 for the box plots of these groups). The results of these tests are shown in Table 2.5 (again, all p-values reported are exact). None of the comparisons were significant: there does not appear to be any statistically, significant difference in how users rated messages, regardless of whether the presented smell was pleasant, neutral, or unpleasant. These results were unexpected: one would expect that the smell valence would impact how users emotionally rated the messages, but as Figure 2.13 and Table 2.5 illustrates, these differences are insignificant.

	Messages									
Msg Grp	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
☺	p=0.15 Q=3.73	p=0.25 Q=2.81	p=0.44 Q=1.65	p=0.001 Q=11.19	p=0.33 Q=2.19	p=0.78 Q=0.5	p=0.47 Q=1.5	p=0.46 Q=1.5	p=0.3 Q=2.42	p=0.55 Q=1.19
😐	p=0.12 Q=4.27	p=0.26 Q=2.81	p=0.06 Q=5.65	p=0.01 Q=9.5	p=0.67 Q=0.81	p=0.74 Q=0.62	p=0.08 Q=5.16	p=0.2 Q=3.23	p=0.08 Q=5.16	p=0.58 Q=1.08
☹	p=0.12 Q=4.27	p=0.25 Q=2.81	p=0.06 Q=5.65	p=0.01 Q=9.5	p=0.67 Q=0.81	p=0.74 Q=0.62	p=0.03 Q=7.04	p=0.34 Q=1.88	p=0.17 Q=3.58	p=0.17 Q=3.5

Table 2.6: Intra-group comparisons of the three smells (pleasant, neutral, and unpleasant) tested in each message for each message group: pleasant (blue, ☺), neutral (grey, 😐), and unpleasant (red, ☹). All tests were done with Friedman with df = 2 for all tests results. The "Messages" shown here as #1-10 are unique for each message group (Message #1 for the pleasant message group was not the same as the Message #1 for the neutral message group). Refer to Appendix A.8 for the Message IDs. The first 10 messages in Appendix A.8 corresponds to the pleasant messages, the next 10 messages corresponds to the unpleasant messages, and the last 10 messages corresponds to the neutral messages. These are labelled in this table as #1-10 for brevity.

A closer analysis of the smell stimuli within each of the three message groups was examined to see if certain message stimuli resulted in significantly different valence ratings than others. As each message had three smells assigned to it during the experiment (which was either 'Pink Grapefruit', 'Water', and 'Mildew', or 'Pure Soap', 'Water', and 'Earthworm), Friedman tests were run on the 3 smells assigned to each message to see if there were any expected statistically, significant effects, of which there should be if subjects rated the three smells differently for each message. Table 2.6 shows the results of these Friedman tests. Of the pleasant messages, only Message #4 "I just cooked a rather nice salmon a la you" produced a statistically, significant result. Of the neutral messages, only Message #4 "Did u find out what time the bus is at coz i need to sort some stuff out." resulted in a significant difference between its three smells. Of the unpleasant messages, only Message #4 "Well I might not come then..." and Message #7 "Hi hope u get this txt~journey hasnt been gd,now about 50 mins late I think." had significance. With these few exceptions, it appears that the type of smell did not affect the valence ratings significantly of the other messages, regardless of which smell was presented to the subject.

To summarize the results of analysing the valence ratings of the data collected from the emotion wheel:

- Subjects rated the smell and message pairs neutrally and pleasantly overall, with few stimuli rated strongly unpleasant.
- The messages' valence did not appear have a significant effect over the perceived valence of the stimuli.
- Likewise, the smells' valence did not appear to have a significant effect over the perceived valence of the messages, regardless of whether the messages were pleasant, unpleasant, or neutral.
- Subjects rated the stimuli valences of the two pleasant smells, 'Pink Grapefruit' and 'Pure Soap', similarly, as well as the valences of the two unpleasant smells, 'Mildew' and 'Earthworm'. However, no significance differences were found between these two pairs of smells.

2.6.3.2 Response Times

Descriptive statistics were performed on the time it took subjects to rate each stimulus after the emotion wheel was presented in front of them. Participants took, on average, 20 seconds to make a response on the emotion wheel per trial, with a standard deviation of 10.3 seconds. As the standard deviation is quite large, the median or mode is more appropriate to analyse in this situation than the mean. Therefore, the median time to rate each trial, across all participants, was 18 seconds and the mode time to rate each trial was 14 seconds. Furthermore, there did not appear to be much variation in the response times when analysing the stimuli categorised by pleasant, neutral, and unpleasant messages or smell. For all message groups (Table 2.7), the median time to complete each trial was the same (18 seconds), and the mode times were similar: 14 seconds, 15 seconds, and 16 seconds for the pleasant, unpleasant, and neutral message groups, respectively. Rating response time by smell type (Table 2.8) also did not appear to vary: the median time range across all smell types was 18-19 seconds, and the mode time range across all smell types was 15-19 seconds.

	Pleasant Msg	Neutral Msg	Unpleasant Msg
Mean	20.4	20	20.9
Median	18	18	18
Mode	14	16	15
Standard Deviation	9.63	9.3	11.8

Table 2.7: Descriptive statistics of the response times, in seconds, categorised by pleasant, neutral, and unpleasant message stimuli.

	A+	B+	0	C-	D-
Mean	21.16	20.34	20.46	19.48	20.82
Median	19	18	18	18	19
Mode	16	19	16	18	15
Standard Deviation	10.99	10.35	10.37	10.41	9.26

Table 2.8: Descriptive statistics of the response times, in seconds, categorised by the smells A+ ('Pink Grapefruit'), B+ ('Pure Soap'), 0 (water), C- ('Mildew'), D- ('Earthworm').

Several statistical tests were run to examine the shape of the distribution and any possible statistical differences in the time subjects took to rate the stimuli. A paired t-test may be suitable for determining the statistical significance of time data, assuming the normality of the data and that the homogenous variance assumptions hold. A Shapiro-Wilk test was ran first on the global time dataset. However, this test was not significant ($p = 0$, $W = 0.8$). Therefore, a non-parametric testing approach was used for further analysis instead of t-tests due to the non-normality of the sample data.

The time responses of the pairs of two pleasant smells and two unpleasant smells were compared using Wilcoxon sign rank tests (exact, two-tailed). Comparing the two pleasant smells' time data with each other resulted in no statistically, significant differences ($p = 0.47$), meaning that the 'Pink Grapefruit' and 'Pure Soap' stimuli required about the same amount of time for participants to emotionally rate them. However, the smell response times of the two unpleasant smells, 'Mildew' and 'Earthworm', were significantly different from each other ($p = 0.03$). This meant that subjects took slightly longer to emotionally rate the 'Earthworm' scent (median = 19) than the 'Mildew' scent (median = 18).

Next, the pleasant, unpleasant, and neutral smell stimuli were compared with each other, to see if the smell's valence resulted in significant differences in the time taken to respond. The results of the three pairwise comparisons made using Wilcoxon sign rank tests are shown in Table 2.9. All tests resulted in no statistically, significant differences between each group's time responses: participants took the same amount of time to rate all stimuli, regardless of whether the smell was pleasant, unpleasant, or neutral. Because of this, it was determined that the type of smell did not affect the time taken to rate the emotional content of the stimuli.

Smell Group Valence	VS	Smell Group Valence
☺	p = 0.47	☹
😐	p = 0.9	☹
☺	p = 0.54	😐

Table 2.9: Pairwise comparisons of the three smell group's time data using Wilcoxon sign rank testing. The p-value results are reported under the 'VS' column and are the exact p-values. The pairwise comparisons are coloured and indicated by the smiley icons pleasant (blue, ☺), unpleasant (red, ☹), and neutral (grey, 😐).

Finally, the effect of message content valence on the response time of the stimuli was analysed like the smells above using Wilcoxon sign rank tests. The results of the three pairwise comparisons are shown in Table 2.10. None of the message group comparisons resulted in statistically, significance differences. Thus, the type of message content also did not have a significant effect on the time responses of the participants.

Smell Group Valence	VS	Smell Group Valence
☺	p = 0.74	☹
😐	p = 0.87	☹
☺	p = 0.42	😐

Table 2.10: Pairwise comparisons of the three message group's time data using Wilcoxon sign rank testing. The p-values result are reported under the 'VS' column and are the exact p-values. The pairwise comparisons are coloured and indicated by the smiley icons pleasant (blue, ☺), unpleasant (red, ☹), and neutral (grey, 😐).

It is important to note that message length had no significant effect on time to rate the stimuli. Additional statistical testing using Wilcoxon tests compared the shortest and longest messages of each message group (when paired with the neutral smell). These results are shown in Table 2.11. No significant differences were found: subjects rated the shortest and longest messages in the same amount of time.

Shortest Message	VS	Longest Message
#2	p = 0.3	#104
#7	p = 0.06	#75
#10	p = 0.59	#13

Table 2.11: Pairwise comparisons of the neutral smell paired with the shortest (left column) and longest (right column) messages of the pleasant (blue), neutral (grey) and unpleasant (red) message groups using Wilcoxon sign rank testing. The p-value results are reported under the 'VS' column and are the exact p-values. Refer to Appendix A.4 regarding the content of the messages.

To summarise the time response findings:

- Participants took about 20 seconds on average, or 18 seconds if judging using the median, to emotionally rate the stimuli.
- The valence of messages, whether pleasant, unpleasant, or neutral, did not have a significant difference on the time taken to emotional rate each stimulus.
- The type of smell also did not have a significant effect on the time taken to rate each stimulus.
- Stimuli with both types of pleasant smells required the same amount of time to emotionally rate the stimuli.
- Stimuli with both types of unpleasant smells required the same amount of time to emotionally rate the stimuli.
- Message length had no significant effect on the length of time subjects took to rate the stimuli.

2.6.3.3 Detection of Stimuli Frequencies

The last set of data that was analysed were the frequencies of when participants did or did not detect a smell when it was presented with the message. First, the frequency data, which consisted of just true or false values for each recorded stimulus, was sorted into three groups: groups containing pleasant smell stimuli, unpleasant smell stimuli, and neutral smell stimuli. On average, participants detected no smell in 8/90 trials (σ = 4.35) when presented with a pleasant smell and detected no smell in 9/90 trials (σ = 4.57) when presented with an unpleasant smell. When given the neutral smell, subjects detected it in 23/90 trials on average (σ = 5.94). On average, in about 40/90 of the stimuli trials (σ = 5.15), or 44% of the time, participants failed to detect the smell presented (and likewise correctly detected the smells 55% of the time on average).

Smell Valence	VS	Smell Valence
Pink Grapefruit	p = 0.03	Pure Soap
Mildew	p = 0.56	Earthworm
Pleasant	p = 0.26	Water
Unpleasant	p = 0.8	Water
Pleasant	p = 0.14	Unpleasant

Table 2.12: Pairwise comparisons of the smell group's detections using McNemar tests. The p-value results are reported under the 'VS' column and are the exact p-values. The pairwise comparisons are coloured and indicated by the smiley icons pleasant (blue, ☺), unpleasant (red, ☹), and neutral (grey, 😐).

To analyse this statistically, the Boolean data that indicated if participants smelled something or not were compared using McNemar tests. The McNemar test (McNemar, 1947) is a special case of a repeated measure CHI square test which tests for consistency in responses across two variables where observations are Boolean. The global Boolean data was first sorted into one of five groups for each of the smell types: 'Pink Grapefruit', 'Pure Soap', water, 'Mildew', and 'Earthworm'. Pairwise comparisons of the Boolean data using McNemar tests were then run between these groups, the resulting p-values of which are shown in Table 2.12 (p-values are exact). Comparing the pleasant smells ('Pink Grapefruit' and 'Pure Soap') with each other resulted in significance, indicating the stimuli containing the 'Pure Soap' smell had significantly higher detection rates (76.9%) than stimuli containing the 'Pink Grapefruit' smell (67.7%). However, all other comparisons resulted in no significance: detections of the 'Mildew' (72.8%) and 'Earthworm' (69.7%) were statistically not significantly different, nor pleasant smell stimuli (72.3%) vs. neutral stimuli (75.9%), the pleasant smell stimuli vs. unpleasant smell stimuli, and the unpleasant smell stimuli (71.3%) vs. the neutral stimuli. Note that these detections do not take into account false positives and negatives, in that that the subject may have detected the smell even though water was presented (and likewise didn't detect the smell even if it was presented). This is why the percentages here are higher than the average (55%) discussed at the beginning of this section.

In summary:

- Participants sometimes did not detect a smell when one was presented, and likewise detected a smell when given the neutral water stimulus.
- The frequency of when subjects did not detect a smell was 44%, or 40/90 trials.
- ‘Pure Soap’ was easier to detect than ‘Pink Grapefruit’, however, there was no significant difference between the detection rates of the ‘Earthworm’ and ‘Mildew’ smells.
- No significant differences were found between the water stimuli and pleasant smells nor between the water stimuli and unpleasant smells and between the two pleasant smells and the two unpleasant smells.

2.6.4 Discussion

A major concern from the above analysis were the enormous errors in the detection ability of subjects to correctly perceive a smell when one was given and also when detecting a smell when water was presented to them. This observation is possibly the most critical: if participants were unable to detect a smell properly, then they most likely rated the emotional feel of the stimuli incorrectly or would have taken too much time to think about assigning emotional ratings to stimuli. Thus, detection is important as it allows insight into how well subjects could correctly perceive a stimulus when presented to them (or if they did not detect a smell).

There are several explanations for this detection issue. One explanation was that odours may have not been fully cleared from the testing environment in between trials. This was supported by observing that several participants reported smelling something in some of the neutral conditions. However, this does not explain why they were unable to smell something when a pleasant or unpleasant smell was dispensed from the Scentee. It is possible that, given the time the subjects took to rate each stimulus, plus the addition of the time between trials to blow out the smell from the room, the subjects may still had not detected the new smell due to their noses adapting to odours persisting in the environment (Engen, 1982). Another explanation for the issue with detections was that smell delivery may have not been optimal and the dispersed scent may had missed their face. Using the Scentee device still proved difficult in enclosed spaces, as the smell lingered despite efforts to clear the smell away and the fine mist it provided. However, running the experiment outdoors would have been impractical due to wind, which may have carried scents away from the users, and surrounding environmental odours, which may have impeded, or mixed, with the smell being administered, causing cross-adaptation effects that were discussed in Section 2.1.

Another observation made, which challenges the use of technology like the Scentee to augment the perceived emotion of the text messages using smell in this context, is that subjects took too long to recognise an emotion when they were asked to emotional rate the emotional feel of a stimulus. On average, participants took about 20 seconds to record a response, with a standard deviation of approximately 10 seconds. In some instances, participants took well over a minute before any recording took place. This indicated that they had to contemplate which emotion they were feeling from perceiving both the smell presented to them and the content of the text message at the same time. The time taken by subjects to rate the combined smell and message stimuli is important to consider: too long of a time reduces plausibility of using smell in real life communication were reactions may need to be more immediate (seconds), otherwise, conversations with smell will take too long and may be distracting. Therefore, the use of smell in this context may be too distracting to be of use to the user.

There was also evidence of a complex relationship with valence occurring between the valence of the odours and the valence of the text message content. This was evident in the observation of the mean valence ratings of the stimuli shown in Table 2.4 in Section 2.6.3.1. These results can be compared to the emotional ratings of the smells and message stimuli by themselves from the pilots. In the message pilot in Section 2.4.2, the pleasant messages had an average valence rating of 3.64. Yet, when combined with any smell, including pleasant ones, this number dropped considerably: 0.86 for pleasant scents, 0.78 for the neutral smell, and 1 for unpleasant scents. This means that adding pleasant smell stimuli to any message type did not augment the pleasure of the combined stimuli. Rather, the added presence of smell appeared to actually *neutralise*, or cause the valence of the messages to become more neutral instead. Unpleasant messages, on the other hand, were emotionally rated pleasantly, regardless of the valence of the presented smell, in addition to the observed neutralisation effect seen with pleasant smell stimuli. For reference, the mean valence rating of the unpleasant messages in the pilot was -2.25, whereas the addition of pleasant, neutral, and unpleasant smells caused the mean valence rating to rise slightly above 0, to 0.61, 0.02, and 0.6, respectively, as seen in Table 2.4. In general, smell appeared to neutralise the valence of the text messages, with the additional effect of making the messages feel slightly pleasant, or above neutral.

Statistical testing revealed that the effect of neutralisation and pleasantness appears to be shared by all smells, regardless of whether the smell was pleasant, neutral, or unpleasant. Smell type did not have any statistically, significant effect on the perceived valence of the messages ($p > 0.05$) using Friedman Tests. Furthermore, the messages' valence also did not have any significant effect on the valence of the combined stimuli ($p > 0.05$). What this meant was that, regardless of the valence of both the smell and the message content, subjects rated the emotional feel of any combination of these stimuli in the range of neutral to slightly pleasant, with mean valence ratings in the range of 0 to 1 on a scale from -7 to +7. This further supports the idea that both stimuli are neutralising the emotional feel of the combined stimuli.

There are several explanations for why the above neutralisation effect is happening. One possibility is the issue of odour re-adaption discussed previously in Section 2.1. This is caused by inadequate time between perceiving two different smells, in which smell receptors cannot return to a neutral state before they can detect a newly presented smell. It is also possible that odour adaptation may have been caused by inadequate smell intensity. Though the smells were diluted with water to normalize the strength so that all smells could be perceived at relatively the same intensity, the intensities may had been still too strong for odour adaption to occur in the 10 seconds between the trials. Sensory adaption is an important issue, as it may cause unintended interactions when stimuli mix with each other. As discussed in Section 2.1, cross-adaptation effects can occur when smells mix with each other, producing new kinds of smells which may not be detectable, depending on the makeup of the mixed smells.

Based on feedback received from participants, it was clear that the lack of context also made it hard to judge how they should have rated the emotional feel of the stimuli. Participants felt that it was difficult to rate the messages when they did not know who the sender was, especially if gender was ambiguous. They remarked that they needed to know how close the sender was to them as it affected how they would react. It may had been more useful to carry out a separate study where participants were told who the sender was and their relationship to them when asking them to rate the emotional feel of the text messages.

A limitation of the study may had been criteria for selecting neutral messages in Section 2.4.2.3, as the criteria had not been applied for selecting neutral stimuli in the smell pilot. These neutral messages may had been rather 'ambiguous' to the subjects (a terminology referred to in the pre-tests when subjects did not unanimously agree on the valence of the messages and smells), since the criteria considered minimising the difference of the subjects' pleasant and unpleasant emotional ratings. Thus, the neutral messages may had not been truly emotionally neutral, though the analysis in Section 2.4.2.3 showed that they were similarly rated.

Another limitation was that the subjects could see the labels on the Scentee devices ('A+, 'B+', etc.) when the device was attached the phone, though they were not told what the labels were. Still, they may had been able to remember what a smell was if they had learned to associate the label with the smell with repeated use. As there were many trials, the subjects may have had enough experience to remember the labels as they progressed. This may had caused unintentional priming to occur as they saw the labels before given the smell stimuli.

Another potential imitation in the study design was the Scentee devices themselves. As they were prototypes sent from the company, they required constant monitoring of the reservoir's liquid contents. Devices were rinsed and cleaned using ethanol alcohol before each participant's arrival using different injection syringes to insure that the scents did not mix with each other. Despite these efforts, there may had still been traces of residue inside the Scentees used for the neutral stimulus which contaminated the water. Participants also claimed to have been distracted by the Scentee technology, since it was seen as a 'cool' piece of technology which enabled an ordinary mobile phone to disperse scents. Consequently, this caused them to focus more on the novelty of the technology rather than the scents, and they admittedly rated the stimuli more pleasantly because of this. This is a subject that has not been reported in literature, even in those that have utilized the Scentee technology in similar research (Braun *et al.*, 2016) and should be noted for future researchers when designing novel olfactory delivery systems.

2.7 Conclusion

This chapter explored the usage of a smell display implementation (Scentee) in order to answer the research question of this chapter: *can a mobile smell display augment the perceived emotional content of SMS text messages*? This chapter found that the Scentee was not very effective at this task: conversely, the Scentee appeared to neutralise the emotion of the text messages. However, the limitations of the study makes it difficult to ascertain whether this is due to the Scentee device itself or due to the difficulty of controlling the experiment. Delivery of smells is important, as evidenced by the high rates of error in detection of the smells, which can lead to smells mixing within the environment to produced unwanted odours that may or may not be pleasant to the user.

This chapter first discussed the challenges of using smell for communication. Classifying smell is difficult and human accuracy of recognising smells is poor, as issues such as cross-adaption effects and odour adaption can make smell detection difficult in the presence of other odours in the environment. Human decoding of smell is done in the limbic system of the brain, which is also responsible for regulating primary drives and emotional behaviours. There is some literature in HCI which has attempted to use smell for communicating emotional qualities, however, most have not carried out sufficient studies to verify the utility of communication through the use of smell.

This chapter conducted pilot studies to find smell and message stimuli which human subjects could categorise as emotionally pleasant, unpleasant, and neutral. Out of the 12 smells studied, two were selected as pleasant smells ('Pink Grapefruit' and 'Pure Soap'), and two were selected as unpleasant smells ('Mildew' and 'Earthworm'). Water vapour, though not tested in the pilot, was selected as a neutral smell stimulus. On the other hand, the message pilot study tested 113 text messages. The results of the message pilot revealed that subjects could agree on the valence of 10 messages as pleasant, 10 messages as neutral, and 10 messages as unpleasant.

The final experiment in this chapter combined the five smell stimuli and the 30 text message stimuli to observe what effect the smells had on the subjects' emotional rating of accompanying text messages using the Scentee. The Scentee technology is a commercial device which was attached to the mobile phone used to disperse scents into the users' faces. The results of the main experiment demonstrated some challenges with using scents emitted from the Scentee to augment the emotional feel of text messages: subjects only detected smells correctly at chance levels, took too long to emotional rate the stimuli, and could not give consistent emotional ratings of the stimuli. No statistical significance was found which supported using the Scentee in this context to augment the emotional content of text messages. In general, the combination of the smell and message stimuli together appeared to cause a neutralisation effect, reducing the valence of pleasant messages, and both inverting and neutralising the valence of unpleasant messages.

The studies carried out in this chapter revealed some important points that should be considered for conducting future olfactory experiments, mainly, the careful consideration of the manner in which scents are delivered to users and the complexity of study designs involving multiple scents to communicate emotion. This was attributed to the method of delivery (using the Scentee) and the (lack) of dissipating scents from within the environment, which may had caused the high errors in detection, as lingering smells can impede with detecting and perceiving subsequent smell stimuli. These cross-adaptation effects are a danger to controlled lab studies, as they can potentially create different scents from mixing with previous ones, making smell challenging to control carefully. The experiment also demonstrated that smell is emotionally subjective from one individual to another. The long time it took for subjects to rate the pairings of smells and messages also limits the practicalities of using the Scentee in real life applications in this context, such as smell-enabled social networks and situations requiring quicker reactions from the user. Because of these issues, the value of using technology like the Scentee in the context presented in this chapter to augment the perceived emotional content of SMS text messages is diminished.

In the next chapter, multimodal haptic and colour lighting sensory modalities will be explored as a method of augmenting the emotional content of text messages. More specifically, the next chapter will investigate the areas of affective haptics and wearable computing to deliver these sensory modalities, which, as will be discussed, are more controllable and faster to perceive relative to smell.

Chapter 3

Augmenting Text Messages with a Wearable, Multimodal, Ring Device

Smell in Chapter 2 was investigated to augment emotion as a form of information in communication using a portable, scent atomising device. However, the chemical use of smell poses portability and manageability issues as evident in the implementation used in the previous chapter. Smell also poses latency issues, requiring tens of seconds to perceive and to decode its emotional meaning. These issues diminish the applicability of using smell in the context of the previous chapter in communication systems.

Therefore, this thesis turned its attention to a modality more widely investigated in multisensory and HCI research: that of touch. Compared with smell, vibro-mechanical touch is a better understood modality in research. The area of haptics, which studies how touch perceptions can be mediated using computers and mechanical equipment, has fostered technology even in commercial applications such as game controllers (Israr *et al.*, 2012). This field has also examined how haptics can be used to present various kinds of information to users, such as emotion. Various kinds of touches, such as holding and squeezing someone, can indicate emotions like anger, disgust, love, gratitude, and happiness higher than chance levels (Hertenstein *et al.*, 2009). These kinds of touches can be incorporated into haptic displays, such as wearable devices capable of mediating emotion with pressure sensors and vibration output (Huisman and Frederiks, 2013).

However, haptics is an enormous area, encompassing research that includes tactile displays, video gaming, virtual reality, portable and personal computing, operation simulation, and medicine, to name a few. Focus is needed to examine the areas of haptics that align with the main research objective of this thesis to investigate different sensory implementations to present kinds of information to users that can be useful. Therefore, this thesis began by examining areas within the sub-domains of affective and wearable haptic interfaces. These areas will be discussed in more detail in the sections that follow in this chapter.

A summary of this chapter is as follows. First, this chapter will present a short literature review of tactile perception (Section 3.1) and its physiological pathway (Section 3.2). These sections will discuss the kinds of tactile stimulations which would be appropriate to use, such as squeezing, pressure, or vibration, and which areas of the body would be suitable for presenting vibrotactile feedback. This will provide requirements that assisted in narrowing the scope of the subsequent literature review in haptics (Section 3.3), which mainly focused on affective haptics and appropriate wearable form factors for investigation. Section 3.4 describes the development of a wearable ring system, 'Ring*U', the technology implementation which sends complex vibrotactile patterns and colour lighting cues between users over a network. Several pilot studies (Section 3.5) evaluated sending different kinds of vibrotactile and colour stimuli with the Ring*U. The main experiment (Section 3.6) then compared and combined these modalities together to observe their effects of augmenting the emotion of text messages. The results of the study demonstrated that the Ring*U neutralises the effect of how subjects emotionally perceive such messages. This provides an answer to this chapter's research question: "can a wearable ring device augment the perceived emotional content of SMS text messages with tactile and colour feedback?"

As the research presented in this chapter was part of a larger group effort involving the work of Pradana (2013), whom assisted in conducting the experiments presented in this chapter, this chapter will cite his thesis where appropriate to clarify his and this thesis author's contributions.

3.1 Tactile Perception

Per the ergonomics ISO standard on tactile and haptic interaction (ISO, 2009), the sense of touch is divided into two areas. First is the *cutaneous* tactile sense, which refers to sensations which arise from direct contact with the skin, such as pressure, stretching, and vibration. The other component of touch is that of *kinaesthesis*, which refers to the sensation of muscular and tendon constraints such as position, torque, and angle. It has been argued that such proprioceptive discharges can contribute to processes underlying emotion, such as setting the hypothalamic balance of the body and facial contraction patterns (Gellhorn, 1964). However, it is unclear how such impulses can be controlled to communicate emotion and thus far have demonstrated limited use in communication systems. Therefore, only the cutaneous sense of touch was examined further.

Cutaneous touch sensations arise when the skin contacts with an object in the environment, either actively or passively. Gibson (1966) argues that haptic technology, examples of which will be discussed in more detail in Section 3.3, can either interactively aid in the exploration of an object or be used if the skin is kept in a stationary position and the object itself moves or provides feedback around it. The former, known as *active feedback*, is useful in cases where feedback is used to guide behavior while the body part stimulated is moving, for example, a surgeon's hand while operating remote surgery equipment (Okamura, 2009). The latter, known as *passive feedback*, is more often used when feedback is presented to alert users, for example, buzzing a phone when a text message has been received.

Skin can be deformed either through stretching, pressure, or through vibration. As will be discussed in the next section, there are also specialized touch receptors for detecting each of these aspects of touch, which depend on the body part being stimulated. Additionally, there are also the technological limitations to consider when stimulating the skin. Mechanical devices that squeeze or apply pressure to the skin can be bulky and complicated to build. As this thesis had made a point of using off-shelf components to build technology-based implementations (refer back to Chapter 1), simpler methods of providing feedback passively were closely examined. This consisted of technology capable of delivering vibrotactile feedback though linear and rotational actuators, which are easy to obtain, consume little power, and can be placed virtually anywhere on the body. As such, the cutaneous sense of vibration was the focus of further enquiry. The remainder of this section will focus on its properties: frequency, duration, rhythm, waveform, and body location of stimulation, to determine how to create vibrotactile stimuli which could be perceived and interpreted as meaningful information.

The perception of vibration is used by the body to primarily detect texture when the skin is in contact with a rough surface (Hollins and Risner, 2000). The idea that vibration is used to perceive an object using small differences in the object's surface texture is known as the *duplex theory of texture perception*, and is important towards the understanding of texture perception as it takes into consideration the temporal aspects of an object's texture, which determine the rate of vibration as the skin surface moves over the object. However, vibrotactile stimulation can also occur when the skin is passively provided feedback from a quickly vibrating object, such as linear or rotatory actuators, without requiring the skin to move to produce the sensation of vibration.

In the case of passive vibrotactile stimulation, vibration frequency is an important parameter to consider. The acuity of the skin's perception of frequency ranges from 10 Hz to 400 Hz (Summers *et al.*, 1994), though optimal sensitivity and spatial discrimination occurs in the middle of this range (Craig and Sherrick, 1982; Van Doren *et al.*, 1987). When smaller actuators, such as a rotatory actuators, are used to conduct the vibrotactile feedback, lower frequencies should be used in order for the skin to be able to discriminate the differences in the tactile signals (Gescheider *et al.*, 1985). Geldard (1960) also suggested using lower frequencies as they are better than higher frequencies at aiding user discrimination of tactile waveforms. However, Geldard never specified the frequencies exactly: "it is clear that wave-form variations should be discriminable if the basic frequency is low enough" (Geldard, 1960, pg. 1586).

The waveform, or the shape and form of a vibrotactile signal, can be a valuable parameter in creating complex vibrotactile patterns. Gunther *et al*. (2002) suggested that the waveform of a tactile pattern could also be equated to its 'texture', which as noted above, is used in the identification of real objects when the skin moves over them. To investigate this claim, Hoggan and Brewster (2007) tested tactile patterns with various waveforms on participants to examine how well they could distinguish vibrotactile produced textures by changing their amplitude modulation, frequency, and shape characteristics. Hoggan and Brewster found that participants perceived square wave-shaped textures as feeling 'rough', while sine-wave shaped textures were perceived to be smoother to the touch.

The parameter of rhythm, which is used to create patterns of vibrotactile pulses of differing durations with spaces of time between them (much like notes and rests in music), plays a very important role in the recognition of vibrotactile patterns. Summers (1992) demonstrated this by encoding speech patterns as vibrotactile waveforms and presenting the patterns to participants who were instructed to discern what was said in the speeches from the rhythm, frequency, and amplitude components of the patterns. The results showed that the participants depended on the rhythms of the patterns more than the patterns' frequencies and amplitudes to decode the speech information. Brown *et al.* (2006) argued that rhythm should be considered the most important parameter in vibrotactile pattern design. Brown *et al.* referred to the vibrotactile patterns created from differing rhythms as *tactile icons* (TCONs). When changing the rhythm of a tactile stimulus to indicate three types of appointments (meeting, lecture, and tutorial) when the subject felt the sensations on their arm, Brown *et al.* found that the subjects were able to discriminate their meaning with 90% recognition rates. Enriquez and MacLean (2008) expanded this to nine TCONS and found that participants could recognize 73% of them correctly.

Another important parameter to consider with vibration is the time duration between stimuli. The minimal time threshold between two separate stimuli has been reported to be around 10 milliseconds (Terhardt, 1974). In other words, if another stimulus is presented within 10 milliseconds of a preceding stimulus finishing, the user will interpret the new stimulus as a continuation of the first. Users also interpret the stimuli differently when the duration parameter is changed. When the time duration between stimuli lasts 0.1 seconds in length or less, the stimuli are perceived by subjects as 'taps' (Gunther *et al.*, 2002). On the other hand, longer duration stimuli can "construct more smoothly flowing phrases" (pg. 374).

Certain areas of the body are more sensitive to touch than others, and the body area of tactile stimulation should be carefully considered. Tactile sensitivity is heavily dependent on whether the skin is glabourous, or non-hairy (Cholewiak and Craig, 1984). These areas include the fingers, hands, arms, thighs, and the torso, which are known to be the most sensitive areas of the body to touch (Cholewiak and Collins, 1995). Out of these, the lips and fingertips are the most sensitive (Sekuler *et al.*, 1973), with the fingertips also known to be the most sensitive area of the body to details (Vallbo and Johansson, 1978). Out of all the fingers, the index finger has been found to have the greatest acuity to touch (Vega-Bermudez and Johnson, 2001).

Combining tactile stimuli with the other senses can also affect tactile sensitivity. Temperature, another aspect of cutaneous touch, has been shown to affect touch acuity (Stevens, 1979). Tactile perception can also improve with supplementary visual cues (Press *et al.*, 2004). Pavani *et al*. (2000) demonstrated improved user performance when a flashing light accompanied a vibrating object held by their subject's fingers. However, if the light and vibration were incongruent, that is, if the light was shown on another finger than the one that was stimulated with vibration, the performance slowed and became inaccurate, even when users were told not to focus on the lights.

This section examined important attributes of vibrotactile feedback, an aspect of cutaneous touch. Parameters involved in vibrotactile stimulation include frequency, duration of stimuli and the time duration between them, rhythm, waveform, and the site of stimulation on the body. Finally, vibrotactile perception is multimodal and can change in the presence of other senses such as temperature and vision.

3.2 Tactile Physiology

This section will provide an overview of the pathway along which tactile signals are propagated from receptors under the skin to the brain. Different classes of receptors will be discussed, particularly those that respond to vibrotactile stimuli. A small discussion on how signals from the touch receptors reach the brain will be provided in this section, mainly to emphasise the speed of the fibre tracts on which signals are conducted, which impacts the latency of which the stimulus prompts a response from the subject. How the brain receives the signals and encodes them will be examined. Finally, the tactile acuity of the hand will be discussed further to defend its appropriateness for stimulation in future studies.

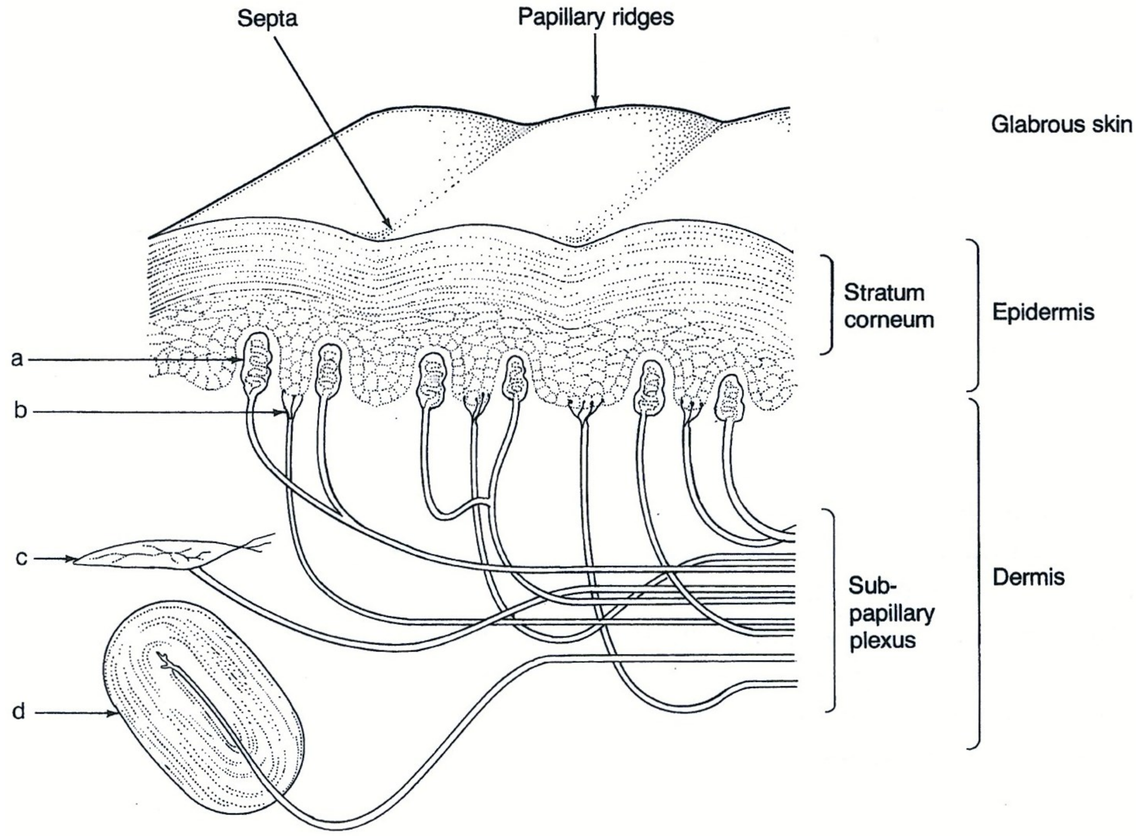


Figure 3.1: The four tactile receptors. A: Meissner corpuscles B: Merkel endings C: Ruffini endings D: Pacinian Corpuscles (image source from Light and Perl, 1984).

The sense of touch is mediated by *tactile receptors* under the skin, which excite through the act of transduction when the skin is deformed by pressure. Researchers have identified four types of tactile receptors, as shown in Figure 3.1. Each receptor type lies within different layers of the skin and is specialized for detecting particular kinds of touches. Messiner corpuscles lie closest to the skin surface and provide fine spatial discrimination (Johansson and Vallbo, 1983). They are primarily located in the fingertips (Levine and Shefner, 2000). Merkel cells and Ruffini endings lie deeper within the skin and are suited for detecting skin stretching (Johansson and Vallbo, 1983). They both fire continuously when a stimulus is applied (Goldstein, 2010). Pacinian corpuscles react to pressure to the skin (Lowenstein and Mendelson, 1965) and only fire once pressure is initially applied (Goldstein, 2010). With regards to vibration, both Pacinian and Messiner corpuscles respond to this type of stimulus, albeit at different frequencies: Pacinian corpuscles react to high frequency vibrations (250 Hz) and Messiner corpuscles respond to vibration at lower frequencies (10 Hz) (Hollins *et al.*, 2001).

Regardless of the stimuli, these receptors all send their signals to the spinal column using *primary afferent fibers* (Levine and Shefner, 2000). Like the four tactile receptors, primary afferent fibres are specialized for relaying specific kinds of sensory information back to the brain. They can be classified by size and degree of their myelination, which determines the speed at which they can conduct action potentials across their membranes. Fibres such as 'A-Delta Fibres', which transmit fast-pain sensations, have little myelination, and are slower at conducting than 'A-Beta Fibres' and 'A-Alpha Fibres' (Levine and Shefner, 2000). Tactile information is carried on A-Beta Fibers, which can conduct the signals at velocities up to 75 m/sec. The consequence of this is that tactile signals are one of the fastest sensations to reach the brain, and thus have little latency to perceive.

Once reaching the spinal column, the A-Beta Fibers branch to take the signal to the brain where it is processed. The signal synapses with a fiber tract called the *medial lemniscuses* in the spinal cord, which ascends into the thalamus in the brain (Levine and Shefner, 2000). Once reaching the brain, the neuron fibres propagate the signals across the brain midline to the thalamus where inputs from each receptor type are segregated and sent to the somatosensory cortex (Blake and Sekuler, 2006). First, the fibres synapse in the *ventrolateral nucleus* in the thalamus (Goldstein, 2010) with some synapsing in the *thalamic nuclei*. From here, the signal travels to the somatosensory receiving area (S-I) or the secondary somatosensory cortex (S-II) (Rowe *et al*., 1996; Turman *et al*., 1998). These two areas comprise the somatosensory cortex, which is an area of the brain whose neurons correspond to parts of the body (Penfield and Rasmussen, 1950). By using a somatotype mapping of the body, the brain can thus discern which area of the body was stimulated.

It is worthwhile to note that of all the locations on the body, the hand is probably the most versatile for tactile stimulation. There are several reasons for this. First, the hand contains all four types of receptors (approximately 17,000 in total) (Blake and Sekuler, 2006). Certain parts of the body, such as the fingers, are allocated a disproportionate area on the cortex relative to other body parts such as the legs (Duncan and Boynton, 2007). The fingertips and palm areas also contain both Meissner corpuscles in the upper layer of skin and Pacinian corpuscles in the lower layer. This means that these two areas are suitable for detecting a wide range of vibrotactile stimulation. The fingertips each contain approximately 40-50 Meissner corpuscles, though this does decline with age (Thornbury and Mistretta, 1981).

Medical studies have demonstrated how areas of the brain that regulate emotion are also activated in the presence of a tactile stimulus. Physical pain caused by touch activates the anterior cingulate cortex, which is also invoked by social exclusion (Eisenberger *et al.*, 2003). This area of the brain can also be activated when watching a loved one experience pain (Singer *et al.*, 2004), suggesting a deeper affinity with the emotional brain, particularly the limbic system discussed in the previous chapter (Section 2.2). Pleasant hand touches are associated with stronger activations of the orbitofrontal cortex than neutral affective touches, and that neutral but intense tactile stimuli strongly activate the primary somatosensory cortex more than pleasant stimuli (Francis *et al.*, 1999). fMRI has also revealed that regions of the orbitofrontal cortex are activated by pleasant and painful touches (Rolls *et al.*, 2003b). These studies have shown that at least parts of the orbitofrontal cortex are involved with representing pleasant and painful touches, and that this area activates differently than taste and smell. Furthermore, Francis *et al.* (1999) claim that the neural encoding of emotion is based on states elicited by rewarding or punishing tactile stimuli.

This section examined the pathway on which tactile signals are conducted on from their origination via tactile receptors under the skin. Tactile stimulation encompasses several attributes such as pressure, stretching, and vibration, and so receptors are specialized for detecting each of these. Tactile signals are quickly passed on to the brain via A-Beta primary afferent fibres, which are myelinated and can conduct signals at approximately 75 m/sec. Once in the brain, signals are decoded by the somatosensory cortex, which uses a somatotype map of the body to discern where the stimulus was perceived. The hands, and particularly, the fingertips and palms, are excellent candidate areas to consider for tactile stimulation, especially for vibrotactile feedback. Lastly, tactile sensations may have a deeper affinity with the emotional part of the brain as studies have shown that the part of the brain which processes emotion is also activated in the presence of physical touch.

3.3 HCI Affective and Wearable Haptics Review

This section will present a review of haptics in HCI, particularly, in the areas of affective haptics and wearable haptics computing. As the primary research question of this thesis was to examine how information may be communicated through technology-based implementations of sensory displays, this literature review will focus on the application of haptic displays to present information via tactile sensations to users with wearable devices. As was noted in Sections 3.1 and 3.2, the fingertips are an excellent location to consider for vibrotactile feedback stimulation, thus ring devices were examined in which to study different form factors, as well as those that combined concepts in research from the domain of affective haptics. This will form the basis of the technology implementation that will be assessed later in this chapter.

The word *haptics* has been used in previous sections but needs a formal definition. It comes from the Greek word meaning ‘to touch’ and in the modern sense is often used to describe systems that incorporates touch and kinaesthetic information (Blake and Sekuler, 2006). Haptics research as a means of communication can be traced to the original works of Geldard (1957), who was one of the first researchers to propose that the skin could be used as an information display. Though most early haptic research was mainly driven by the need to manipulate hazardous materials remotely (Sheridan, 1995), it has since found usage in a variety of specialized areas, and as mentioned in Section 3.1, has been investigated in research as a means of providing information encoded as vibrotactile patterns or TCONs. Research that has investigated using this information to arouse or influence emotional states of users is also known as *affective haptics*, which can be defined as “the acquisition of human emotions through the human touch sensory system, the processing of emotion related haptic data to detect affect, and the display of emotional reactions via haptic interfaces. Emotions may be solely communicated through the sense of touch or coordinated/integrated with other sensory displays (such as audition or vision) in a multimedia system" (Eid and Al Osman, 2016).

Section 3.1 briefly discussed tactile icons (TCONs), which are structured vibrotactile ‘messages’ for communicating information without visual stimuli (Brown, *et al.* 2006). This concept is analogous to icons in visual displays, except TCONs are more useful in circumstances where vision is obscured, unavailable, or where there is too much visual information for the user to process at once. TCONs, however, are not very useful if they cannot be discriminated. Lee and Starner (2010) demonstrated, however, that users could discriminate up to 24 kinds of vibrotactile patterns at almost perfect, 99% accuracy levels, if users were thoroughly trained for 40 minutes to recognize them.

Shin *et al.* (2007) created a physical interface called the 'TCON Display' to support emoticons in instant messaging. Their display consisted of a pair of hand-like devices attached to a keyboard and a lip-shaped device fixated to a monitor. These devices were comprised of pressure sensors for input, vibrating motors, pin actuators, heating coils, and colour output. By squeezing and touching these devices, users could send up to six 'enhanced TCONs': 'Grin', 'Cry', Anger', 'Surprise', 'Kiss', and 'Sleepy', which were complex and consisted of pulses of different vibrotactile wave forms with specific time durations and pauses. An evaluation study showed that users were able to identify which TCON represented each emoticon on the monitor. The study also revealed that users felt some of the TCONs ('grin' and 'sleepy') were more appropriate than others ('kiss'), for representing the emotion they were mapped to.

It appears that TCONS might be a good substitute for expressing emotional states in normal, everyday communication, which relies on the sense of touch (Smith and MacLean, 2007). However, even if such cues can be discriminated, it remains to be seen if humans can use vibrotactile cues like TCONs in day-day language. Chang *et al.*, (2002) provided some insights of human adaption to vibro-haptic technology though an exploratory study. They augmented voice communication by converting participants' hand pressure into a vibration that was sent to a recipient in real time. The results demonstrated that participants independently developed a system like Morse code, which allowed them to use the technology based on emphasis, mimicry, and turn-taking, during their conversations.

Research has also shown that tactile-enabled technologies can provide rapport in human-to-human communication and relationships, as in the cases of affective haptic research previously mentioned. An example of early work in affective haptics was *InTouch* (Brave and Dahley, 1997). This system consisted of two pairs of cylindrical devices that the user placed his or her hand on top of. When one of the participants rolled their hand across one of the devices, the other device synchronized their rolling movements to allow for tangible user presence detection. However, no study was carried out to verify this.

Another example of communication with affective haptics was *Cubble* (Kowalski *et al.*, 2013), which allowed couples to sense each other's presence by touching an illuminated, haptic-augmented cube, the parameters of which could be changed from their partner's phone. Partners could send signals to approximate nudging, tapping, and holding hands with their partner, which illuminated the cube with different colours and shook it with vibrotactile patterns. An exploratory study used different setups, such as using the phones only, using both the Cubbles and the phones, and a hybrid setup where only one of the partners had both a Cubble and a phone and the other partner used only a phone. The results showed that partners were more likely to tap and hold hands when they were given the Cubble instead of just the phone, which increased the 'closeness' they shared between each other instead of simply nudging them.

The previous example demonstrated the need for additional hardware in addition to a phone for vibration feedback interfaces. Lee and Starner's *Buzzwear* (2010) also demonstrated this necessity when using vibrotactile patterns to send alerts to users. Buzzwear was a wrist worn device used to study perceptual sensitivities to different vibrotactile feedback patterns when users were visual distracted. In their study, even when participants were visually distracted, performance was better at detecting alerts when subjects used the device instead of being notified directly with their phones. Thus, it is important to consider using a separate hardware component, instead of mobile phone displays, to deliver the modality of touch to users. This thesis turned its attention to such devices that could be worn for exciting emotion to users.

Uğur *et al.* (2011) proposed that such wearable technology could be used to communicate emotion through form factor. They performed user test studies where subjects evaluated prototypes of different, shape-changing garments worn on manikins by measuring the subjects' body arousal, self-expression, and posture. Uğur *et al.* found that the subjects associated aesthetically pleasing garments with positive emotions and disorderly shapes with negative emotions. Exciting emotions were linked with fast movements of the garments as they changed shape, and relaxation was linked with slower movements. A follow up study had users wear a necklace acting as a 'dynamic skin' moving around the neck, and the users reported on their impressions after an hour of usage. Users remarked that pulling down on the necklace caused them to relax but became distracted from the conversational topic at hand. When the necklace moved without the subject’s intent, the necklace caused feelings of mistrust. Uğur *et al.* therefore proposed that communicating emotion with such technologies can be measured by people's reactions and psychological state while they used a wearable, or what Tiger (1992) originally referred to as *Psycho-Pleasure:* a pleasure that derived from cognition, knowledge, and discovery, to satisfy the intellect of a human.

Within the wearable HCI domain, haptics has been incorporated into smaller form factors for displaying information. *Haptic Shoes* (Fu and Li, 2005), for example, allowed users to sense financial data wirelessly using wearable vibrators embedded in shoe soles. *Haptic Notification System* (Tam *et al.*, 2013) was another wrist worn device, like the Buzzwear system previously discussed, that was designed to help reduce distraction and improve awareness of time when speaking to an audience. Kobayashi *et al.* (2011) created an information display bracelet that guided users in a 3D space using vibration and colour. While these examples are not necessarily related to emotion, they do demonstrate the ability of using vibrotactile cues with a wearable device to guide behaviour and present information to the skin.

Gooch (2013) looked at measuring presence with several implementations: a thermal hug belt, which will be discussed in the next Chapter (Section 4.3), and YourGlove, a robotic arm looking device which mimicked hand holding when the user grasped the hand-like apparatus of the device, which caused the device to contract around their hand. Gooch claimed that the benefit of the device was its familiarity, and that by using clothing and items from a user’s partner, such as jewellery, the user could associate their partner with the device. In a study with 12 users, the users remarked that they understood hand holding as the main metaphor for the device and in dealing with relationships over a distance. Some users, however, were hostile to using the technology, as they believed it was intended to replace hand holding with their partners. They also complained that the device appeared 'creepy', as subjects were unfamiliar with the appearance of a dismembered limb.

There have been some efforts in the wearable space to augment emotion with haptics, though most were prototypes and no significant studies were carried out. *Hug Over a Distance* was an inflatable vest worn by a friend or partner, which could be triggered by another user when they rubbed their stuffed animal (Mueller *et al.*, 2005). *Hug Shirt* (Circuit, 2008), could send and receive hug information via sensors and actuators embedded into the fabric of the shirt. *Huggy Pajama* (Teh *et al.*, 2008) was a child worn vest outfitted with valves to inflate and deflate the vest remotely by a parent using an input remote control device. Again, while these technologies were novel, they were not backed by studies to verify their designs.

Wearable ring devices, or *ringterfaces* (Rissanen *et al.*, 2013) represent a great advancement in wearable electronics, due to their small and recognizable form factor. Most however, have been used for remote control of ubiquitous, smart environments, such as the *i-throw* (Lee *et al.*, 2007), which used gesture recognition to allow users to point at and control objects within the environment. However, these ring devices were not used to augment emotion or communication. Still, they incorporated novel technologies for input which could be repurposed for sending recipients emotional TCONs. Iwamoto and Shinoda (2007) created a ring which measured fingertip vibrations to estimate the finger's position on a surface. *Magic Ring* (Jing *et al.*, 2013) used an inertial detector to detect finger gestures. Zhang *et al.* (2011) built a ring that could control large screens without finger contact using an accelerometer, a gyroscope, and skeletal friction sounds. *Nenya* (Ashbrook *et al.*, 2011) allowed users to make selections by moving the ring around their finger and sliding it back and forth. More examples of ringterfaces can be found in Rissanen *et al.*'s summary of this field (2013).

A ring device could provide similar and more noticeable feedback than a mobile phone, especially since a ring could be firmly attached to the user's body on the finger, whereas a phone is not necessarily stored in contact with a user's body. Furthermore, the form factor of a ring could be used as justification for augmenting the emotion of the wearer, especially if the device appears like a piece of jewellery (Miner *et al.*, 2001). Such items are often associated with affection and relationships, as in the case of friendship bracelets or wedding rings, the latter's shape of which symbolizes unity and eternity. Therefore, this basic concept could be extended as a communication medium to allow couples and friends to share intimate moments over as distance, as is done with texting and social networks.

Very few works, however, have explored this idea with ring devices. The most relevant work by Labrune and Mackay (2006) consisted of several jewellery prototypes, collectively called *Telebeads,* to explore what they referred to as *mobile mnemonic* *artefacts,* which act as mnemonics by associating them with people on a network. One of the prototypes consisted of a ring which could output luminous and tactile information. However, no study was carried out. Another relevant work in this area was *United Pulse* (Werner *et al*., 2008), which allowed for remote intimacy by measuring a user's heartbeat and sending it to their partner's ring using vibrotactile feedback. A qualitative study interviewed participants, who responded that the technology allowed them to feel their partner and made them calmer, though the users were concerned with the issue of privacy. Another project also relevant was *Pingu* (Ketabdar *et al*., 2012), a ring outfitted with proximity sensors, LED lights, and vibrotactile feedback to investigate a variety of use case scenarios, including social interaction. The authors envisioned their ring could measure handshakes and proximity to others, which could then be used to connect to other people using social networks. However, the authors did not conduct any studies with the Pingu to validate their scenarios.

This section reviewed a variety of studies in haptics, wearable computing, affective haptics, and wearable ring implementations. The area of haptics can be divided into cutaneous and kineasthetic perception. The former was investigated for providing affective haptic feedback in the form of tactile icons, or TCONs, which are structured vibration patterns. These patterns can encode a variety of information and be discriminated by users to decode their meanings. This chapter examined if the meanings could hold emotional value, and concluded that form factor of the technology was important, especially if the technology could be worn like jewellery. Previous research using ring devices were explored, and it was found that surprisingly little literature has covered this area to present information like emotion to users. This presents a gap in the literature that addresses the research question posed by this chapter: *can a wearable ring device augment the perceived emotional content of SMS text messages with tactile and colour feedback?*

To provide an answer to this question, this thesis first constructed a ring-shaped device, called *Ring*U*, to explore augmenting the emotional perception of text message content with vibrotactile patterns and colour lighting effects. The basic idea was a device that could connect through a smartphone app to allow friends and partners to send hug expressions to each other over the internet, which could be used in tantrum with sending social media, such as text messages, to their friends and loved ones in their social networks. The technology went through several design iterations, due to the difficulty of creating a tiny and complex circuit that could communicate wirelessly and be self-powered. The development process will be described in the following section.

3.4 Development of Ring*U

*Figure 3.2: Ring*U system overview.*

Ring*U is a ring-shaped, wearable device that uses subtle tactile and lighting expressions to communicate expressions of intimacy and affection between partners over social networks. Figure 3.2 illustrates the system. Partners and friends can send vibrations and colours to each other by pressing the top of their ring, which sends a signal to their partner's ring over a wireless network. The partner receives the signal on their paired ring which will vibrate and light up according to the colours and tactile expressions selected by their partner. Depending on the paired combination, a user may interpret this as a hug, a notification, or a poke, along with other such actions.

This section will document the design process for the Ring*U. The device went through three iterations. The first iteration, which will be discussed in Section 3.4.1, was to quickly prototype the idea for feasibility. Prototype 2, discussed in Section 3.4.2, will describe a more sophisticated system that was self-contained and could connect to social networks. Ultimately, this design was discarded due to technological difficulties, and a third design, discussed in Section 3.4.3, was used in further evaluation studies later in this chapter.

3.4.1 Prototype 1

The aim of the first prototype was to demonstrate the basic concept of sending tactile expressions and colours with a ring. Only one colour and one vibration could be presented with this prototype, as the colour and vibration parameters were hard coded: no interface was provided to select the colours and vibrations other than pressing the Ring*U itself to signal when to send the cues to the other ring. Another limitation was that the device could not connect to social networks and that the wireless range was limited due to the use of ZigBee. This early, lo-fi design is shown in Figure 3.3.

In this system, a simple ring design was constructed using 3D modelling software and 3D printing with the assistance of a PhD design student in Singapore. The ring was designed to be assembled in two halves allowing for easy assembly. Inside each ring was a DC vibration coin cell motor, a push button switch, and a RGB LED. The top of the ring housed the LED, which was anchored on top of a moveable plate. When a user pressed on the top movable part, the button beneath it became pressed.

*Figure 3.3: Ring*U first prototype (image from Appendix H.1).*

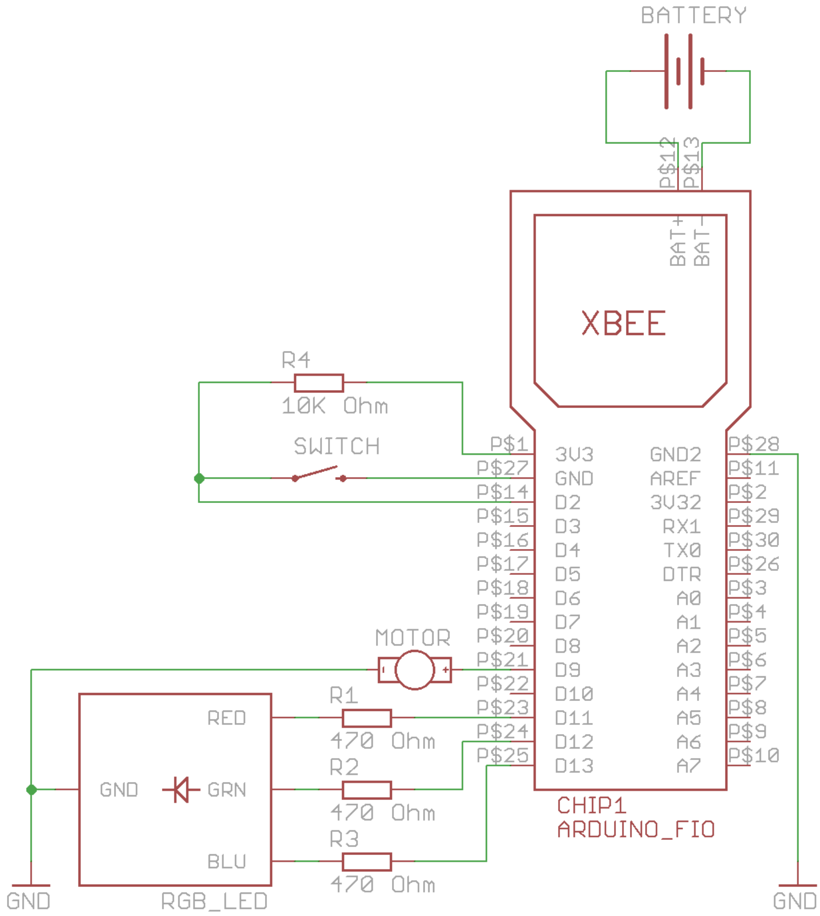


*Figure 3.4: Ring*U first prototype schematic.*

The ring was wired to a box containing an Arduino Fio microcontroller, an 850 mAh lithium ion battery, a custom PCB shield, and an Xbee radio antenna. After the user pressed their Ring*U, the Arduino detected the press and sent the signal over the wireless ZigBee protocol to their partner's Ring*U, which received the message and activated its LED and motor. The schematic for the circuit is shown in Figure 3.4.

To evaluate the prototype, the device was demoed at a showcase held at Keio University in Japan and was used by a dozen pairs of subjects (participant information was not collected as the evaluation was informal). The participants' reactions were observed, with some comments recorded as qualitative data. Participants were given an opportunity to try the device with their accompanying friend(s). They were told about the nature of the device and its purpose before trying it. They were then handed the device and were told to wear it on whichever hand they felt comfortable with. They then took turns squeezing their ring, signalling their ring's pre-programmed colour and vibration back and forth with their friend. At the end of the demo, they were given a chance to explain how they felt about the system, mainly to observe if they felt the input (pressing the button at the top) was an appropriate way of signalling the feedback to their friend.

Subjects generally reported a good impression of the system, but were naturally taken back by the bulkiness of the box containing the Arduino Fio board attached to the ring. Many subjects also mentioned a desire to control the lighting colours and vibration parameters and to send different kinds of touches depending on how hard they pressed the Ring*U. Some subjects also requested the ability to send the vibration and colour feedback to particular friends in their social network.

From this feedback, a more elaborate prototype was designed. First, the ring needed to be redesigned so that it could accommodate both the control processor and the battery. Second, an app was designed so that users could control the lighting and vibration effects when they squeezed their ring. Third, the switch was replaced with a pressure sensor so that users could specify the strength of the vibration and colour with their finger. Finally, the ZigBee antenna was replaced with Bluetooth so that the ring could connect to an app and hence social networks, like Facebook, through the internet.

3.4.2 Prototype 2

The next stage was to contain the entire system inside the ring which could be worn like a normal piece of jewellery. This required significant changes to the hardware for the Ring*U to be self-contained. Another significant addition was the inclusion of an app which could be used to change the colours of the LED and kinds of vibrations, as well as choosing which partner in a social network a user could connect to.

The new hardware discarded Arduino and ZigBee in favour of Bluetooth 4.0, which was low energy and was offered on several system-on-a-chip solutions, such as Texas Instrument's 8051 based CC2541 chip. However, development proved slow and difficult as the chip required an expensive compiler and had to be programmed in C. The CC2541 chip itself was also not self-contained as it required additional hardware peripherals such as an antenna.

This chip was eventually discarded in favour of using Bluegiga's BLE113 smart module, which integrated the CC2541 chip along with the additional necessary peripherals onto a single chip module. This solution also simplified firmware development as it used a proprietary scripting language called bgscript for programming most of the functionality. It also allowed for easy configuration of the hardware and the Bluetooth GATT profile using XML. The GATT profile was necessary as it was used to define how data was transferred from the Ring*U hardware to the app on the phone. A Ring*U 'service' was defined which contained several 'characteristics' for each LED colour, the motor intensity, and the touch sensor. The bulk of the firmware was developed using the DKBLE113 Development Kit until the actual hardware was manufactured by a local PCB fabricating company in the UK.

The biggest challenge of the new hardware was that the PCB board had to conform to a small size. The final PCB had to be contained in a space less than 18 mm^2, otherwise, the ring would have become too bulky to be wearable. A decision was made to create two, double-sided PCBs using Surface Mount Device (SMD) components. Figure 3.5 shows the schematic for the top PCB, which contained the Bluegiga module and the LEDs. Figure 3.6 shows the schematic for the bottom PCB which contained the battery charging circuit and the vibration motor circuit. Both PCBs were then connected like a sandwich using fine pitch SMD header connectors. Careful consideration was paid to the size of each component so that both PCBs utilized as little surface area as possible on the PCB board.

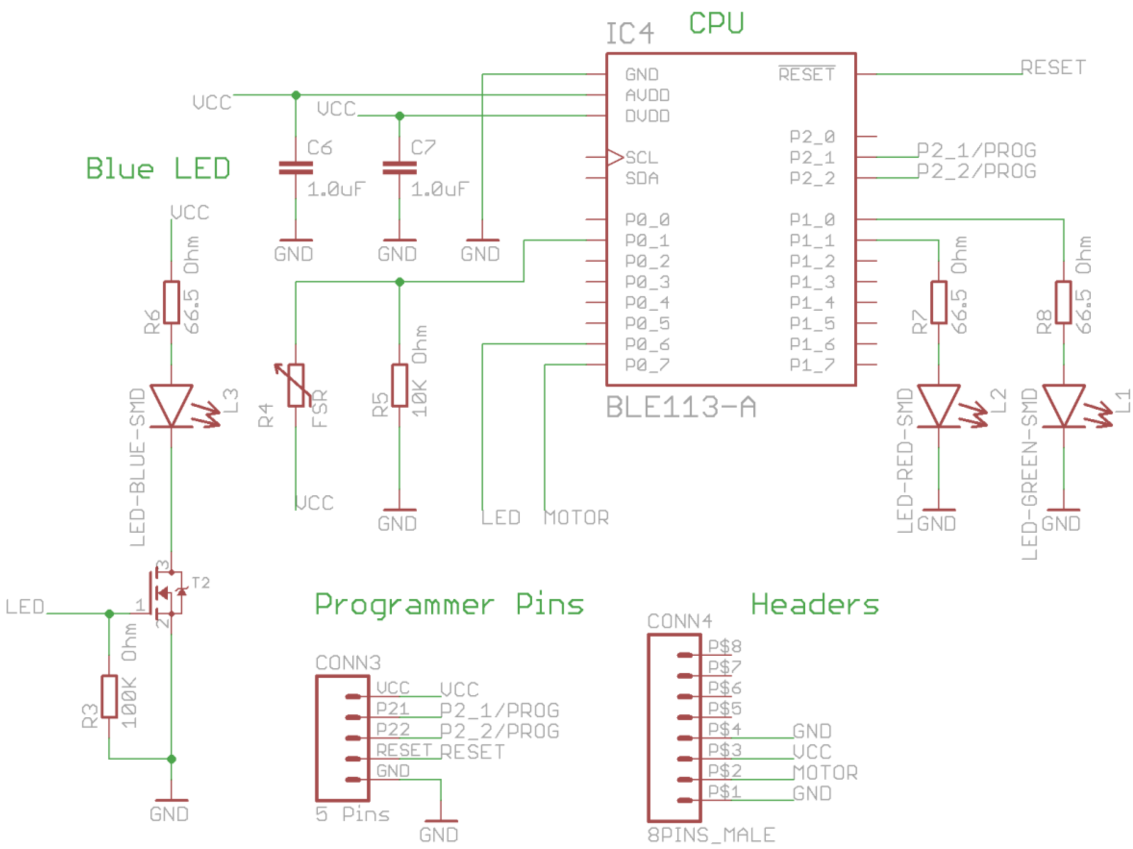


Figure 3.5: Top PCB schematic for Prototype 2.

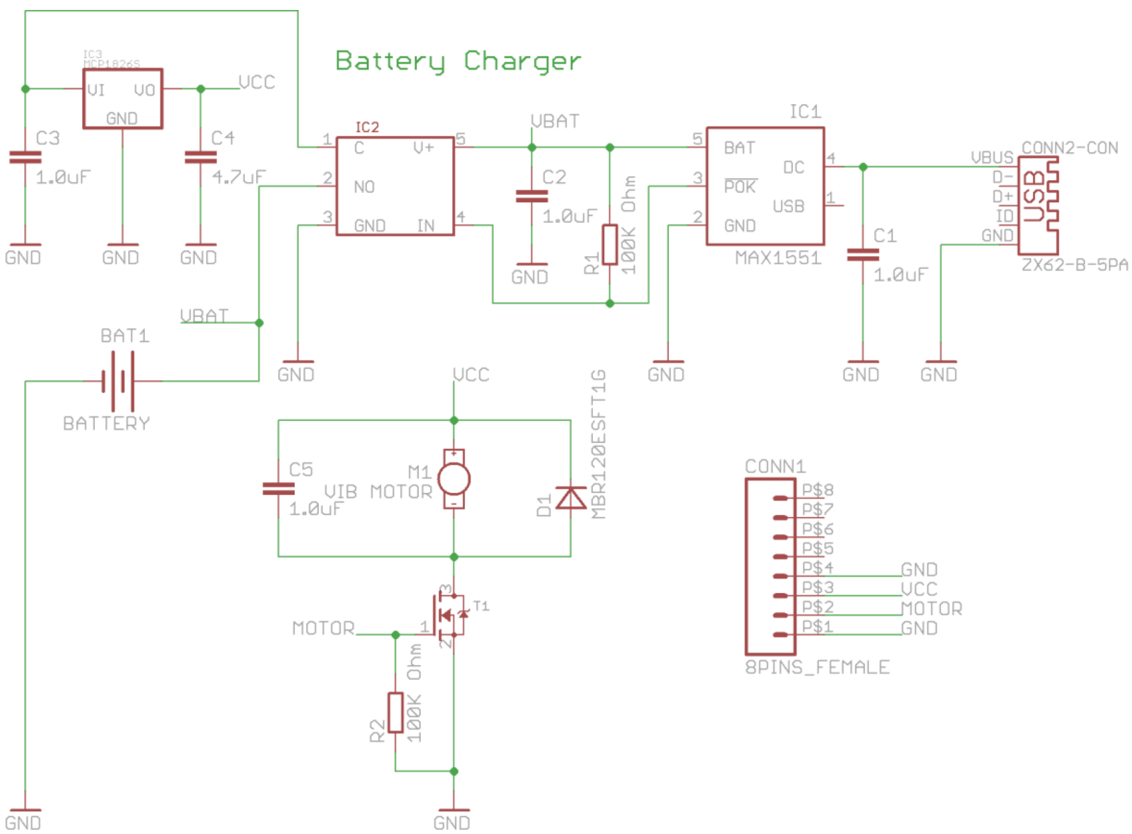


Figure 3.6: Bottom PCB schematic for Prototype 2.

Figure 3.7 shows the PCB layout design from the CAD software to illustrate the density of the board. Both board areas measured 17 mm^2. The board on the left is the bottom board containing the motor and battery circuits, and the board on the right contains the BLE113 module and the LED diodes. 4-layer PCB technology was employed to conserve further area by running power and ground traces from dedicated VCC and GND planes inside the PCB. Traces on both sides of the board were stitched together using micro vias, the small, green circles shown in Figure 3.7. The PCB was both fabricated and assembled by Newbury Electronics in the United Kingdom, as a pick and place machine was needed to solder the SMD components, some of which were less than a millimetre in size.

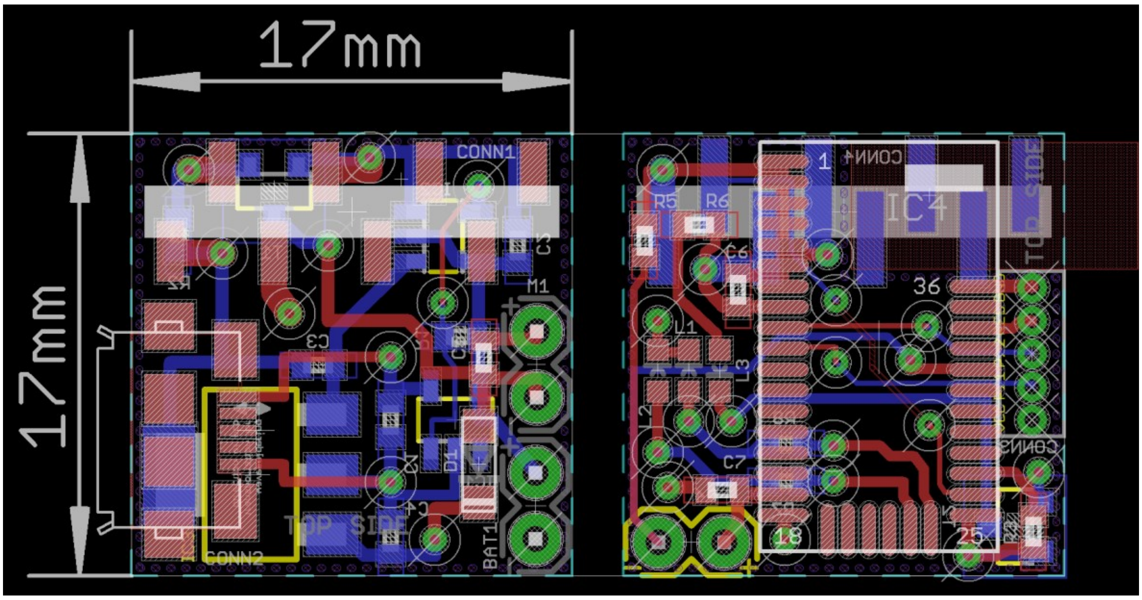


Figure 3.7: PCB layout for both bottom (left) and top (right) boards for Prototype 2.

Figure 3.8 shows the fabricated PCB. The images on the right show the PCB as it was shipped from the fabrication company, with the top right image showing the topsides of each PCB and the bottom right image showing the bottom sides. A 70 mAh lithium ion battery, supplied from a manufacturer in China, was used to power the Ring*U. An 8 mm diameter coin cell vibration motor was used, the smallest coin cell motor offered on the market. A force sensitive resistor (FSR), acting as the touch sensor in place of the button from the first prototype, was mounted upside as shown on the top board and wrapped around the entire PCB unit to be attached to the top PCB. After cutting out the PCBs, they were connected and insulated with insulation tape. Figure 3.8**,** *Left,* shows the completed hardware with the blue LED turned on.

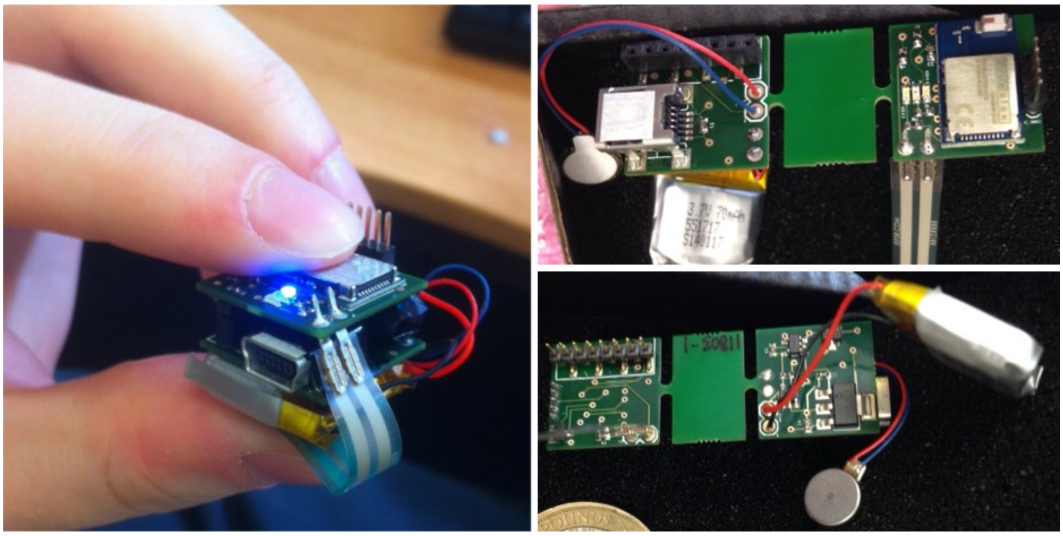


Figure 3.8: Fabricated PCB for Prototype 2. Left - Completed top and bottom PCBs connected, Top-Right - PCBs' top sides before cutting, Bottom-Right - PCBs' bottom sides before cutting.

A designer in Japan designed several iterations of the Ring*U's casing, as shown in Figure 3.9. As the final PCB specs were not known throughout most of the development, a conservative design was accommodated as shown in Figure 3.9, Left. Two different materials were used at this stage, one that used a silver alloy (far left) and one that used Watershed, a composite resin (middle left). The top of the ring for both was made using F25 material: a translucent, polyurethane elastomer. After confirming the PCB size, the designer made a newer version shown in the right images in Figure 3.9. This version better accommodated the PCB and was smaller. The light showed through a plastic rim around the device, as the F25 material was hard to press down on to activate the FSR underneath.

*Figure 3.9: Left - Early Ring*U design, Right - Revised Ring*U design.*

A fellow colleague (Pradana, 2013) designed and programmed the user interface for the app. He selected Pubnub (https://www.pubnub.com) as the means to push the data over the internet from the user's iOS device to their partner, and Parse (http://parseplatform.org) to save the details of the message logs. After the user logged in through their Facebook profile, they were presented with the interface shown in Figure 3.10. When they pressed on the image next to their avatar, the app connected to the Ring*U device and displayed a 'Connected' message under the icon. The user could then select one of three vibration types and toggle which colours to send, which was facilitated when they pressed the 'Send' button at the bottom of the UI or the top of their ring.

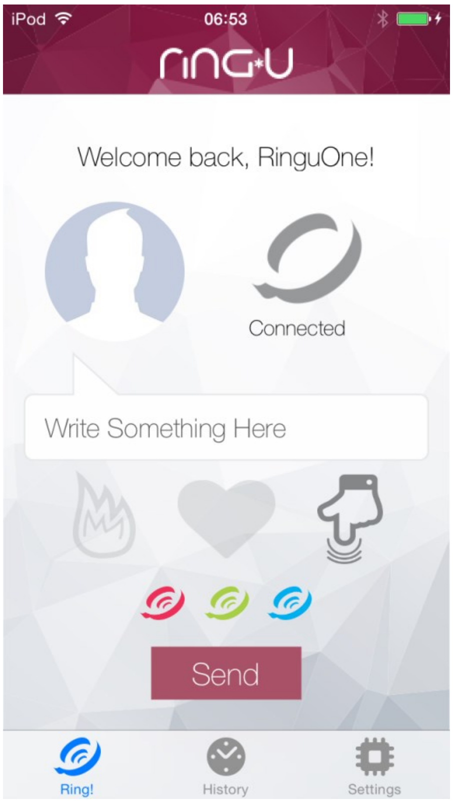


*Figure 3.10: Ring*U app user interface.*

Similar to the first prototype, the second prototype was demoed at a showcase event, this time in London, UK. Though the device was operational, it was apparent it would have been unsuitable for proper user testing in the lab due to several major technological issues. First was the issue with the antenna, which caused the ring to disconnect randomly from the app after an irregular amount of time. This may had been caused by the Ring*U antenna signal failing to reach the iPhone's antenna from within both the plastic and metal casing. The second issue was that the battery charge could only sustain the Ring*U for about 20 minutes of constant use due to its small size and capacity. Because of this, it would not have been possible to use the Ring*U in an experiment lasting longer than this time. Another issue was that it was difficult to use the pressure sensor as input; most users just pressed the Ring*U as hard as they could and did not seem to appreciate the different levels of vibration and colour it could actuate. Users also found it easier to just send the transmission from within the app using the 'Send' button shown in Figure 3.10 instead of selecting the colours and vibrations using the app and then squeezing their ring to send the transmission.

Thus, a decision was reached to make a simpler version of the Ring*U for experiments. Due to the antenna issues, wireless transmission of data was discarded in favour of wiring the Ring*U directly to the PC. To combat the battery issues, the Ring*U's power supply was also wired from the PC. Both issues were resolved by using a USB connection to transmit data and to power the circuit. Since Arduino uses USB, it was decided to revert back to the Arduino design for the third prototype. This would mitigate concerns so that the Ring*U could be used for longer experiments more reliably without concern for the battery or antenna. Lastly, the pressure sensor was removed as input.

3.4.3 Prototype 3

It was necessary to make a USB version of the Ring*U that would be reliable enough to use for experiments. This version was based off the simpler Prototype 1 design with a few modifications. First the Arduino Fio was swapped with an Arduino Uno board. The switch was removed and only the motor and LEDs remained. The ring casing from Prototype 1 was reused as it was smaller than the one from Prototype 2. The schematic for the third prototype is shown in Figure 3.11.

The prototype was designed specifically for experimentation in mind. To increase signal and power reliability, Bluetooth was discarded in favour of a wired connection to the PC using USB. A web application was developed that utilized Breakout, a JavaScript-based toolkit that allowed the Arduino functionary to be called from a web based application. The application displayed a user interface in a web browser, like the interface used in the previous chapter for selecting emotions in the emotion wheel. The program could also read in .csv files that contained the ordering of trials, and then it would call the appropriate Arduino functions from JavaScript to control the Ring*U. The application interface will be discussed in more detail in the next sections.

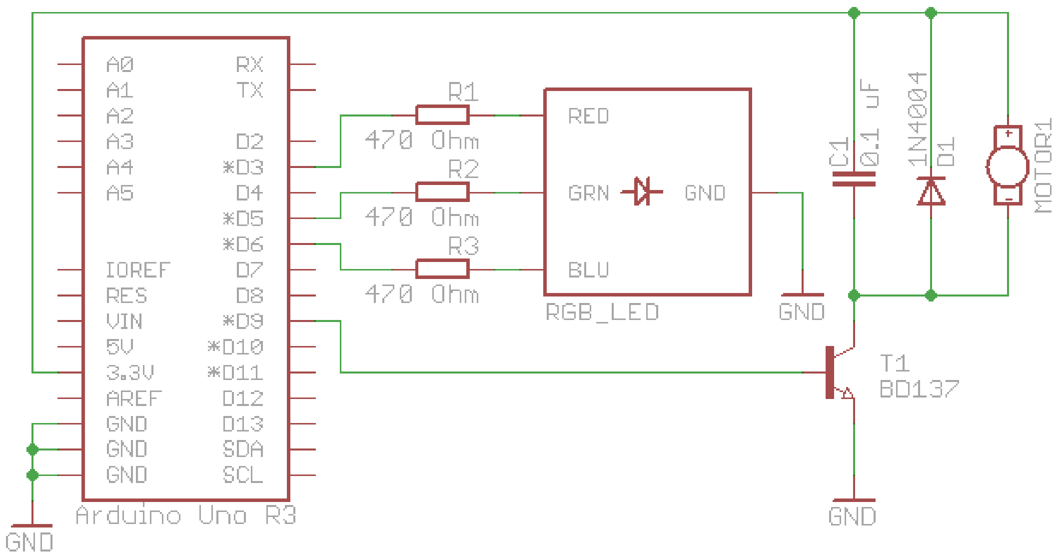


Figure 3.11: Prototype 3 schematic.

This section described development of Ring*U, a wearable ring-shaped device for use in experimentation with various vibrotactile waveforms and colour lighting effects. Though the original idea was to create a completely self-contained device, technological issues concerning connectivity and power impeded with its use in controlled studies. A more conservative design was utilized to circumvent these issues.

3.5 Pilot Tests

The Ring*U was used in three pilot tests to validate using it for an augmentation study as well as to collect pre-rated TCON and colour stimuli for later use (Section 3.6). The first (Section 3.5.1) and second (Section 3.5.2) pilot studies examined different TCONs and asked participants to rate them using the emotion wheel from Section 2.4.1.1. The third pilot study (Section 3.5.3) asked participants to similarly rate colour lighting effects sent from the Ring*U, also using the same emotion wheel from the TCON pilots. These pilot studies provided TCON and colour stimuli which were rated by subjects according to valence, which were used as independent variables in the main experiment (Section 3.6).

3.5.1 Pilot 1 – Simple TCONs

The first pilot study tested various types of vibrotactile waveforms (TCONs) that could be generated using the Ring*U. The pilot was run under similar conditions as the smell (Section 2.4.1) and message (Section 2.4.2) pilots from the previous chapter.

Subjects were given a stimulus, in this case, TCONs, while wearing the Ring*U on their finger, and responded to each TCON by rating how the TCON made them feel emotionally by making a selection on the emotion wheel.

3.5.1.1 Stimuli Design

To design the TCONs, the work of Sievers *et al.* (2013) was considered by which they used animation parameters, such as speed, to increase or decrease user perception of valence. Based on this work, it was believed that more intense and longer vibrations might be perceived as unpleasant, and shorter, less intense vibrations would be interpreted as pleasant feedback. Arousal was also believed to be mapped to the intensity of the stimuli, so that intense stimuli would be perceived as exciting and that low intensity stimuli would be perceived as calming.

Vibration ID	Duty Cycle	Length (sec)	Vibration ID	Duty Cycle	Length (sec)
0	0%	0	13	60%	3
1	20%	1	14	80%	3
2	40%	1	15	100%	3
3	60%	1	16	20%	4
4	80%	1	17	40%	4
5	100%	1	18	60%	4
6	20%	2	19	80%	4
7	40%	2	20	100%	4
8	60%	2	21	20%	5
9	80%	2	22	40%	5
10	100%	2	23	60%	5
11	20%	3	24	80%	5
12	40%	3	25	100%	5

Table 3.1: Simple TCONs made from varying the two parameters of intensity (duty cycle) and duration (measured in seconds).

Therefore, two parameters were initially considered for crafting simple TCON stimuli designs: time duration (valence) and intensity (arousal). The time duration of the TCON stimuli were given selected durations of 1 second, 2 seconds, 3 seconds, 4 seconds, and 5 seconds. The intensity of the TCON's vibration was achieved by altering the duty cycle of the Pulse Width Modulation (PWM) waveform generated by the Ring*U hardware. This was set at 20%, 40%, 60%, 80%, and 100% duty cycles. From these two parameters, 25 unique combinations of stimuli were obtained along with a control stimulus with 0% duty cycle and 0 second duration (the absence of stimulation for a neutral stimulus). Table 3.1 shows the 26 TCON stimuli that were created for testing.

3.5.1.2 Procedure

Three participants agreed to take part in pre-testing these TCONs. They were given the consent form shown in Appendix H.2 (this form was used for all subsequent studies in this chapter). The participants wore the Ring*U device on their dominant hands' index finger (they were asked beforehand which hand this was). Subjects were given the instructions shown in Appendix G.4. Trials were randomized and sent to the participants sequentially after they clicked the 'Next' button in the web form. The setup and interface was the same as the user interface (Figure 2.4) used in the previous chapter: participants were presented with an emotion wheel and had to select an emotion and intensity rating that corresponded to how the TCON trial made them feel.

Vibration ID	Length (sec)	Duty Cycle	Emotional Valence
7	2	40%	Pleasant
16	4	20%	Pleasant
23	5	60%	Pleasant
14	3	80%	Unpleasant
18	4	60%	Unpleasant
19	4	80%	Unpleasant
24	5	80%	Unpleasant
0	0	0%	Neutral

Vibration ID	Length (sec)	Duty Cycle	Emotional Arousal
10	100%	2	High
17	40%	4	High
18	60%	4	High
25	100%	5	High
3	60%	1	Low
7	40%	2	Low
20	100%	4	Low
24	80%	5	Low
0	0%	0%	Neutral

Table 3.2: The selected TCON pilot results where all three subjects rated the shown stimuli the same, showing the length of time they were displayed to each user, the duty cycle or intensity of the vibrations, and the emotion (Left - valence, Right- arousal) that all three subjects agreed the stimuli made them feel.

The stimuli that all three participants agreed to have either the same valence or arousal ratings from the pre-test are summarized in Table 3.2, and the full dataset can be referred to in Appendix B.1. The other TCON stimuli had varied valence and arousal response ratings across all three subjects (they were rated as 'ambiguous'). During the test, some trials were not recorded due to a bug caused by an array size difference in the database. The results nevertheless demonstrated that there were so few neutrally rated stimuli, though the presence of no vibration was perceived to be neutral. The length of time and the strength of the stimuli intensity also appeared to be unrelated, especially for the three trials rated as pleasant. Furthermore, the hypothesis that intense stimuli would be rated as highly arousing did not appear to hold, as no stimuli with 20% duty cycles were given a consistent, low arousal rating. Conversely, it appeared that high intensity stimuli were rated as either exciting or calm, regardless of the time duration.

To examine this further, more data was clearly needed, so a larger pilot using 20 subjects was run after fixing the software bug. This full pilot study was run using the same conditions as the pre-test. Subjects were 8 females and 12 males. Their ages ranged from 19 - 27, with a mean age of 23.5 years (σ = 2.01 years). These were the same 20 subjects that participated in the pilot studies in Chapter 3 (Appendix A.2). Their collected data can be referred to in Appendix B.2. To summarise the procedure:

- 20 participants came to the lab and sat down in front of a computer display.
- Participants wore the Ring*U on their dominant hand's index finger.
- Participants were given 26 stimuli, consisting of TCONs of varying intensity and duration presented in random order once each.
- After the Ring*U vibrated, the participants were presented with the same UI from Chapter 3 (Figure 2.4) in a web form, which consisted of the emotion wheel.
- Participants were instructed to rate the emotional feel of the TCON by making a selection on the emotion wheel.

3.5.1.3 Results

Like in the pre-test, participants appeared to rate the TCONs as mostly slightly unpleasant to slightly pleasant, with substantial varying responses in arousal. Using the mean rating method from the previous chapter (Section 2.4.1.1), the mean valence ratings were calculated to be in the range of from -2.4 to 2.5. Average arousal ratings ranged from -2.6 to 4.2.

Again, like in the pre-test, few trials were rated neutral by the subjects. Judging by both the valence and arousal ratings of the stimuli, TCON #0 (no vibration) was rated emotionally neutral by 70% of participants, with a mean valence rating of -0.4 (σ = 2.28) and a mean arousal rating of -1 (σ = 2.08). For comparison, the second most neutrally rated TCON (TCON #17, duty cycle = 40%, duration = 4 seconds), was rated neutral by only 15% of the sample, with a mean valence rating of -0.25 (σ = 3.49) and a mean arousal rating of -0.55 (σ = 3.46).

In general, longer stimuli appeared to elicit lower valence ratings, and there did not appear to be a relationship between using different intensities, durations, and the subject's perceived emotional arousal of the stimuli. A few TCONs (#15, #14, and #4), however, were given almost 'consistent' valence and arousal ratings ('consistent' is defined as having 70% frequency counts of subjects rating the stimuli for both valence and arousal ratings, and less than 70% is considered inconsistent/too ambiguous.) Using this threshold, TCON #15 (3 sec, 80% intensity) was both unpleasant and exciting: 80% of the subjects rated it to be unpleasant, with a mean valence rating of -1.7 (σ = 4.74), and 70% of the subjects rated it to be arousing, with a mean arousal rating of 3.8 (σ = 3.21). TCON #14 (3 sec, 80% intensity) was a low valence/low arousal TCON, with 80% rated it as unpleasant, with a mean valence rating of -2.4 (σ = 3), and 70% of subjects rated it as arousing, with a mean arousal rating of 1.6. (σ = 3.52). Lastly, TCON #4 (1-second duration, 80% intensity) was a high valence/high arousal TCON as 85% of the sample rated it as pleasant, with a mean valence rating of 2.5 (σ = 2.48) and 65% of participants rated it to be highly arousing, with a mean arousal rating of 1 (σ = 3.42). However, No TCON trials were observed that could have represented the high valence/low arousal stimulus category. As Tellegen (1985) remarked, stimuli with high valence and low valence both involve with high levels of arousal, which is hard to obtain.

Thus, this pilot study raised issues over the usage of designing TCONs using only intensity and duration as parameters. Varying the duration and intensity did not lead to consistent valence and arousal ratings for all but a few TCONs, and mainly with only valence. As discussed in Section 3.1, rhythm is an important parameter of TCON design to help in discrimination, as it provides a 'texture' to the TCON. Therefore, a new pilot study was designed that incorporated rhythm into the TCONs to see if more consistent emotional ratings could be obtained.

3.5.2 Pilot 2 – Complex TCONs

This pilot used new TCON stimuli that incorporated rhythmic pulses. The procedure for the pilot was the same as the previous TCON pilot study: participants came to the lab and sat in front of a computer display from which they rated the TCONs with an emotion wheel. They saw the same instructions (Appendix G.4). They wore the Ring*U the same way as in the previous TCON pilot study for all 9 TCON trials, which were presented in random order only once. The same 20 subjects from the previous pilot were used. Unlike the first pilot, no pre-test was ran with a few subjects.

3.5.2.1 Stimuli Design and Procedure

A fellow colleague (Pradana, 2013), who was part of the Ring*U project and programmed the web application interface, conducted the pilot study, as well as the studies in sections 3.5.3 and 3.6. This was due to the physical absence of this author during these parts of the experiments (though the analysis and discussion of the results of these studies presented in this chapter is entirely this author's own work).

Rather than crafting new TCONs, Pradana (2013) proposed using TCONs suggested by Shin *et al.* (2007) instead, along with TCONs #4 and #19 from Table 3.1. The new TCON stimuli Pradana selected are shown in Table 3.3 and have been given the names suggested by Shin *et al.* (2007) to describe their intended emotional effect. Many consist of complicated tactile patterns that can be broken into simpler 'signals'. These signals are like the simpler TCON stimuli from before (Table 3.1), which had intensities that lasted for a specific time duration. Intensities are expressed as a percentage in Table 3.3, shown in the 'P' column, and have a time duration in seconds, shown in the 'T' column. For example, the 'Kiss' pattern first starts at 20% power for 0.8 seconds, increases to 40% for 0.8 seconds, increases to 60% for 0.8 seconds, and then finally increases to 100% power for 1.5 seconds before stopping.

Name	Signal 1		Signal 2		Signal 3		Signal 4		Signal 5		Signal 6		Signal 7		Signal 8		Signal 9	
	P	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*	*P*	*T*
Blank	0	0																
Fast Loud	80	1																
Slow Loud	80	4																
Grin	60	0.1	0	0.1	60	0.1	0	0.1	60	0.1	0	0.1	60	0.1	0	0.1	60	0.1
Cry	100	0.5	20	0.7	60	0.9	20	1.1										
Anger	100	0.2																
Surprise	0	3	100	0.8	20	0.2												
Kiss	20	0.8	40	0.8	60	0.8	100	1.5										
Sleepy	20	1.5	60	1.5	20	1.5	60	1.5										

Table 3.3: Pilot 2 TCON stimuli designs, showing their names and signal breakdown by P (percentage of duty cycle) and T (time duration in seconds) for each signal.

The procedure for this pilot followed the previous pilot study with minor alterations:

- 20 participants (the same from the first TCON pilot in Section 3.5.1) came to the lab and sat down in front of a computer display.
- Participants wore the Ring*U on their dominant hand's index finger.
- Participants were given 9 stimuli, which consisted of TCONs of varying intensities, durations, and rhythms, presented in random order once each.
- After the Ring*U vibrated, the participants were presented with the same UI from Pilot 1 (Figure 2.4).
- Participants were instructed to rate the emotional feel of the TCON by making a selection on the emotion wheel.

3.5.2.2 Results

The collected raw data can be referred to in Appendix B.3. The summarised descriptive statistics of the valence and arousal rating results are shown in Table 3.4 below. This table shows the frequency of the number of ratings for the pleasant/excited, neutral, and unpleasant/calm responses in the '+', 'N', and '– ' columns, respectively, for both valence and arousal. This table also shows the average valence and arousal ratings for each pattern across all subjects under the 'Rating' column. As shown in the table below, the average valence ratings ranged from -1.65 to 2.80 and the average arousal ratings ranged from -0.75 to 2.7.

From Table 3.4 some observations can be made. First, TCON #3, or 'Grin', had the most pleasant ratings reported by 90% of the sample, with a mean valence rating of 2.8. TCON #4, or 'Cry', had the most unpleasant mean valence rating of -1.65, and was rated unpleasant by 65% of participants. Pattern 0, 'None', had a mean valence rating of 0.55, indicating again, the absence of tactile stimuli was perceived to be neutral, in this case, it was reported by 70% of the sample size. The other patterns, except for TCON #1, did not have a single subject rating it as neutral on the emotion wheel, and no stimuli produced consistently low arousal ratings with calm rating counts of 13 or above, as can be seen in the '-' frequency column under 'Arousal'.

TCON ID	TCON Name	Valence					Arousal				
		+	N	-	Rating	σ	+	N	-	Rating	σ
0	None	5	14	1	0.55	1.76	0	14	6	-0.75	1.68
1	Fast Loud	10	1	9	0.65	3.66	8	1	11	-0.15	3.72
2	Slow Loud	11	0	9	0.6	4.35	9	0	11	0.7	4.33
3	Grin	18	0	2	2.8	2.76	13	0	7	1.3	3.76
4	Cry	7	0	13	-1.65	3.41	10	0	10	-0.35	3.79
5	Anger	7	0	13	-1.4	3.86	12	0	8	0.9	4.01
6	Surprise	13	0	7	1	3.93	16	0	4	2.7	2.98
7	Kiss	12	0	8	1.35	4.69	15	0	5	1.85	4.51
8	Sleepy	9	0	11	-0.75	4.41	10	0	10	0.75	4.41

Table 3.4: Pilot 2 valence and arousal frequency, mean rating results, and standard deviations of the rating results for each of the 9 tested TCONs. For frequencies, the '+' column shows the pleasant and exciting counts, the 'N' columns shows the neutral counts, and the '-' columns shows the unpleasant and calm counts.

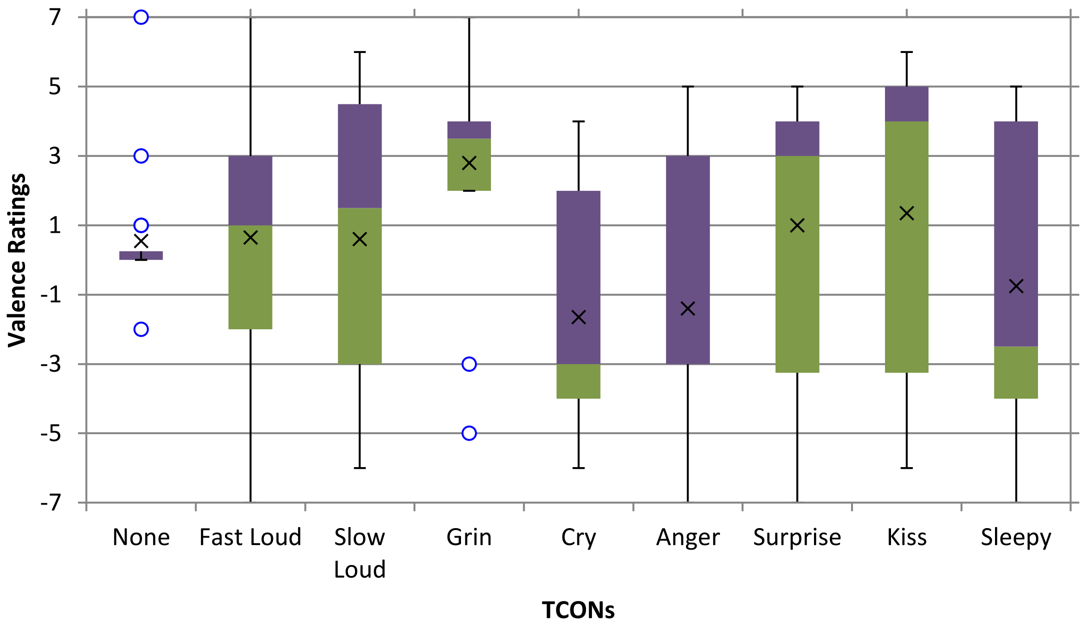


Figure 3.12: Boxplots of the valence ratings of the 9 TCONs.

To illustrate this data better, box plots for the valence and arousal ratings were generated, shown in Figures 3.12 (valence ratings) and 3.13 (arousal ratings). Again, from Figure 3.12, one can see that 'Grin' was given mostly positive valence ratings with few negative outliers. 'Cry' had the lowest valence ratings, with most of the 2nd, 3rd, and 4th quartiles rated below 0 (neutral). 'None' was given mostly neutral ratings, with a few positive outliers and one negative outlier. From Figure 3.13, 'Surprise' appeared to cause the most arousal and 'None' appeared to be neutral. However, very few

TCONs produced low mean arousal ratings, with the exception of the 'Cry' TCON and possibly 'Fast Loud'.

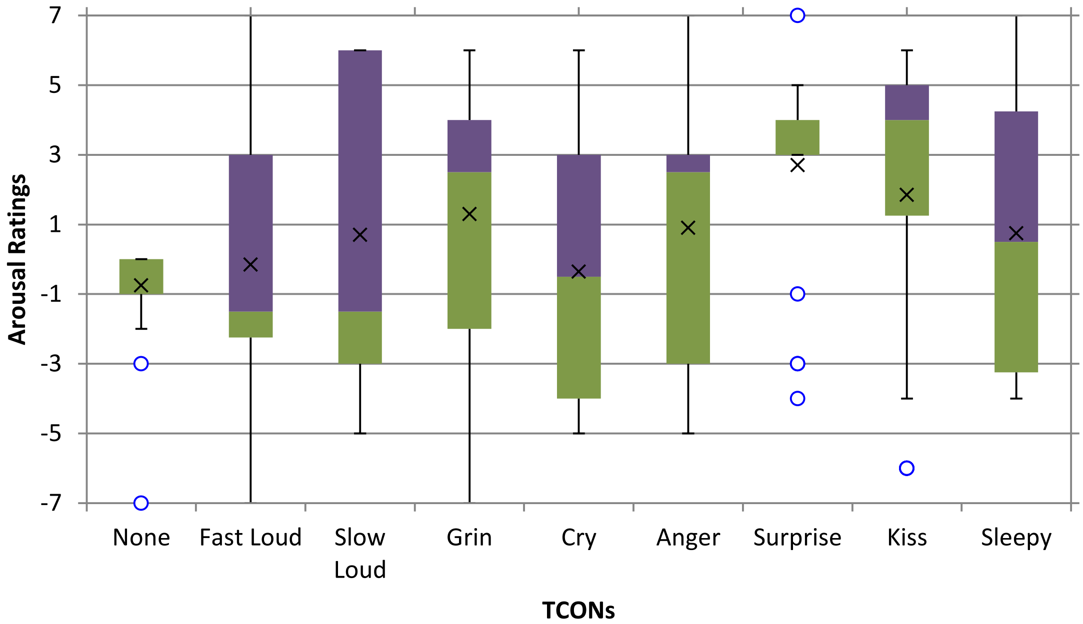


Figure 3.13: Boxplots of the arousal ratings of the 9 TCONs.

To examine these observations further, tests were run on the global valence and arousal rating datasets, which were then followed up with post-hoc Wilcoxon tests. For both valence ($p < 0.001$, $W = 0.93$) and arousal ($p < 0.001$, $W = 0.93$) the data was found to be non-normal using Shapiro-Wilk tests, thus non-parametric tests was subsequently used. First, the valence ratings will be analysed, and then the arousal ratings will be similarly tested afterwards.

A series of Friedman tests were run on the global valence rating data for all 9 TCONs, shown in Figure 3.12, and then, on subsets of this data. A statistically, significant difference in at least one of the treatments was found across all 9 TCONs using a Friedman test, producing $p = 0.02$ ($Q = 18.22$, $df = 8$). As 'Grin' produced the highest mean valence rating (2.8), the neutral stimulus produced the closest mean valence rating to 0 (0.55), and 'Cry' produced the lowest mean valence rating (-1.65), these stimuli were selected for further investigation. When comparing these three TCONs, a Friedman Test produced ($p = 0.001$, $Q=14.16$, $df = 2$), indicating that at least one of them was rated statistically, significantly different from the rest.

Next pairwise comparisons of the three TCONs were ran using Wilcoxon sign rank tests, shown in Table 3.5 (all p-values reported are exact p-values). All results were significant, implying that the 3 TCONs were rated differently from each other. This indicated that they represented their assigned valences: ‘Grin’ for pleasantness, ‘Cry’ for unpleasantness, and ‘None’ for neutral.

TCON Valence	VS	TCON Valence
Grin	p = 0.003	Cry
None	p = 0.03	Cry
Grin	p = 0.004	None

Table 3.5: Pairwise comparisons of the ‘Grin’, ‘Cry’, and ‘None’ TCONs using Wilcoxon sign rank tests. The p-values reported under the ‘VS’ column are exact. The TCONs’ name cells are colour coded to indicated their valence (pleasant = blue, unpleasant = red, and neutral = grey).

On the other hand, the arousal ratings of the TCONs was not found be significantly different. Running a Friedman Test across all 9 TCONs produced p = 0.10 (Q = 13.19, df = 8), meaning that subjects rated their arousal similarly. Further testing the three selected TCONs conditions from above (‘Grin’, ‘Cry’ and ‘None’) using a Friedman Test resulted in no statistically, significant differences either, producing p = 0.2 (Q = 3.23, df = 2). As the overall arousal rating median for all 9 TCONs was only 0.5, and quite close to a neutral rating of 0, it can be implied that these TCONs were not very effective in arousing participants and were thus rated overall very neutral in this respect.

The three TCONs ‘Grin’, ‘Cry’, and ‘None’ were rated different from each other in terms of valence. Arousal on the other hand, was not rated to be statistically, significantly different between the three TCONs (or any of the TCONs). Because of this, further testing of arousal in this study and the main experiment was not further examined, and only valence was analysed further. ‘Grin’ was selected as the pleasant TCON and ‘Cry’ was selected as the unpleasant TCON. TCON #0 ‘None’ was designated as the neutral TCON. These three TCONs were carried over for further testing in the main study of this chapter (Section 3.6) to analyse their effect on augmenting the perceived emotion of text messages with the Ring*U.

3.5.3 Pilot 3 – Colour Pilot

In addition to vibrotactile feedback, the Ring*U was also outfitted with a colour RGB LED. Colour could be a useful *control* condition, as it is a primary modality which could be used as a second dependent variable for augmenting emotion in text messages. In addition, the two conditions (TCONs and colours) could also be added together to see if there is an additive effect, or to observe if both types of modalities could enhance one another to provide additional informational dimensions (Blattner and Dannenberg, 1992), in this case, enhancing the richness of a messages' perceived valence or pleasantness. Therefore, the Ring*U was assessed in a third pilot study to see if subjects could consistently rate the emotion of colours emitted from its LED.

3.5.3.1 Stimuli Design

The colour pilot study consisted of asking participants to rate the emotional perception of the colours shown in Table 3.6 in Section 3.5.3.3, emitted from the Ring*U's LED at maximum brightness. Pradana (2013) suggested using colours from a previous study conducted by Manning and Amare (2009), whom evaluated the emotional qualities of the colour spectrum. Although it was not tested in this study, the absence of a colour stimulus was presumed to be neutral. All colours were emitted at full intensity using the hex values shown in Table 3.6.

3.5.3.2 Procedure

20 participants, the same 20 subjects in the pilots in Chapter 2 (the reason being they were recruited to do all pilot studies for both this Chapter and Chapter 2), were asked to come to the lab and test the colour stimuli. Participants were shown the instructions in Appendix G.5. Like the TCON pilots, the colour stimuli were randomly presented to users using a web script, which displayed the colours using the Ring*U's RGB LED, while simultaneously presenting the user with the emotion wheel user interface on the computer screen in front of them. To summarise the procedure:

- 20 participants came to the lab and sat down in front of a computer display.
- Participants wore the Ring*U on their dominant hand's index finger.
- Participants were given 11 colour stimuli, consisting of colours presented in random order once each.
- After the Ring*U emitted a colour, the participants were presented with the same emotion wheel UI from previous studies (Figure 2.4).
- Participants were instructed to rate the emotional feel of the colours by clicking on the emotion wheel.

3.5.3.3 Results

Appendix B.4 contains the raw data for referral. Table 3.6 shows the summarised results: the frequency of the pleasant, neutral, and unpleasant responses in the '+', 'N', and '–' columns, respectively, as well as the mean valence ratings for each colour. The mean valence ratings across all the colours ranged from -4.05 to 4.7. The colour orange was rated to be the most pleasant, with a mean valence rating of 4.7, with all 20 participants rating it with a pleasant emotion. Blue was rated to be the most unpleasant colour, with a mean valence rating of -4.05, with all 20 participants ranking it as unpleasant. None of the tested colours, including the colour white, evoked strong neutral responses. To illustrate this, boxplots of the 11 colours were generated, which are shown in Figure 3.14. White, orange, tangerine yellow, and green were given high pleasant ratings with a few negative outliers, while only blue was given consistently negative (unpleasant) valence ratings. Therefore, orange and blue were carried forward for further statistical testing.

ID	Name	Hex Value	Example	+	N	-	Rating	Std Dev
0	White	FFFFFF		16	2	2	2.75	2.9
1	Red	CC0000		9	0	11	-1.8	3.96
2	Orange	FF9900		20	0	0	4.7	1.49
3	Tangerine Yellow	FFCC00		18	0	2	2.7	2.7
4	Yellow	FFFF00		16	0	4	2.45	3.36
5	Green	009900		16	1	3	2.3	3.13
6	Cyan	00CC99		12	0	8	0.6	3.72
7	Blue	0000FF		0	0	20	-4.05	1.64
8	Dark Blue	000066		10	0	10	-0.45	3.27
9	Purple	660099		9	0	11	0	3.29
10	Pink	CC0066		16	0	4	2.6	2.68

Table 3.6: Colour stimuli from Manning and Amare's study (2009) and this pilot's valence frequencies, the mean valence rating results of each colour, and the standard deviations of the rated valences for each colour.

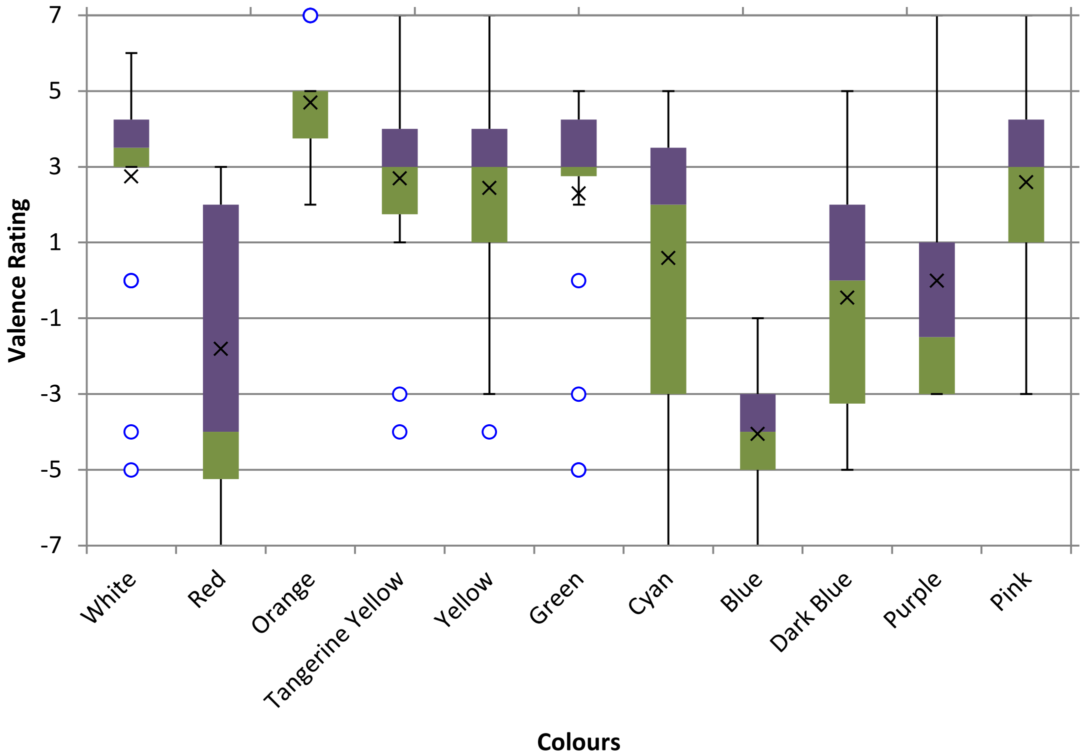


Figure 3.14: Boxplots of the valence ratings of the 11 colours tested.

First, the distribution of the global valence ratings was analysed, followed by Friedman testing and finally post-hoc Wilcoxon tests. Running a Shapiro-Wilk test on the global valence ratings produced $p < 0.001$ ($W = 0.92$), meaning the data was not normally distributed and non-parametric testing was subsequently used. Examining all 11 colours as treatments in a Friedman test resulted in a strong, statistically, significant difference in the ratings of at least one of the colour treatments ($p < 0.001$, $Q = 82.22$, $df = 10$). Finally, comparing the orange and blue colours also resulted in a statistically, significant difference between the two treatments using a Wilcoxon sign rank test ($p < 0.001$, exact). This indicated that these two colours were significantly different and thus the orange colour was found to be a very pleasant colour stimulus, as it resulted in the highest mean for valence (4.7), and the blue colour was found be a very unpleasant colour stimulus, with its mean rating of -4. These two colours, orange and blue, were carried over to be used as the pleasant and unpleasant colour stimuli for the main study, respectively, in the next section.

3.6 Main Experiment

The pilots in Section 3.5 demonstrated that the Ring*U technology developed in Section 3.4 could be used to effectively convey valence using TCONs and colours. Another outcome of the pilots was finding the strongest pleasant and unpleasant stimuli for the TCONS and the colours. These two modalities were experimental variables in the main experiment, which examined if the TCONs and colours could augment the emotion perceived from text messages. The three TCONs selected from the pilot in Section 4.5.2, 'Grin' (pleasant), 'Cry' (unpleasant), and 'None' (neutral) were tested by pairing them with the three text messages shown in Table 3.7 in Section 3.6.1 (pleasant, unpleasant, and neutral) and the two colours 'Orange' (pleasant), and 'Blue' (unpleasant), which were selected from the pilot in Section 3.5.3, with the addition of a no colour stimulus as the neutral colour. The two types of modalities and the message stimuli were thus combined into 27 unique combinations that participants were required to rate using the emotion wheel.

3.6.1 Stimuli Design

For the final experiment, 27 trials, consisting of a TCON, a colour, and a message stimulus, were created. Their makeup can be referred to in Appendix B.5. These 27 trials were combinations of the three TCONs selected from the outcome of Pilot 2 in Section 3.5.2, the two colours selected from Pilot 3 in Section 3.5.3, as well as a neutral colour that was simply set to off, and three SMS messages from the SMS message pilot in Section 2.4.2.

As was stated at the end of Section 3.5.3.3, two colours were selected from the colour pilot. These were 'Orange' as the pleasant colour and 'Blue' as the unpleasant colour. There was also a no colour condition, where the LED was turned on. This was presumed as the neutral colour.

Three tactile patterns were also selected from the second TCON pilot, as was discussed at the end of Section 3.5.2.2. These were 'Grin' as the pleasant TCON, 'Cry' as the unpleasant TCON, and 'None' as the neutral TCON. Again, these TCONs were complex and consisted of several phases of varying intensity and duration, each separated by a period. In the case of the 'None' TCON, the Ring*U did not vibrate at all.

Finally, three messages were selected from the previous SMS Message pilot from Chapter 2 in Section 2.4.2. These messages, along with their frequencies and mean valence ratings, are shown in Table 3.7. Message #1 was the pleasant message, Message #2 was the neutral message, and Message #3 was the unpleasant message. These were selected on the basis on their mean valence rating and frequencies relative to the other messages tested in that pilot, and these messages had the strongest valences of the 113 messages that were tested.

ID	Message	+	N	-	Rating
1	"Yay! Finally lol. I missed our cinema trip last week"	20	0	0	4.8
2	"At home by the way"	6	6	8	-0.3
3	"No, but you told me you were going, before you got drunk!"	1	0	19	-3.1

Table 3.7: The three SMS messages selected for use in the main experiment.

3.6.2 Procedure

16 subjects participated in the main experiment, which was conducted by Pradana (2013) and took approximately 15 minutes to complete. Participants were instructed to come to the lab and sit down in front of a computer display terminal for the duration of the test. They were asked to wear the ring on the index finger of their dominant hand and to hold the iPhone in their other hand. The iPhone displayed the text messages in a SMS message-like application, while the ring provided the vibrotactile and colour lighting feedback. Figure 3.15 shows this setup for one of the trials.

The three TCONs, the three colours, and the three text messages provided 27 unique combinations of vibrotactile, colour, and message stimuli. Each of these 27 *conditions* was presented once to each participant in a randomized order. A condition consists of three *channels,* specifically for each of the two modalities, and the text message content. For example, the 'Grin' TCON, the colour orange, and the pleasant message comprise the condition were all channels are set to pleasant.

Participants were told to focus on both the contents of the screen and the feedback they were provided with by the Ring*U. They were instructed to then rate the emotional perception they felt when reading the text message, feeling the TCON, and seeing the colour of each condition using the emotion wheel on the computer display in front of them (Appendix G.6). Once they made a selection on the emotion wheel, they were instructed to press the 'Next' button underneath the wheel to proceed to the next condition. All stimuli, including presentation of the emotion wheel, were presented simultaneously. The TCON would play until it finished the pattern, and then afterwards, the motor would turn off. The colour and message, on the other hand, would continue to appear until the participant pressed the 'Next' button to end the trial for the currently presented condition. There was no time limit for completing the experiment.

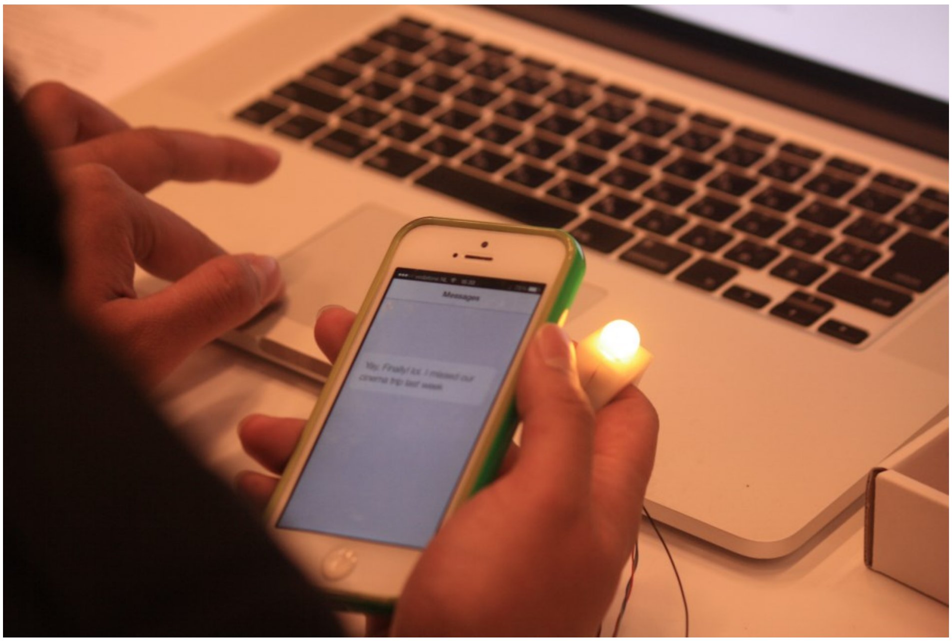


Figure 3.15: Experimental setup (image from Appendix H.1).

To summarise the procedure:

- 16 participants came to the lab and sat down in front of a computer display.
- Participants wore the Ring*U on their dominant hand's index finger, and held an iPhone with their other hand.
- Participants were given 27 stimuli trials, consisting of a unique combination of a TCON, a colour, and an SMS message.
- Each of the 27 trials was presented in random order once each.
- While Ring*U vibrated and/or emitted a colour, the participants were simultaneously presented with a text message on the iPhone screen, along with the emotion wheel UI on the computer display.

- Participants were instructed to rate the emotional feel of all three of the TCONs, the colours, and the messages, by clicking on the emotion wheel.

3.6.3 Results

As the dataset collected is quite complex (the raw data can be referred to in Appendix B.6), this section will first provide a descriptive statistics section (Section 3.6.3.1) and afterward, it will break the main question "can a wearable ring device augment the perceived emotional content of SMS text messages with tactile and colour feedback?" up into smaller sub-questions:

1. Are there significance differences in how users rated the most pleasant, most unpleasant, and most neutral conditions? (Section 3.6.3.2).
2. How strong is the effect of setting just one modality to either pleasant or unpleasant on the perceived emotion of the text messages? (Section 3.6.3.3).
3. Which modality (colour or touch) had the greatest effect on messages? (Section 3.6.3.4).
4. Does wearing the Ring*U change the perceived valence of text messages? (Section 3.6.3.5).

The discussion section that follows (Section 3.6.4) will then discuss each sub-question and bring their findings together as evidence to address answering this chapter's main research question.

3.6.3.1 Descriptive Statistics

This section first examined the global dataset to identify any trends or patterns. The general expectation was to see if conditions with more pleasant modalities would be rated higher than conditions that contained unpleasant modalities. The other expectation was to see if there existed a relationship between the users' emotional ratings of the conditions and the quantity of modalities within the conditions set to the same valence (referred to in this section as *valence congruency*). One would expect that having more unpleasant modalities within a condition would increase the likelihood of the condition rated as more unpleasant, and similarly, the more pleasant modalities within a condition, the more likely the condition should be rated as pleasant.

First, descriptive statistics were calculated for each condition: the mean and standard deviation. To review again, the dataset consisted of 27 different conditions, each made up of 3 different modality channels: messages, TCONs, and colours. For all 27 conditions, the mean valence rating was calculated (see Section 2.4.1.1 for how this mean was calculated using the emotion wheel) across all 16 participants. These calculations are displayed in Table 3.8, which shows the ID of each condition (row 1), the channel makeup of all their conditions (rows 2 - 4), their mean valence ratings (row 5) and the standard deviation of the ratings in each condition (row 6). Rows 1 - 4 are colour coded to illustrate the valence: whether the channel and overall condition presented to the subject was pleasant (blue ☺), unpleasant (red ☹), or neutral (grey 😐). For example, Condition #22, which was comprised of the neutral SMS message, the unpleasant TCON 'Cry', and the pleasant colour orange, resulted in a mean valence rating of 0.9 across all the subjects. The condition ID cells have been additionally colour coded according to the following: rating scores greater than or equal to 1 are coloured coded blue, scores in the range of 1 to -1 are colour coded grey, and scores less than or equal to 1 are colour coded red. The conditions are ordered by the mean valence rating, starting with the condition with the highest mean valence rating on the far left side of the table, to the condition with the lowest mean valence rating on the far right side.

Condition	15	21	3	16	9	10	24	6	4	5	18	0	25	22	12	11	19	13	7	1	23	17	2	20	14	8	26
Message	☺	☺	☺	😐	☺	😐	☺	☺	😐	☹	☺	☺	😐	😐	☺	☹	😐	😐	😐	😐	☹	☹	☹	☹	☹	☹	☹
TCON	☺	☹	☺	☺	😐	😐	☹	☹	☺	☺	☺	😐	☹	☹	😐	😐	☺	😐	☹	😐	☹	☺	😐	☺	😐	☹	☹
Colour	☺	☺	😐	☺	☺	☺	☹	😐	😐	☺	☹	😐	☹	☺	☹	☺	☹	☹	😐	😐	☺	😐	😐	☹	☹	😐	☹
Rating	3.8	3	2.3	2.2	2.1	1.8	1.6	1.5	1.5	1.3	1.2	1.1	1	0.9	0.8	0.8	0.4	0.2	0.2	0.1	0.1	-0.4	-0.6	-0.6	-1.8	-1.9	-2.8
Std Dev	2.2	3.5	1.3	1.6	2.0	1.3	3.2	3.5	2.6	3.0	2.7	1.7	4.1	4.2	2.3	2.4	3.2	2.1	3.9	1.5	4.4	2.5	2.0	3.1	2.1	3.1	3.1

Table 3.8: The 27 conditions tested in the main experiment, showing their channel makeup (Message, TCON, and Colour), their mean valence ratings, and the standard deviations of their valence ratings. Conditions are ordered by the mean valence rating, starting with the highest rated condition, Condition #15, on the far left side.

From Table 3.8, some observations can be made. First, most of the blue (pleasant) channels are concentrated on the left side and most of the red (unpleasant) channels are concentrated on the right side. This follows the expectation that the more pleasant the makeup of the condition, the more likely they will be expected to be situated on the left of the table, and likewise, the unpleasant conditions should lay on the right of the table. However, there appears to be an inclination from subjects to rate conditions more pleasantly than unpleasantly: almost half of the conditions were rated above 1 and only three conditions were rated less than -1. Finally, the message valence channel appears to have less variance than the TCON and colours: most of the unpleasant message conditions tend to clump towards the right side of the table than the TCON and colour channels, which appear to be more spread out towards the left side of the table.

To assess the possible relationship between the mean valence ratings and the channel valence makeup, these 27 conditions were further combined into ten groups of conditions, or *grouped-conditions*, according to their number of valence congruencies of their underlying channels. This generalises the dataset further in order to simplify it to identify possible trends.

Table 3.9 shows these groups, their underlying conditions, and the mean of the group's valence score. The 'Condition' row shows which conditions were grouped together: the reader can refer back to Table 3.8 to see the underlying channel makeup of each condition. As an example, Condition #3, #9, and #16 had one channel set to neutral and the other two channels set to pleasant, hence they were grouped together. The 'Group' row shows the ID of the groups, illustrated with three face symbols and colours, following the convention so far to representing the channel valences (pleasant/red = ☺, unpleasant/blue = ☹, and neutral/grey = 😐), with colour blends illustrating the amount of pleasantness being blended together for each grouped condition. The grouped condition ratings, shown in the 'Rating' row in Table 3.9, is simply the mean of all their underlying conditions' valence scores. Note that a consequence of this is that some grouped conditions contain more conditions than others, and that the order of the faces shown in the 'Group' row is irrelevant, only the valence of their three modality channels represented is important here.

Condition	15	3	9	16	0	4	10	1	2	7	13	25	14	8	26	12	6	19	22	5	11	17	21	18	24	20	23
Group	☺☺☺	☺☺😐			☺😐😐			😐😐😐	😐😐☹			😐☹☹			☹☹☹	☺😐☹						☺☺☹			☺☹☹		
Rating	3.8	2.1			1.4			0.1	-0.1			-1.5			-2.8	0.6						2.4			0.1		

Table 3.9: The 10 grouped-conditions, which are grouped by the number of conditions within them that have a similar number of congruent valence channels.

The seven grouped-conditions in Table 3.9: '☺☺☺', '☺☺😐', '☺😐😐', '😐😐😐', '😐😐☹', '😐☹☹ ', and '☹☹☹', are the most relevant to examine further for two reasons. First, they do not contain a mix of both pleasant and unpleasant channels within them, making it simpler to examine the effect of either pleasant or unpleasant valence emotions separately. Second, when looking at these particular grouped conditions' rating scores, one can see a gradual drop in the ratings starting on the far left of the table (the grouped condition '☺☺☺') and proceeding right to the '☹☹☹' grouped condition. To understand this trend further, the ratings of these seven grouped conditions are plotted side by side in the order above shown in Table 3.9 in Figure 3.16. This figure illustrates the decrease in ratings as a negative linear trend as the channel makeup becomes made up of more unpleasant valences.

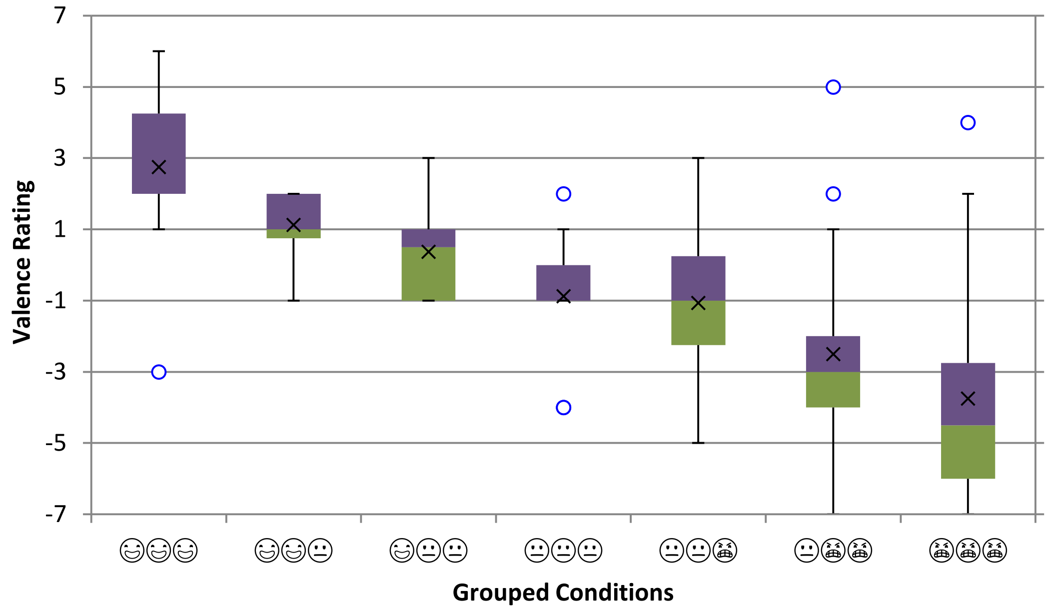


Figure 3.16: Box plots of the first seven grouped-conditions from Table 3.9, showing what appears to be a negative relationship between the conditions' mean valence ratings and their channel valence congruencies, as the channels within the grouped conditions become more unpleasant.

Figure 3.16 illustrates (but does not prove as statistical testing is needed) that the Ring*U does appear to be exerting an effect on how users emotionally rated the combined, perceived modalities. Conditions made up of pleasant modalities tended to result in higher valence scores than unpleasant conditions, and as conditions became increasingly unpleasant, so did the valence ratings drop. It remains to be seen if these results are significant and specifically if the conditions with the highest, lowest, and most neutral scores were statistically, significantly different from each other. The next section will examine this in closer detail.

To summarise this section's findings on identifying trends in the dataset:

- The more pleasant a condition's valence congruency, the more likely the condition's mean valence rating was observed to be higher and more pleasant.
- The more unpleasant a condition's valence congruency, the more likely the condition's mean valence rating was observed to be lower and more unpleasant.
- Grouped conditions were plotted as box plots using their valence ratings, and a negative relationship emerged as conditions became more unpleasant.

3.6.3.2 Extreme Case Conditions

To begin statistical testing, this section first addressed whether the 'extreme case conditions', the conditions where all the message, TCON, and colour channels were all set to pleasant or unpleasant valences, were significantly different from each other and the 'neutral condition', where all three channels where set to neutral. One would expect that the differences in how subjects emotionally rated these three conditions would be strongly, significantly different from each other: the most pleasant condition should result in the highest mean valence score, the most unpleasant condition should result in the lowest mean valence score, and the most neutral condition should result in a mean valence score close to or at zero. On the other hand, no significances between these conditions may imply that was no added benefit of blending, or adding modalities of similar valence *congruency*, to augment the overall intended emotion of the perceived stimulus, which would indicate complications with using the Ring*U at changing the emotional perception of the text messages.

Referring back to Table 3.8 in Section 3.6.3.1, the extreme case conditions are, as would be expected, located at opposite ends of the table (Condition #15, the most pleasant and Condition #26, the most unpleasant) and at the middle of the table (Condition #1 – the most neutral condition). This is because Condition #15 had the highest rating of 3.8, Condition # 26 had the most negative rating of -2.8, and Condition # 1 has the closest rating to zero of 0.1, which is again, expected of these extreme case conditions. So far, these observations do appear to support the hypothesis that setting all channels to the same valence appears to augment one another, resulting in the most extreme rated conditions.

To test the significance of these observations, statistical tests was run on the global valence ratings for all 16 subjects (referring to the original ratings each subject gave for each condition, shown in Appendix B.6). Testing this data for normality using a Shapiro-Wilk test produced $p < 0.001$ ($W = 1$), indicating that the data was not normally distributed. Thus, non-parametric tests were subsequently used. A Friedman Test was run on the 27 stimuli conditions. The result indicated a strongly, significant difference among at least one of the conditions across all 16 participants ($p < 0.001$, $Q = 105.08$, $df = 26$). This was expected: no difference would indicate that subjects emotional rated all conditions the same.

Post-hoc, Wilcoxon sign rank tests were run on the three pairs of extreme conditions. These three pairs and their statistical test results (p-values reported are exact) are shown in Table 3.10. All results are significant, as should be expected, meaning that all three conditions were rated to be statistically, significantly different from one another.

Cond.	Text	TCON	Colour	VS	Colour	TCON	Text	Cond.
#15	☺	☺	☺	$p < 0.001$	☹	☹	☹	#26
#1	😐	😐	😐	$p = 0.004$	☹	☹	☹	#26
#15	☺	☺	☺	$p = 0.001$	😐	😐	😐	#1

Table 3.10: Results of the Wilcoxon sign rank tests on the three pairs of extreme conditions, with their channel makeup shown. All p-values are exact.

The tests so far examined the differences between the extreme pleasant and unpleasant cases and the extreme neutral case. However, does there exist similar significance between the extreme cases and the conditions with only one modality active? In other words, the conditions where only one channel was set to pleasant or unpleasant and the other two channels were set to neutral? To investigate this, Wilcoxon sign rank tests were run between the two pleasant and unpleasant extreme conditions (Condition #15 and #26) and conditions that set just one of their channels to pleasant (Condition #0, #10, and #13) or unpleasant (Condition #3, #7, and #2). This allowed each modality channel to be explored individually against the most pleasant and unpleasant conditions.

Table 3.11 illustrates which pairs were tested along with the results of their Wilcoxon tests. The first column (green) shows which modality channel in the condition was set (either pleasant or unpleasant, the other two channels were set to neutral). The blue columns show the pair comparisons of the pleasant conditions and the red columns show the comparisons of the unpleasant conditions. As can be seen in the table, all pairwise tests resulted in significance, implying there existed a significant *additive* effect when blending multiple modalities together to augment the desired valence of the text message. This is evident when comparing the extreme case conditions: Condition #15 was rated to be more pleasant than conditions with only one of their channels set to pleasant, and Condition #26 was rated to be more unpleasant than conditions that just set one of the channels to unpleasant.

		Condition #15	**Condition #26**	
Message	**Condition #0**	$p < 0.001$	$p = 0.03$	**Condition #2**
TCON	**Condition #4**	$p = 0.018$	$p = 0.017$	**Condition #7**
Colour	**Condition #10**	$p = 0.012$	$p = 0.013$	**Condition #13**

Table 3.11: Wilcoxon test results comparing the most pleasant condition (#15) with conditions where only one channel was set to pleasant (blue columns) and comparing the most unpleasant condition (#26) with conditions where only one of their channels was set to unpleasant (red columns). The green column indicates which channel was set to either pleasant or unpleasant for the conditions compared against Condition #15 and #26. All p-values are exact.

"Are there significant differences in how users rated the most pleasant, most unpleasant, and most neutral conditions?" Yes, it appears that blending the modalities together with the same valence congruence appears to have an additive effect to produce the most extreme condition cases. In the case of the extreme conditions, which was tested in this section, the Ring*U was indeed enhancing the messages' valences, and that the TCON and colours did not cancel out each other's or the messages' valences, nor drove the messages' valences in the opposite direction. In summary:

- Condition #15 had the highest mean valence rating (3.8), resulting in a very pleasant emotional feeling when all three channels were set to pleasant.

- Condition #26 had the lowest mean valence rating (-2.8), resulting in a very unpleasant emotional feeling when all three channels were set to unpleasant.
- Condition #0 had the mean valence rating closest to zero (0.1), resulting in the most neutral emotional feeling when all three channels were set to neutral.
- All three conditions above were statistically, significantly different from each other.
- There were significant differences comparing the most pleasant condition to all conditions where only one modality channel was set to pleasant.
- There were significant differences comparing the most unpleasant condition to all conditions where only one modality channel was set to unpleasant.

3.6.3.3 Effect of a Single Modality

The first sub-question examined the effect of setting all three channels to the same valence (having the same congruency), revealing that setting three channels resulted in significant differences. A question remains as to how many channels needed to be set to a particular valence in order to see any significant difference from these extreme conditions: "how strong is the effect of setting just one modality to either pleasant or unpleasant on the perceived emotion of the text messages?" Could one modality (TCON or colour) strongly influence the valence of the neutral message to feel either pleasant or unpleasant?

To examine this further, Wilcoxon tests were run on pairs comparing the six conditions tested in Table 3.11 and the extreme case neutral condition (Condition #1). The results, shown in Table 3.12, show only significance when comparing the neutral condition with pleasant conditions #4 ('Grin' TCON) and #10 (orange colour). This indicates adding a single, unpleasant modality had no significant effect on influencing the valence of the neutral text message: setting just one of the channels to unpleasant was not sufficient enough to augment the neutral message to feel unpleasant. In addition, the effect of the user witnessing just the pleasant and unpleasant messages while wearing the Ring*U was also not significantly different than if the user saw the neutral text message instead.

		Condition #1	Condition #1	
Message	Condition #0	p = 0.104	p = 0.128	Condition #2
TCON	Condition #4	p = 0.032	p = 0.955	Condition #7
Colour	Condition #10	p = 0.013	p = 0.851	Condition #13

Table 3.12: Wilcoxon test results comparing the neutral condition (grey) with conditions where only one channel was set to pleasant (blue column) and conditions where only one of their channels set to unpleasant (red column). The green column indicates which channel was set to either pleasant or unpleasant for the conditions compared against the neutral condition.

"How strong is the effect of setting just one modality to either pleasant or unpleasant on the perceived emotion of the text messages?" Setting one modality to pleasant was able to change how subjects emotionally perceived the neutral message, but setting one modality channel to unpleasant did not augment the emotional perception of the neutral message. However, as was examined in the previous section, blending both modalities with the same valence with a message type of the same valence resulted in a strong significant difference when compared with these 'single modality' conditions. Therefore, the naive assumption implies that at least two or more modalities set to the same valence would be needed to sufficiently augment the emotion of the text messages to feel pleasant or unpleasant. To summarise the results of this section:

- There were significant differences comparing the neutral condition to conditions where only one modality channel was set to pleasant ('Grin' and orange) but not when the message channel was set to pleasant.
- There were no significant differences comparing the neutral condition to conditions where only one modality channel was set to unpleasant.

3.6.3.4 TCONs vs. Colours

To address the next sub-question: "which modality (colour or touch) had the greatest effect on messages?" this section examined the six conditions from Table 3.12 in more detail, as they had one of their three channels set to either pleasant or unpleasant, and the other two channels set to neutral. Thus, these conditions are useful for understanding the effect of each modality on the emotional content of the neutral message.

To illustrate how users may have rated these three channels by themselves, the mean valence ratings of these six conditions (and the all-neutral condition) were plotted using a line chart shown in Figure 3.17. The y-axis denotes the mean valence ratings of these seven conditions. On the x-axis are three categories: ‘Unpleasant’, ‘Neutral’, and ‘Pleasant’. The lines are colour coded to represent each modality channel shown on the key on the right.

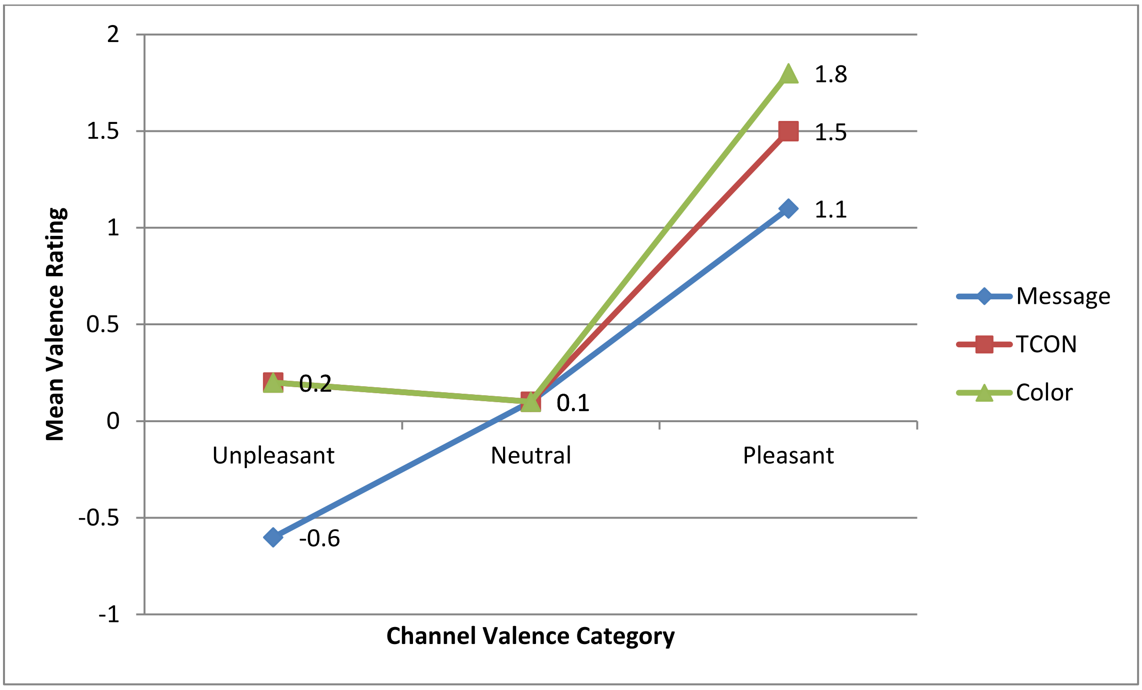


Figure 3.17: Graph of the mean valence ratings for the very neutral condition and the six conditions were one of their channels was set to pleasant/unpleasant and the other two channels were set to neutral. This allows examining channels’ valences separately: message text, touch, and colour, which are coloured coded by the legend on the right side.

Figure 3.17 illustrates four important points which will be addressed in this section. First, each of the channels’ mean valence ratings increased as they went from unpleasant (Conditions #2, #7, #13) to neutral (Condition #1) to finally pleasant (Conditions #0, #4, #10), which is expected. Second, conditions that were dominated by the valence of the message content diverged greatly from conditions that were dominated by either the TCON or colour channels. Third, TCON and colours appear to be rated similarly: when the TCON and colour channel valence was set to unpleasant, the mean valence rating for both conditions was 0.2, and for the two pleasant TCON and colour conditions, the mean valence rating was 1.5 and 1.8, respectively. Fourth, only the pleasant message condition, Condition #0, resulted in a negative mean valence rating, whereas when the TCON and colour channels were set to unpleasant, their mean valence ratings remained slightly above zero, or neutral. This indicates that users may had felt these unpleasant modalities were emotionally neutral. Conversely, when the TCON and colour channels were set to pleasant (Conditions #4 and #10), the resulting mean valence ratings were distinctively positive, indicating that subjects found these conditions to be quite pleasant.

A series of Wilcoxon Signed-Rank tests tested whether the first point above was significant. The results are shown in Table 3.13. The messages and colour pairwise comparisons resulted in significance, but not the TCON condition pair (p = 0.095). Thus, despite the appearance of Figure 3.17, it appears that participants rated the unpleasant and pleasant TCON dominated conditions (Condition #4 and #7) similarly.

Cond	Text	TCON	Colour	VS	Colour	TCON	Text	Cond
#0	☺	😐	😐	p = 0.033	😐	😐	☹	#2
#10	😐	😐	☺	p = 0.032	☹	😐	😐	#13
#4	😐	☺	😐	p = 0.095	😐	☹	😐	#7

Table 3.13: Results of the Wilcoxon sign rank tests on the three pairs of conditions where one channel dominated over the others.

To test the significance of the other points, this section will refer back to the results of Table 3.12, which tested the extreme case neutral condition with the conditions shown in Table 3.13. Table 3.12 showed that the Wilcoxon tests results of both types of text messages, as well as the unpleasant modalities, were not statistically significantly different from the neutral condition. When examining which modality had the most influence over the neutral message, only Conditions #10, (the pleasant colour) had any significant difference (p = 0.013) as well as Condition #4 (the pleasant TCON) (p = 0.032, Q= 1). Thus, it appears that only the pleasant modalities were significantly different from the very neutral condition.

“Which modality (colour or touch) had the greatest effect on messages?” No modality had an advantage over the other. Both appear to have a similar effect on augmenting the valence of the messages, and only when they were set to pleasant: when set to unpleasant, neither had an effect on the neutral message. These results, and the results of comparing the messages which had no effect regardless of their valence, imply that there was an effect of neutralisation when the other two channels were set to neutral. This *neutralisation effect* will be discussed at more length in

Section 3.6.3.5 when comparing these results with the pilots of Sections 2.4.2 (messages), 3.5.2 (TCONs), and 3.5.3 (colours). To summarise the results of this section:

- The pleasant message and unpleasant message dominated conditions were significantly different from each other, but NEITHER were significantly different from the neutral condition.
- The pleasant colour (orange) and the unpleasant colour (blue) dominated conditions were significantly different from each other, but only the pleasant, orange dominated condition was significantly different from the neutral condition.
- The pleasant TCON ('Grin') and the unpleasant TCON ('Cry') dominated conditions were NOT significantly different from each other, and only the pleasant TCON dominated condition was significantly different from the neutral condition.

3.6.3.5 Pilot Comparisons

To understand if blending modalities from the Ring*U augmented or neutralised the perceived valence of text messages, this section will return to the message pilot data from Section 2.4.2 and the TCON and colour pilot data from Sections 3.5.2 and 3.5.3. In these experiments, subjects rated each individual modality alone. This section will compare those results with the results of the six message, TCON, and colour dominated conditions examined in sections 3.6.3.3 and 3.6.3.4.

Modality Channel	Unpleasant		Pleasant	
	Pilot	Main Study	Pilot	Main Study
Touch	-1.65	0.2	2.8	1.5
Colour	-4.05	0.2	4.7	1.8
Text	-3.1	-0.6	4.8	1.1

Table 3.14: Pilot and main study mean valence rating comparisons.

Table 3.14 shows the mean valence ratings of the six conditions from Table 3.12 (where only one channel was set to pleasant or unpleasant, and the other 2 channels were set to neutral), listed under the 'Main Study' columns. Table 3.14 also shows the mean valence ratings of the corresponding pilot conditions for the 'Grin' and ‘Cry’ TCONs, the blue and orange colours, and the two pleasant and unpleasant messages under the ‘Pilot’ columns.

What is quickly apparent from this table are the rather large differences between the mean valence ratings in the pilot studies and the ratings of the similar conditions from the main experiment. The main experiments results appear to be closer to 0, or neutral, than their ‘equivalent’ pilot results, particularly with unpleasant stimuli (equivalent conditions here again refers to those in the main experiment that set the modality being tested to pleasant or unpleasant, and set the other two modalities to neutral). Therefore, the immediate question is to why such differences exist. First, the only difference in procedure with the main study with regards to the messages, was that participants were wearing the Ring*U when viewing the text messages, whereas in the pilot study they were rating messages without wearing the Ring*U. Second, for both TCONs and colours, the only difference in the pilots was the absence of viewing the text messages, as well as the absence of colours in the TCON pilot and the absence of TCONs in the colour pilot.

To attempt to analyse this effect further, the ratings of the conditions shown in Table 3.12 were compared against their equivalent pilot conditions in pairwise testing. As the pilot results were rated by different subjects than the main experiments, Wilcoxon Sign rank tests were not used (as the observations here are independent), and Mann-Whitney U tests (for two independent samples) were used instead. The results of these pairwise comparisons are shown in Table 3.15. One would expect to see the following results:

1. Main experiment pleasant conditions should have no significant differences with the pilot’s pleasant conditions.
2. Main experiment unpleasant conditions should have no significant differences with the pilot’s unpleasant conditions.
3. Main experiment neutral conditions should have no significant differences with the pilot’s neutral conditions.
4. Main experiment neutral conditions should have significant differences with the pilot’s pleasant and unpleasant conditions.

		Main Experiment Colour Conditions		
		Pleasant	Unpleasant	Neutral
Pilot Colours	Pleasant	p < 0.001, U = 22	-	p < 0.001, U = 3.5
	Unpleasant	-	p < 0.001, U = 17.5	p < 0.001, U = 10

		Main Experiment TCONs		
		Pleasant	Unpleasant	Neutral
Pilot TCONs	Pleasant	p = 0.08, U = 105	-	p < 0.001, U = 42
	Unpleasant	-	p = 0.10, U = 109	p = 0.10, U=109.5
	Neutral	-	-	p = 0.94, U = 158

		Main Experiment Texts		
		Pleasant	Unpleasant	Neutral
Pilot Texts	Pleasant	p < 0.001, U = 32	-	p < 0.001, U = 11
	Unpleasant	-	p = 0.01, U = 80	p < 0.001, U = 57
	Neutral	-	-	p = 0.68, U=147.5

Table 3.15: The results of pairwise Mann Whitney U tests for two independent samples (two tailed, ties correction), comparing the pilot results and the results from the main experiment study. The '-' denotes that no test statistic was calculated for that pairing. Sample sizes were 16 for the main experiment treatments and 20 for the pilot studies.

However, the results of Table 3.15 state otherwise:

1. Statistically, significant differences were found with the pleasant message and colour conditions, and only the pleasant TCON conditions were rated similarly.
2. Statistically, significant differences were found with the unpleasant message and colour conditions, and only the unpleasant TCON conditions were rated similarly.
3. Statistically, significant differences were found with the neutral message, but the neutral TCON conditions were rated similarly.
4. Statistically significant differences were found comparing the main experiment's neutral condition with all pilots' pleasant and unpleasant conditions, except when comparing the unpleasant TCON.

What these results indicate is that the colour and message main study results were rated differently than the pilot study, and only TCON conditions were rated similarly. Furthermore, the mean valence ratings of the main study's conditions were observed to be closer to neutral than that of the pilot study's conditions. This observation, of bringing the ratings to 0, or neutral, can be described as *neutralisation,* or nullifying the effect of valence, and appears to be significant, based on the results shown in Table 3.15.

This section examined the difference in ratings of the TCONs, messages, and colours from the earlier pilot studies with that of their equivalent conditions in the main study to address the sub-question “Does wearing the Ring*U change the perceived valence of text messages?” Yes, wearing the Ring*U does change the emotion, however instead of augmenting the emotion, it appears to actually neutralise it instead. This effect of bringing the ratings to 0, or neutral, can be described as *neutralisation,* or nullifying the effect of valence. To summarise this section:

- The mean valence ratings of the main study’s conditions were observed to be closer to neutral than that of the pilot study’s conditions (neutralisation effect).
- This effect appeared to affect colour and messages the most, as the ratings were all significantly different between the pilot and the main study.
- Conversely, TCON testing showed no significant differences between how users rated the TCONs in the pilot and the main study.

3.6.4 Discussion

This chapter investigated “*can a wearable ring device augment the perceived emotional content of SMS text messages with tactile and colour feedback?*” To provide a more informed answer to this question based on the data collected, descriptive statistics (Section 3.6.3.1) and four sub-questions were proposed and answered:

1. Are there significance differences in how users rated the most pleasant, most unpleasant, and most neutral conditions? (Section 3.6.3.2).
2. How strong is the effect of setting just one modality to either pleasant or pleasant on the perceived emotion of the text messages? (Section 3.6.3.3).
3. Which modality (colour or touch) had the greatest effect on messages? (Section 3.6.3.4).
4. Does wearing the Ring*U change the perceived valence of text messages? (Section 3.6.3.5).

When examining the global dataset for trends, three points became apparent. First, the more pleasant a condition's valence congruency, the more likely the condition's mean valence rating was rated higher and more pleasant. This was also observable for unpleasant conditions: The more unpleasant a condition's valence congruency, the more likely the condition's mean valence rating was rated lower and more unpleasant. Lastly a trend emerged as conditions went from extremely pleasant to extremely unpleasant: this relationship appears to be linear (see the box plots in Figure 3.16). These results were expected and hence statistical testing proceed to address the four sub-questions posed above.

The answer to the first sub-question "Are there significance differences in how users rated the most pleasant, most unpleasant, and most neutral conditions?" was yes: the Ring*U did appear to have a significant effect on the valence of the text messages when the extreme cases were examined. When the Ring*U blended the pleasant TCON and the pleasant colour while the user viewed the pleasant message, the resulting rating was the highest among all the conditions (mean valence rating = 3.8). This effect is also apparent when viewing an unpleasant message with unpleasant modalities: the colour blue and the 'Cry' TCON. In this case, the mean valence rating resulted in -2.8, considerably below 0. All of these comparisons were statistically significant (see Table 3.10) indicating that blending channels of similar valence congruency produced a strong additive effect on the valence of the message. Furthermore, there was statistical significance when comparing these three extreme case conditions with conditions where only one modality channel was set to valences other than neutral (see Table 3.11). These results were to be expected and, to refer to the main research question of this chapter, it appears the Ring*U was augmenting the perceived emotional content of SMS text messages with tactile and colour feedback.

The second sub-question "How strong is the effect of setting just one mobility to either pleasant or unpleasant on the perceived emotion of the text messages?" was answered in Section 3.6.3.3. Significant differences were found when comparing the extreme case neutral condition to the conditions where only one modality channel was set to pleasant ('Grin' and orange). However, there were no significant differences when comparing the neutral condition to conditions where only one modality channel was set to unpleasant. Therefore, the effect of setting one modality to a non-neutral valence did not appear to be strong with unpleasant modalities: the naive assumption here is that both modalities needed to be blended to exert a significant, unpleasant effect on the perceived emotion of the text messages. These results were not expected and seems to dissuade the Ring*U's ability at augmenting the perceived emotional content of SMS text messages with unpleasant tactile feedback.

The third point examined "which modality (colour or touch) had the greatest effect on messages?" was answered in Section 3.6.3.4. First, statistical analysis revealed that only the pleasant TCON and colour conditions were rated differently than the neutral condition, and that both modalities seemed to have a similar effect on augmenting the pleasant valence of the messages. Furthermore, the statistics revealed when either the colour or TCON channels were set to neutral, they appeared to exert a strong neutralisation effect on the overall stimulus, even when the message content was pleasant and unpleasant. These results indicate that the Ring*U is only effective at augmenting the perceived emotional content of SMS text messages with pleasant, but not unpleasant, tactile and colour feedback, and that it may actually be neutralising the emotion of the messages instead of enhancing them.

The neutralisation effect was examined in closer detail when addressing the last sub-question: "Does wearing the Ring*U change the perceived valence of text messages?" Section 3.6.3.5 revealed that the Ring*U does, however, when compared to the pilot results of messages, colours, and TCONs, the mean valence ratings of the main study's conditions were observed to be closer to zero (neutralisation effect). This effect appeared to affect colour and messages the most, as the ratings were all significantly different between the pilot and the main study. Conversely, TCON testing showed no significant differences between how users rated the TCONs in the pilots and main experiment. In other words, wearing the Ring*U did not actually augment the pleasantness or unpleasantness of the text messages' rated valences at all, even when all modalities were set the same valence.

This effect of neutralisation is undoubtedly the most important finding of this experiment. It ultimately reduces the utility using multimodal cues provided by the Ring*U to augment the perceived emotion of text messages within the context of reading text messages on a mobile phone described in this chapter. This does not render the Ring*U useless, however. As evidenced by the results of the pilot studies, the Ring*U can convey emotional content, particularly pleasant valences, using multimodal vibrotactile and colour cues on their own. However, it is not as effective at augmenting the emotional content of text messages using such cues, as the combinations of the cues, and perhaps due to the Ring*U itself, neutralises the perceived emotion of the text messages instead of augmenting their valences. Using multiple modalities together appeared have the same effect on the perceived valence of the messages compared to when the participant was viewing the messages without wearing the Ring*U.

Why did the Ring*U not augment the valence of the text messages, but neutralised them instead? There are some possible explanations for why this occurred. The participant could have been influenced by the message content to rate the main study's colour dominated conditions as neutral compared to their pilot's equivalents. It is also possible that users were distracted as well: in the pilot they rated only the message and did not wear the ring, so they could not had been distracted by wearing it. This second point can be backed by the analysis in Section 3.6.3.5, showing significant differences when users rated the messages without wearing the ring and when they did wear the ring, where all channels, including the message, was set to either pleasant or unpleasant.

The Ring*U's shape and form factor may had also influenced how subjects perceived emotions while using it. Uğur (2013) proposed that, as humans desire wearable technology to be viewed as an extension of their bodies, the technology also needs to be aesthetically pleasing, like garments or jewellery, otherwise the wearer may reject it due to its 'uncanniness'. "Test results show that people want technology that does not look so different from their normal clothing" (Uğur, 2013, pg. 98). Though the Ring*U attempted this, it may have not been aesthetically pleasing enough to convince subjects to view it as such. Like the Scentee in the previous chapter, the Ring*U is a novel technology, and therefore was also unfamiliar to the subjects, who may have felt uncomfortable while using it. It may had been better to have held a calibration session beforehand to help familiarise the users with the Ring*U's functionality instead.

Another explanation Uğur (2013) also proposed is that the body location of the wearable itself can be an important factor in how users will perceive it. Though the finger was selected due to its excellent tactile acuity for touch (Vega-Bermudez and Johnson, 2001), Uğur argued that, due to a somatic effect, certain areas of the body are better than others at being associated with particular emotions. In a study, Uğur asked subjects to identify parts of the body that corresponded to six emotions: joy, surprise, sadness, fear, love, and anger. Only 12% of the subjects associated the hand area with an emotion, particularly, the angry emotion. Furthermore, Uğur found that not all emotions are felt at the same time: emotions like fear and sadness are felt more suddenly than others. This was an area overlooked in this research, and future work should consider stimulating other areas of the body which are associated with more than one emotion, like the upper frontal part (Uğur, 2013).

3.7 Conclusion

Multimodal vibrotactile and color lighting cues were explored to augment the emotional content of text messages using a ring-shaped device. Literature in touch perception and physiology was reviewed to examine which facet of touch, like pressure, stretching, and vibration, would be most useful for conveying emotional content. Previous research in affective haptics was reviewed which have used vibration to convey emotion. Furthermore, wearable haptic technology was explored, however, little work has examined the form factor of such technology, especially using ring-shaped devices to convey emotion using vibrotactile cues (TCONs) and colored lighting effects.

A device, Ring*U, was created, to explore presenting different TCONs and colored lighting effects to users. The Ring*U was conceived as a technology which could present vibrations on the finger, which would then be interpreted as buzzing sensations to remind the wearer of their partner who missed them, in addition to a LED light which could emit a colour of the sender's choosing. Three prototypes were created: the first prototype explored using pre-programmed vibrations and colors, the second prototype explored a small form factor and network connectivity, and the third prototype was used for the experimentation of presenting emotional content in the form of TCONs and colour lighting cues.

Three pilot experiments were conducted using the Ring*U. The first pilot study experimented with sending simple TCONs of varying intensities and durations to subjects, who were asked to rate the perceived emotional content of the TCONs using an emotion wheel. However, the results revealed the difficulty of this task: few TCONs were strongly felt as pleasant/unpleasant and exciting/calm. A second pilot study experimented with sending complex TCONs of varying rhythms to subjects and asked them again to rate the stimuli with the emotion wheel. The results were more successful and three TCONs, pleasant ('Grin'), unpleasant ('Cry'), and neutral (no vibration) were identified which could be used in the main experiment. However arousal was dropped as a variable as it was difficult to identify TCONs with consistent arousal ratings across subjects. Finally, a third pilot study examined how subjects rated the perceived emotional content of colours emitted from the Ring*U's LED. Two colours were identified that could also be used in the main experiment, pleasant (orange) and unpleasant (blue).

Finally, the main experiment examined if these two modalities of TCONs and colours sent from the Ring*U could augment the perceived emotional valence of the pleasant, neutral, and unpleasant text messages. First, the three conditions that were most pleasant, unpleasant, and neutral were found to be significantly different from each other and resulted in the most extreme mean valence ratings on the emotion wheel. Second, conditions which were dominated by the valence of a single modality were examined, and it was found that their pleasant modalities were significantly different from the neutral condition. However, the similar unpleasant conditions were not significantly different from the neutral condition. Third, both TCON and colour appeared to exert the same effect on the text messages' emotions. Finally, and most importantly, the Ring*U was found to neutralise the perceived emotional content of the text messages, by making their original valence more neutral instead of augmenting pleasant messages to feel more pleasant, and likewise, making unpleasant messages to feel even less pleasant.

As multimodal cues comprised of vibrotactile and color lighting signals did not augment the perceived emotion of text messages, this thesis discontinued further investigation with the Ring*U device. Instead, this thesis turned its attention to another aspect of touch: thermo-touch. The next chapter will provide an overview of this sense and will describe the development of an implementation, with the aim of using it to provide information using temperature.

Chapter 4

Thermal Array Display: a System Description

The previous chapter discussed the use of touch as a means of communicating information (Hertenstein *et al.*, 2009; Francis *et al.*, 1999; Rolls *et al.*, 2003b) and the various manners in which haptic technology could be used to initiate communication in interactions (Huisman and Frederiks, 2013; Shin *et al.*, 2007; Chang *et al.*, 2002; Brave and Dahley, 1997; Kowalski *et al.*, 2013; Lee and Starner, 2010; Gooch, 2013). The chapter proposed a technology implementation, Ring*U, and was assessed in a controlled study. The multimodal feedback provided by the Ring*U was hypothesised to augment the effect of emotion communicated by the content of the text messages. However, the Ring*U device did not add or subtract from the emotional valence of the text messages' contents, but conversely neutralized them when the TCONs and colour lighting expressions were signalled simultaneously with the text messages.

This does not render the idea of wearable, haptic technology useless, however. Rather, the sense of touch could be further explored to discover if there is a dimension of the modality which could be utilized to augment, rather than neutralize, information communicated by media with a technology-based implementation. As was previously discussed in Section 3.1, there are three facets of cutaneous touch perception: pressure, vibration, and stretching. In addition to these three facets of cutaneous touch, there is another feature of touch seldom reported in HCI or even in perception literature: *thermoception,* or the body sense of temperature. Thermoception is broadly defined, as will be discussed in the next section (Section 4.1), therefore, this chapter concentrated on the haptic aspects of temperature within the focuses of HCI (Section 4.3) and how temperature could be used to communicate information. A unique implementation of a thermal display (Section 4.4) was then constructed to investigate the research question of this chapter: "*Can a wearable array of thermal stimulators be constructed to provide information using temperature?*"

This chapter will proceed as follows. First, it will discuss the psychophysical aspects of thermoception (Section 4.1) and then provide a brief, physiological background on how the body perceives and processes the sense of temperature by the brain and the receptors in the skin (Section 4.2). It then will examine some methods which utilized off-the-shelf technology to deliver thermal stimuli to the skin, known as *thermal displays* (Section 4.3). Virtual reality thermal displays will be examined first to differentiate their characteristics from *ambient* thermal displays used in HCI. The thesis concentrated on the latter, particularly applications of thermal displays which had been used to augment communication and guide behaviour. Section 4.4 will then describe the development of a thermal display implementation, referred to as the *Thermal Array Display* (TAD).

4.1 Thermal Perception

Thermoception serves three roles: thermoregulation of internal body temperature, protection from tissue damage, and finally, haptic sensation from touching (Green, 2004). This triple nature has several implications that wear on the perceptual acuity, or how sensitive humans are to perceiving thermal stimuli, of human thermal haptic performance. This is because the central nervous system, which manages thermoception, must compensate haptic perceptual acuity by additionally monitoring the internal body temperature and ensuring minimal localised damage to skin tissue in the presence of imminent threats, like reacting quickly after touching a hot stove. Management of these three roles thus has consequences for how poorly humans can differentiate different objects on areas of the skin, where thermo-sensory 'illusions' like 'synthetic heat', (see Section 4.3.2.4), may predominate in the absence of more acute senses, such as tactile feedback. Such illusions and studies of thermo-perception are well documented in the field of thermo-psychophysics, which can be broadly broken down into 10 areas: thresholds, location of stimulation, rate of change, magnitude, direction of change, age, gender, touch temperature, re-adaptation, and psychological zero points.

A thermal threshold is reached when participants report perceiving a temperature sensation, that is, they have become consciously aware of the change, and thus is the smallest change in temperature needed for the participant to perceive the stimulus. Such thresholds are also known as *just noticeable differences* (Kenshalo *et al.*, 1961). Psychophysicists use thresholds to determine how well humans (and other mammals) can perceive changes on the skin by varying a thermal stimulus' variables such as skin *location*, thermal *rate of change*, and the *magnitude* of the thermal difference. These factors, and those unique to thermal haptic perception, such as *re-adaptation, direction,* and *psychological zero points*, must be considered in the design of apparatuses for thermal feedback, such as where the skin should be stimulated on the body for maximum perceptual acuity as well as the temperature and time needed to re-adapt the skin temperature. These points will be discussed more thoroughly in the remainder of this section. Additionally, the factors of age and gender's effect on thermal perception will also be examined and considered as well in this section.

The contact *location* on the body has enormous implications as to how temperature can be perceived, as some areas of the body are more adept at sensing temperature differences than others. Stevens *et al*. (1974) examined ten areas of the body and subjected them to levels of heat from a radiant source. They found the forehead and cheeks to be the most sensitive of the ten areas investigated. The thigh and calve areas, on the other hand, required larger irradiance levels to produce a constant level of warmth. Stevens and Choo (1998) also found that regions on the face were the most sensitive (lips, cheek, and forehead), while areas on the legs, especially the feet, had the highest threshold values. On the arm, the fingers and the upper arm areas fared the poorest, while the thenar region on the hand was the most sensitive, followed by the forearm. Hagander *et al*. (2000) also confirmed this and reported that hand areas were more sensitive than the feet, particularly the thenar eminence, the dorsum of the hand, and the volar wrist surface. Regarding body symmetry, Meh and Denišlič (1994) found no significant differences between the left and the right sides of the body. In general, areas closer to the head and centre of the body are more sensitive than at the extremes, especially the legs.

Another variable studied in thermal psychophysics is *rate of change*, or how fast the temperature change occurs over a period of time. Pertovaara and Kojo (1985) found that increasing the rate of change of a stimulus pushed the thresholds higher of warm stimuli in their subjects. In other words, the faster the increase in temperature, the bigger a change was needed before it became noticeable by the individual. While Pertovarra and Kojo reported that the rate of change had no reliable effect on the thresholds of cool stimuli, Swerup and Nilsson (1987) found that if the temperature was reset to a *neutral* temperature of 32°C, cold thresholds could decrease as well. Furthermore, slow rates of change had a greater effect on warm thresholds than cool ones (Kenshalo *et al.*, 1968). Kenshalo concluded that as the rate of change continues over time, the skin's rate of *re-adaption* to the temperature change slows so that rate of change eventually exceeds adaptation. When this occurs, a threshold sensation is produced, leading to a stimulus perception.

Temperature *magnitude* is another variable studied in the measurement of thermal thresholds. Magnitude depends on the level of radiation, the areal extent on the surface of the skin, and the location of where it occurs on the body (Stevens *et al.*, 1974). The size of the effect these parameters have on thermal perception due to magnitude depends on the contribution of contact size that the skin has with the stimulus. In other words, varying the amount of skin stimulated has a directly proportional effect on the temperature intensity perceived by the subject. To address this in another manner, Stevens and Marks (1971) reported that the intensity of a stimulus and the area of the skin it contacts with could be traded for one another to preserve a constant level of warmth. This has the consequence that if two thermal stimuli are presented at the same temperature, they will be perceived as different if one has a greater contact surface with the skin.

Although somewhat obvious, the direction of change (warming or cooling), is another parameter studied in temperature perception. Direction can specifically refer to whether the skin touching the object or ambient environment surrounding the skin is in the process of heating up or cooling down to match the object's or ambient environment's temperature. Heat and cold are not symmetrical in perception: as will be explained in Section 4.2, different nerve fibres carry each but not both, which has implications on how humans perceive differences in cold and hot temperatures.

Studying the effect of *age* on thresholds has been a contentious topic in thermal perception research. Stevens and Choo (1998) have argued that thermal sensitivity does decrease with age. However, many publications have debated this rigorously. Gray *et al.*, (1982), for instance, found that neither age nor gender had any significant influence on the median thresholds of cool and pain stimuli in their participants. In support of this alternative view, Kenshalo (1986) reported that only the sensitivity of mechanical tactile stimuli, that is, pressure, stretching, and vibration, was affected by age. Conversely, Stevens and Choo (1998) reported that there did appear to be an age effect, but it varied all over the body's surface. The greatest changes with age-related sensitivities occurred at the extremities, particularly the foot, where thresholds became even impossible to measure safety in elderly subjects.

Gender also may or not play a role, as some research has shown that females may be more sensitive to temperature changes than males. Research has provided evidence for this view by demonstrating that females could detect lower thresholds of heat than males. However, cool thresholds remained the same regardless of gender (Lautenbacher and Strian, 1991). Females also demonstrated increased sensitivity to smaller temperature changes (Meh and Denišlič, 1994). However, Lautenbacher and Strian (1991) noted that the thermal threshold sensitivity may be attributed due to body size and weight differences. Furthermore, the method of stimulation plays a significant role as well (Lautenbacher and Rollman, 1993). A more recent study by Defrin *et al.* (2009) showed there were no gender differences between either warm or cool thresholds applied to the palm and dorsal surface of the hand. Thus, along with age, gender is a debatable factor in influencing thermal perception and thus was not a factor considered for this research.

Another area explored in thermal perception is the process of how heat is transferred from the environment to the skin. Gibson (1966) referred to the perceived temperature of an object as its *touch temperature*, which can be markedly different from its true, or *veridical temperature.* The *intensity* of touch temperature is determined by both the thermal properties of the environment and object as well as the area of skin making the contact. This will be discussed more thoroughly in Section 4.3.1 as it pertained to virtual reality displays. Touch temperature can also augment the tactile qualities of objects, for example, hardness (Blake and Sekuler, 2006) and perceived weight (Stevens, 1979). This suggests that mechanoreceptors responsive to pressure are also activated by temperature and continuously influenced by it.

One sensory phenomenon that is unique to temperature is the process of *thermal re-adaption.* When the skin is exposed to a sustained temperature after a period, the skin will adapt its temperature to the surrounding environmental temperature so that perception of the temperature is no longer noticeable. The precise range of temperatures over which this process occurs is debatable. Abbott (1914) found adaption occurred between the ranges of 17°C to 40°C and Gertz (1921) reported adaptation in subjects between 12°C to 42°C. A conservative report given by Hensel (1950) found adaption at a much tighter range of only 19°C to 40°C. In well controlled studies, complete adaptation takes place over a period of 10 minutes to 20 minutes, with the skin adapting faster to warmer temperatures than cool ones, with respect to the initial skin temperature. Rapid adaptation occurs for temperatures closer to the base skin temperature (Kenshalo and Scott, 1966), though skin temperature does not affect thresholds in the range of 27°C to 37°C (Hagander *et al.*, 2000).

This base, or resting skin temperature, is important to consider in experimental designs using temperature stimuli, as it forms the reference point from which human subjects judge aspects of any subsequent temperature differences. As can be expected, the body usually keeps this temperature point near the middle of the re-adapting ranges described above. One estimate put this temperature around 33°C (Mower, 1976). However, this temperature can depend on a myriad of external factors, such as time of day and an individual's health (Blake and Sekuler, 2006). This temperature, which is perceived as neither warm nor cool, is also known as the *physiological zero* (Kenshalo, 1972). In the literature review in Section 4.3, the physiological zero will also be referred to in experiments as the *neutral temperature*, as well as in original work presented in this thesis.

This section examined some key temperature variables involved in the perception of thermal thresholds: magnitude, rate of change, and location. Individual differences such as gender and age were discussed, and unique characteristics such as direction, re-adaptation, and the psychological zero were examined. These numerous factors compound the opportunities of exploring usage of thermoception to communicate information. As such, many variables need to be considered in this research: which ranges of temperatures should be used? What magnitude values of temperatures in the selected range should be used and how many can subjects discriminate? Which temperature value should be used as the psychological zero? What are the rates of change that could be achieved with current thermal display technologies? Where on the body should the skin be stimulated? Finally, how well can humans discriminate several areas of stimulated skin at once?

To explore these questions further, the next section of this chapter (Section 4.2) will examine the thermal pathway: how receptors under the skin signal to the brain that a temperature stimulus has been presented. This will reveal some challenges, such as the time it takes to perceive such changes and phenomena like 'paradoxical heat'.

4.2 Thermal Physiology

Temperature is sensed in the skin by a class of receptors. This thesis refers to these receptors simply as 'temperature receptors'. Temperature receptors are free nerve endings of neurons (Levine and Shefner, 2000), which can respond to non-contiguous and infinite ranges of cutaneous, noxious (dangerous) or innocuous (harmless) thermal stimuli. Cold receptors, for example, can respond to temperature changes on the skin in the range of 10°C - 30°C, and from 45°C onward (Long, 1977).

Temperature receptors correspond to small and specific receptive fields on the skin. These fields map to a single receptor that responds to either cold or hot stimulations. The fields have an average diameter of 1 millimetre (Kenshalo and Duclaux, 1977; Duclaux and Kenshalo, 1980). There are more cool receptors than warm receptors (Jones and Berris, 2002). The ratio of cool to warm receptor density depends on body location, for example, on the forearm, it is estimated that there are seven cool fields and 0.24 warm fields per 100 mm^2 (Jones, 2009). Figure 4.1 shows these fields on a portion of the underarm skin, demonstrating a grid of spots on the skin which detect either hot or cold stimuli. The grid may explain phenomena such as 'paradoxical heat' (Hamalainen, *et al.*, 1982), when cooling the skin may make the sensation feel warmer as a warm field may had been activated instead of a cool one.

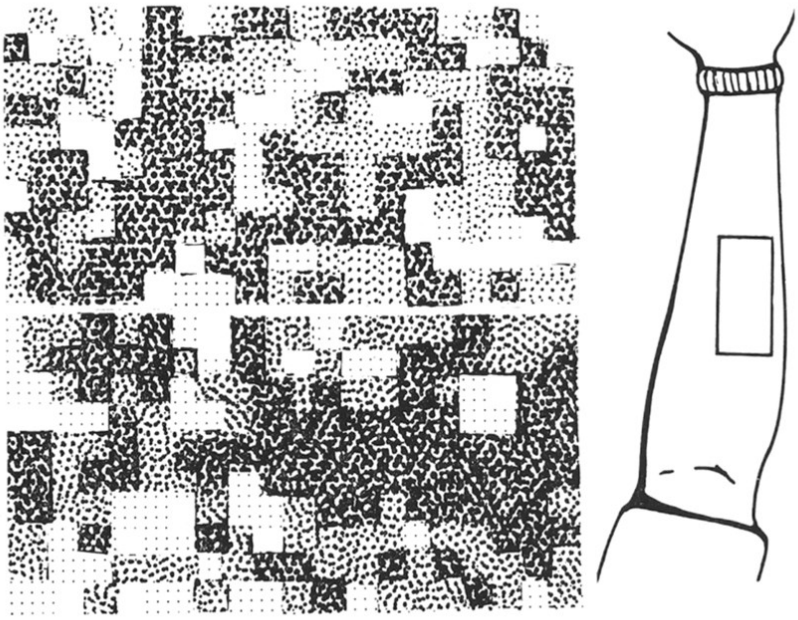


Figure 4.1: Grid-like distribution mapping of cool (Top Left) and warm (Bottom Left) stimuli from the underside of the arm (Right). The darker gradients indicate areas with increased sensitivity to cool/warm (image from Melzack et al., 1962).

Similar to tactile perception, thermal signals are sent to the spinal cord on primary afferent fibres (Levine and Shefner, 2000). As previously discussed in Section 3.2, these fibres are classified by the size and degree of myelination around the axon, which determines the speed at which they can conduct the action potentials. Thermal signal propagation is sent via 'C Fibres', which are small and have no myelination, in comparison to tactile information which is sent on faster transmitting fibres. Thus, temperature stimuli are the slowest type of touch sensations to reach the brain. Cool and warm stimuli speeds differ: warm receptor fibres transmit action potentials at speeds of only 1 metre per second. For cold transmitting fibres, the speed is significantly faster at about 10 metres - 20 metres per second (Darian-Smith, 1984). This has the consequence of cool stimuli being perceived faster than warm ones (Jones, 2009).

The thermal signal pathway is shown in Figure 4.2. When a thermal stimulus is applied to the skin, the receptor detects the change via temperature sensitive ion channels (Dhaka *et al.*, 2006). An action potential is fired from the receptor, which travels along its fibre, joining peripheral nerve motor and sensory fibres along the way (Levine and Shefner, 2000). The signal enters the spinal cord via the 'dorsal root', further joining several fibre bundles known as 'tracts'. These tracts synapse with the neurons that comprise the grey matter within the spinal column, where they begin their accent to the brain via the 'anterolateral' system. This system is comprised of three separate fibre tracts that mediate 'fast pain' on the 'lateral spinothalamic tract', temperature on the slower 'spinoreticular tract', and burning pain on the 'spinomesencephalic tract'.

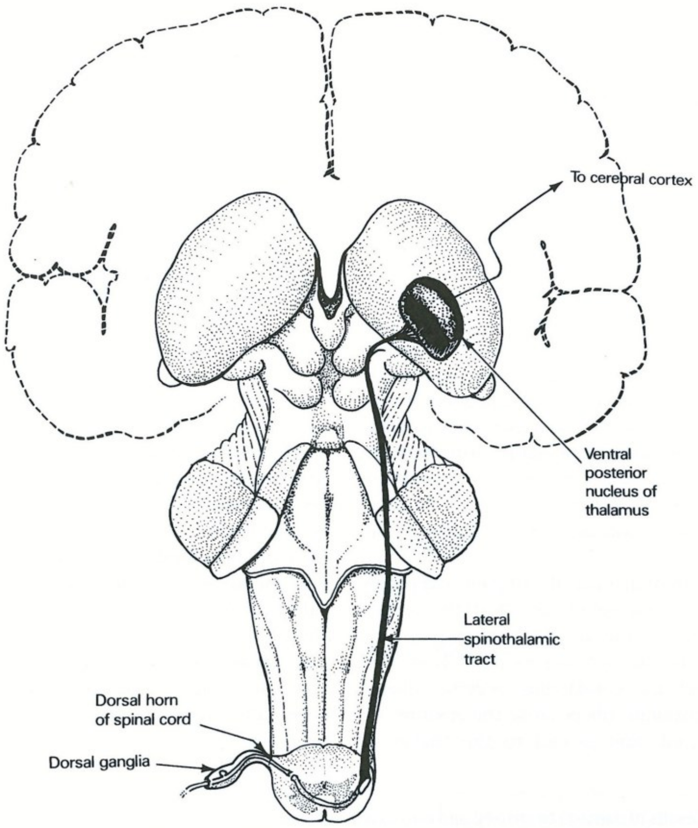


Figure 4.2: Thermal pathway (image from Levine and Shefner, 2000).

After reaching the spinal column, the synapse then must then travel to the brain where it is decoded. The tracts synapse with the 'reticular formation', an area of the brain that extends from the medulla to the thalamus. Temperature and pain related synapses reach further into the central lateral nucleus in the thalamus and finally into the cerebral cortex. Specifically, the coding of temperature and pain takes place in the 'cingulate cortex', in the very centre of the brain (Levine and Shefner, 2000).

The slower transmitting fibres and tracts on which temperature signals propagate on to reach the brain highlights a very important constraint of temperature signalling: latency. This *perceptual latency* compounds with *technology latency* of thermal displays, which will be discussed in more detail in Section 4.3. Both latencies, which will be collectively referred to as *thermal latency* in this thesis, impose a constraint on what kinds of information can be transmitted fast enough using thermal cues. However, as will be discussed and later demonstrated, this does not reduce the usefulness of such feedback in practical studies where perception does not need to be immediate.

4.3 Thermal Displays

This section will provide a literature review of working thermal 'display' devices that have been used in various scientific research. First, thermal displays developed for virtual reality usage will be examined. These utilized the most advanced thermal haptic technologies to allow for fast delivery of stimuli. The review then will focus on slower, more ambient displays used in various HCI fields, such as pervasive computing and wearable technology. These cheaper displays, while having higher latencies resulting in temperature changes in the order of seconds, are still suitable for presenting information to users. To provide an overview:

- VR thermal displays have faster rates of change, operate in a wider range, and have a much higher operating resolution for greater precision of thermal delivery.
- VR thermal displays are often used to deliver thermal feedback that is more immediate with little latency to perceive.
- HCI thermal displays usually operate with lower resolutions (0.1°C or higher), a smaller range, and slower rates of change (6°C/sec or less).
- HCI thermal displays are used to produce thermal sensations that are less immediate and more ambient, to indicate that a change has occurred over time.

4.3.1 Virtual Reality Displays

In the realm of virtual reality, research has investigated temperature perception models to simulate a real object's tactile qualities. This could have uses such as in telesurgery, where doctors can perform surgery remotely using temperature as one of many kinds of feedback for assistance (Okamura, 2009). More generally, it could be used to convey material properties of physical objects in a virtual space, such as in a video game, where a player could feel game objects such as a cold, iron sword or hot sand. In these cases, mathematical models based on the material's *thermal conductivity*, or the ability of a material to conduct heat away from the skin, measured in watts per metre kelvin ($W{\cdot}K^{-1}$), were developed to mimic the sensation of touching a real object (Jones and Berris, 2002).

Several ways to model thermal perception have been proposed, and most research have used thermoelectric cooler (TEC) components and involved participants touching the TECs to try to discriminate the temperature sensation from a fixed choice of different materials. For example, Benali-Khoudja *et al.* (2003) tested the ability of participants to identify several materials such as wood, glass, aluminium, and copper using a *thermal transfer* model. This modelled heat transfer as it interacted with human tissue such as bone, blood, and skin. Ho and Jones (2006) also tested the ability of subjects to identify six materials and examined the effect that material cues (shape, surface texture, compliance, and thermal characteristics) had on their discrimination and localization using a *semi-infinite body* model. This modelled the heat conduction between the skin and the contact material. More examples of modelling thermal properties and cues can be found in the works of Yamamoto *et al.* (2004), and Yang *et al.* (2008), to name a few.

However, no models so far have successfully enabled participants to accurately identify materials consistently. For example, Ino *et al.* (1993) reported that only 16% of participants could accurately identify rubber with their model, while polyacrylate (plastic) and wood had near chance levels of correct identification rates of 46% and 56%. However, all participants could correctly detect aluminium.

Additionally, the technology needs to be sufficiently advanced to 'display' the temperature quick enough to emulate the process of how heat transfers from objects in the environment to skin tissue (Jones and Berris, 2002). Such advisable features that a thermal display should possess are a high accuracy resolution in the order of milli-degrees (0.001°C), an operating range of 22°C - 40°C, and a rate of change of up to 20°C/sec. These requirements may not be feasible as it takes considerable energy to drive technology, such as TECs, in some cases up to 700 watts (Gallo *et al.*, 2014). Gallo *et al.*'s system, while of very low latency, also illustrated the issue of non-portability from using such technology, especially for use in the mobile and wearable space. The advised features posed by Jones and Berris (2002) also requires expensive and specialized equipment to drive components fast enough, such as temperature controllers used to monitor laser diodes, which can cost thousands of pounds. It is also doubtful if such accuracy and speed is necessary when utilizing thermal cues to provide more ambient feedback, which can be slow and is minimally disruptive to the user for conveying information.

4.3.2 Human Interaction Displays

4.3.2.1 Communication Displays

As temperature reception is two directional and continuous, it is thought that warmth and cool could be used to communicate positive and negative meanings, respectively (Suhonen *et al.*, 2012). *AffectPhone* (Iwasaki *et al.*, 2010), for example, mapped arousal of the sender to temperature on the recipient's phone. The authors measured arousal using GSR sensors attached to the phones and used TECs mounted on the backs of the phones to send the converted temperature response. When the sender's arousal increased, the recipient's phone warmed up. However, no study was carried out to test the effectiveness of sending arousal information with temperature.

Lovelet (Fujita and Nishimoto, 2004) enabled partners to convey their affection for one another using temperature cues. For instance, when their partner was in a cold environment, the sender could transmit a warm sensation to their partner's device to convey a feeling of remembrance. Both partners wore an identical device on their wrists, which sensed air temperature. Both devices then transmitted the sensed ambient temperature information to the other paired device, using an LED colour on the recipient device that notified the recipient of their partner's situation. When they saw the colour, they then pressed their device, using a touch sensor, which sent a heat signal back to their partner's device to be felt. A study using two couples showed that the device could also be used in conjunction with conventional communication tools, like phones and SMS messaging. However, the authors did not collect qualitative data from the participants' subjective thoughts of the technology, nor reported any statistics on usage.

Thermal Hug Belt (Gooch and Watts, 2010) used temperature to communicate social presence via instant messaging. It consisted of a backpack harness with three TECs attached to approximate the arm positions of someone giving the wearer a hug. The 'hugger' would send virtual 'hugs' accompanied by text messages by rotating a dial switch and pressing a hug button in the IM application which controlled the TECs. An exploratory study showed a significant difference in the scoring of questionnaires, using scales from 1 (low) to 10 (high) between those who received the thermal hugs and those who did not, revealing that the virtual hugs communicated higher levels of social presence.

Bolton *et al.* (2015) created a wrist-worn thermo-haptic device. They described its potential use for context-aware notifications, for example, to notify the user of valuable information that was not urgent or critical. They used temperature because of its gradually changing characteristics (as opposed to vibrotactile feedback which can startle the user). A pilot study, which ‘displayed’ different kinds of thermal stimuli from a computer, was used to verify that the subjects could perceive the feedback from the device. However, the authors did not investigate their device’s usage in scenarios that utilised the idea of thermal-enabled notifications.

Temperature could also be used to communicate abstract and intangible ideas or concepts that cannot be described with real world metaphors. One such idea is social distance (Hall, 1966), which is the physical distance between two or more people for initiating formal conversations, like those in business settings between colleagues and for greeting strangers. Narumi *et al.* (2009a) demonstrated how social distances could be communicated using temperature in a public space. They created earmuff devices outfitted with TECs and infrared sensors which cameras could use to track the subjects wearing the device. This location information was then used to provide the thermal feedback, depending on the subjects’ location in the space. The authors showed that temperature could be used to mediate social interactions between strangers.

Another abstract concept temperature has been used signal is presence within rooms. *Aladdin* (MacLean and Roderick, 1999) was a haptic door knob that could indicate presence in a room. When the room was occupied, the knob, attached to TECs, would change temperature, warning visitors not to disrupt the occupant. No experiments were carried out to verify these scenarios or what temperature mappings would be appropriate. Wilson *et al.* (2015) further explored the idea of whether a thermal door knob interface could indicate physical presence in a room and how it could indicate availability by conducting studies using a similar door knob apparatus. The authors found that participants strongly agreed that cool temperatures indicated absence, neutral temperatures indicated availability, and that warm temperatures indicated that the occupant was busy.

4.3.2.2 Behaviour Regulation Displays

In addition to communication, prototypes that used temperature have been designed to support a range of behaviours, though most authors did not conduct thorough studies to evaluate the effectiveness of their systems. *Thermoscore* (Miyashita and Nishimoto, 2004) was a piano keyboard that heated desirable keys (the notes that the composer wanted the musician to play), or undesirable keys to represent pitch notation frequency and to prevent improvisation. The authors did not conduct a study however.

ThermoGame (Baba *et al.*, 2010) was a controller that provided thermal feedback to users as they played a game. Two TECs were mounted to the sides of a custom, 3D printed game controller which could heat up or cool down based on the game interaction. For instance, when the player was near warm or cold objects in the game, the controller could provide the appropriate temperature sensation on their hands. Again, however, the authors did not conduct a study to verify if users felt the feedback was useful or appropriate.

Quido (Balata *et al.*, 2013b) presented thermal feedback along with pressure tactile feedback to help orient and navigate players to a goal in a 2D maze. The apparatus consisted of a joystick controller with a button on top that the player used with their right hand and a thermo-haptic pad that they rested their left hand on to feel the feedback. As the player, represented by a balloon in the game, moved closer to the exit of the maze, the thermo-haptic pad would increase its temperature. The pad also vibrated when the player moved near dangerous objects. Though the authors collected data in the form of scores, which indicated how many steps it took to complete each of the three levels in the game, they did not compare the feedback against a ‘no feedback’ condition.

Hiya-Atsu (Nakashige *et al.*, 2009) presented a spatial navigation game where users searched for an object using temperature cues using a computer mouse outfitted with a TEC located under the user’s palm. The authors did not specify how the feedback was mapped, though they stated that players were able to find the hidden objects. However, it was unclear how effective their approach was, given that the authors also did not compare the users' performance with temperature cues to a control condition with no feedback.

4.3.2.3 Augmentation Displays

Temperature can also be used as an augmenting modality, though most prototype systems developed have not been evaluated with studies. *Feel & See the Globe* (Huber *et al.*, 2015) was an interactive installation that mapped global warming to world regions on a display which could be felt by participants using a hand held apparatus when they inserted the device into the map. Using climate data, the authors could let users feel changes to world regions over periods of time, which augmented visual colour changes on the world map at the same time.

Thermo-Paradox (Kushiyama *et al.*, 2010) was another thermal-visual, interactive installation which consisted of a grid of 80, small TEC stimulators, each arranged in an 8 x 10 matrix. A projector above the stimulators would project 8 x 10 pixel art on top of the stimulators. The system was designed so that when the participant placed their hand on top of the stimulator grid display, the visuals would be projected on top of their hand instead, and would be augmented with the temperature being felt directly underneath the users' hand corresponding with the pixel's position. The purpose was to illustrate 'thermo-paradoxical sensations', which will be described more in Section 4.3.2.4.

Hannah *et al.* (2011) proposed augmenting movies on a television display using a phone equipped with TECs. They suggested that metadata could be embedded within media content which could specify the timing and temperatures accompanying media watched on a television display. For example, hot feedback could reinforce happy scenes and cool feedback could be used in conjunction with sad scenes. However, they did not run any studies to verify if the feedback would be appropriate, especially considering how latency or how slowly the temperature changes would impact the synchronisation of such feedback of the content being watched. Halvey *et al.* (2012a) similarly explored the idea of augmenting images with temperatures to evoke emotional responses. Unlike Hannah *et al.*'s work, they did carry out significant studies, which will be discussed in further detail in Chapter 7 as that chapter will focus on work with more controlled studies than presented in this section.

Hribar and Pawluk (2011) used a device which could provide temperature and haptic feedback to blind users for 'viewing' paintings. They used a pin matrix to relay textural features of the brushstrokes, along with temperatures, which were mapped to the warm-cold spectrum of the paintings' colours (warm colours, like red and yellow, have higher frequency wavelengths than cool colours such as blue and purple). However, no studies were performed to demonstrate how their system would work or how effective blind users could detect the painting details.

Most of the work discussed so far developed novel prototypes for communication, regulating behaviour, and augmentation with temperatures. With the exceptions of Wilson *et al.* (2015), Narumi *et al.* (2009a), and Gooch and Watts (2010), these works, however, lacked extensive, empirical studies to verify either the effectiveness of the hardware or the design of the user feedback. As was noted in Section 4.1 and 4.2 of this chapter, the human physiology underlying temperature perception is likely to limit the effectiveness of thermal communication with users, and a more detailed examination was needed.

4.3.2.4 Array-Based Displays

A suggestion for increasing the amount of information conveyed by temperature displays may be to increase the number of stimulators in contact with the user. The thermal displays discussed so far, with the exception of Kushiyama *et al*.'s 'Thermo-Paradox' (2010), mainly used one stimulator to convey information. Hannah *et al.* (2011) and Wilson *et al.* (2011) used two stimulators in their works, but their devices were configured to behave as one in order to discriminate their work from 'thermal arrays', which, as will be discussed in this section, have two or more stimulators spaced apart with the aim of stimulating close areas of the skin with different temperatures.

However, this approach of adding additional stimulators in contact with the skin presents some challenges, which are primarily due to the nonlinear temperature effects that occur when multiple areas of skin are exposed to differing temperatures. Due to the low ability of people to discern the detailed spatial resolution of the skin's sense of heat, adjacent stimulations have been known to affect one other, creating perceptual temperature illusions. These physiological limitations create potential barriers to the effective use of thermal displays.

A key physiological phenomenon observed in prior studies were *domination sensations*, where stronger thermal sensations outweighed the weaker ones and carried over, or referred, to another location that may not had been directly stimulated. Green (1977) demonstrated these in an experiment where participants placed their index, middle, and ring fingers on three TEC stimulators that were set to patterns of hot and cold. The illusion of *referral* occurred when stimulation of the ring and index fingers created a sense of heat or cool applied to the middle finger. When adjacent stimulators were set to the same temperature, participants found the middle sensation strongest: a domination effect Green called *enhancement.* Green also observed an effect this thesis refers to as *de-enhancement*, where stronger, colder, and adjacent sensations dulled the heated middle finger. Lastly, Green noted another illusion effect, *synthetic heat,* which occurred when adjacent fingers were warmed and cooled simultaneously. This resulted in participants feeling a mild, burning sensation on the stimulated fingers.

Oron-Gilad *et al.* (2008), created a thermal display comprised of three TEC stimulators worn on the arm to investigate the synthetic heat phenomenon. They primarily looked at spatial configurations of two stimulators being turned on in pairs of hot and cold. They found there was great variance in detection times among participants, and that the thermal detection threshold varied more for hot temperatures than for cold. However intriguing and effective this approach, their use of multiple stimulators was focused only on studying the synthetic heat phenomenon, and they did not examine the potential of a multiple stimulator display to communicate thermal patterns to augment communication or guide behaviour.

Other researchers have used multiple stimulators to explore thermal sensitivity of different body locations. Watanabe *et al.* (2014) used two stimulators mounted on a surface that the user's arm rested on. The authors sent mixed pairs of hot (40°C), cold (20°C), and neutral (33°C) temperatures to participants, who reported the sensations felt at each stimulator. A major discovery were their findings on the extent of referral, the phenomenon discussed in the beginning of this section, where stronger thermal sensations outweighed weaker ones and carried over, or referred, to another location that may had not been directly stimulated (Green, 1977). Referral was found to increase for warm sensations nearer the elbow, or towards the body centre. Conversely, cold stimulation had a greater referral distance near the hand, or towards the periphery. Participants could judge correctly when both stimulators were set to the same temperature, but had trouble distinguishing if one was set to neutral because of referral. Synthetic heat was also perceived asymmetrically: the wrist area was not as sensitive to it as compared to the area nearer the elbow. Thus, stimulator location influenced user detection accuracy and perception for hot, cold, and synthetic temperatures.

4.3.3 Summary

This section reviewed thermal displays which had been utilized to investigate a variety of purposes in different research domains: virtual reality, HCI, and studying perception. Virtual reality displays are used to validate models of temperature perception for re-creating the temperature of objects using computer controlled technology, such as thermo-electric components (TECs). For HCI, prototype displays have been developed to communicate qualities such emotion or to provide feedback for guiding behaviour. Similar displays had been proposed to augment media, such as the emotional state of scenes in movies or to communicate abstract ideas such as social distance. Lastly, Section 5.3.3 illustrated the problem of spatial discrimination and reviewed work that utilized multiple stimulators to investigate these psychophysical aspects of temperature perception. However, most work presented here, particularly in the field of HCI, has lacked extensive studies, and none have examined the usage of an array-based system to convey information, if even to test its feasibility. Later chapters will examine more controlled studies than was described in this section (See Sections 5.3, 6.1, and 7.1) as they pertain to those chapter's research questions.

Research has proposed that temperature could communicate meanings, such as emotions. Multiple stimulators have been used to investigate the psychophysical aspects of temperature perception such as synthetic heat. However, a gap in the knowledge remained as to whether using more than one stimulator in the design of a thermal feedback implementation could relay more information using two or three stimulators instead of a single stimulator. A similar analogy can be found in the system used by Brown *et al*. (2006) for research in vibrotactile interaction, where the authors used an array of three vibrotactile stimulators worn on the forearm to convey information simultaneously with each stimulator. It remained if this analogy of using *spatial location* as a parameter could be applied in the thermal haptic domain. Therefore, *can a wearable array of thermal stimulators be constructed to provide information using temperature*?

To examine this chapter's research question, this thesis developed an implementation of a thermal display. The 'Thermal Array Display', or simply, 'TAD', is a multi-stimulator thermal display, which consists of three TEC stimulators that are worn on the arm. Patterns of warm, cool, and neutral temperatures could then be sent to the user's arm using the device, which is connects to a computer that sends to the TAD the patterns to be presented, or 'displayed', to the user. The device was designed to be worn by subjects safely in controlled studies to test the feasibility and usefulness of multi-stimulator feedback, which will be assessed in the chapters that follow.

4.4 Thermal Array Display

This section will provide a technical description of the 'Thermal Array Display', or 'TAD' device, which was designed for presenting patterns of warm, cool, and neutral temperatures to a user. The development of the technical aspects of the system design will be presented chronologically in three sections. First, the hardware design will be described (Section 4.4.1), followed by the design of the stimulators (Section 4.4.2), and then finally, the system software: both the firmware on the device and the control program on the PC (Section 4.4.3).

4.4.1 Hardware

The first goal was to understand how to drive and test a thermoelectric cooler (TEC) module. Figure 4.3 shows the setup of the first prototype of the TAD using an Arduino Uno R3 Microcontroller and a prototype board for connecting most of the other components in the circuit. A 12V laptop AC adapter powered the TECs using a terminal block. Two TEC modules, shown in the figure attached to the terminal block, were tested at this stage. The larger TEC had a temperature sensor (thermistor) attached with yellow insulation tape on top to measure the surface temperature of one of the sides of the TEC.

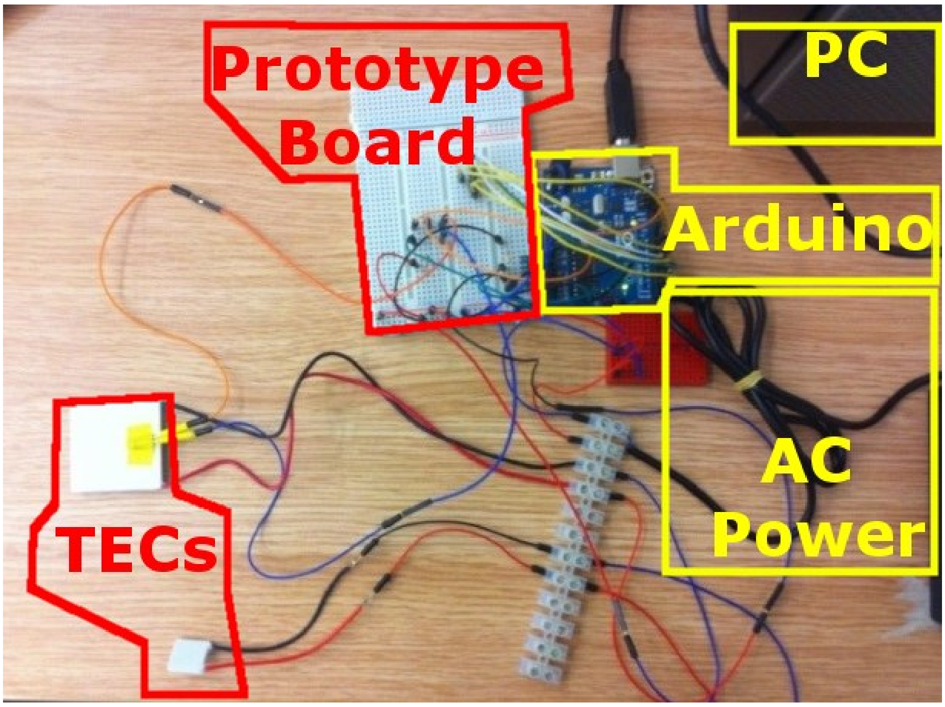


Figure 4.3: The first prototype. Two TECs were tested at this stage using an AC adaptor and an Arduino, which was connected to both a PC via USB and a circuit on a prototype board.

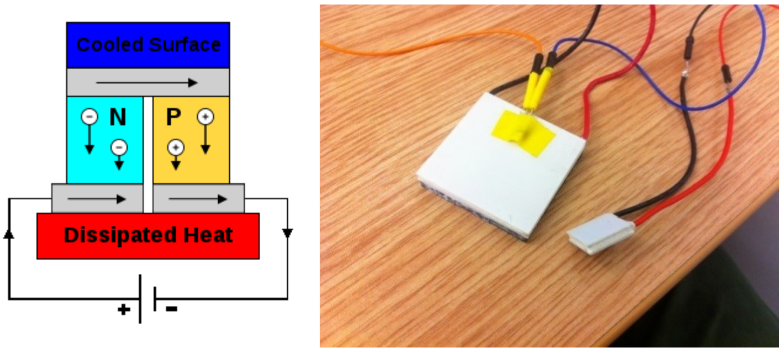


Figure 4.4: Peltier Effect and TECs. Left - diagram of the Peltier Effect, the arrows indicate the direction of the electric current which passes through the junction of the two semiconductors, labelled N and P, causing the top surface to cool down and the bottom surface to warm up. Right - individual TEC samples of varying sizes acquired for testing.

A TEC (Figure 4.4, *Right*) is a thermoelectric component that operates based on the *Peltier Effect* (Figure 4.4, *Left*). The Peltier Effect is the phenomena of heating and cooling which occurs when an electric current passes through a junction between negatively charged and positively charged semiconductors. This causes one of the TECs ceramic sides to radiate heat and the other side to absorb heat, feeling cool to the touch. Power determines the temperature range of the modules, which is dictated by the rated voltage and amperage of the TEC. The modules are fabricated in various sizes and shapes. Figure 4.4, *Right* shows the two TECs that were tested, with areas of 40mm² and 15 mm² respectively.

TEC modules can be driven using a DC power source, and by varying the voltage one can change the temperature difference between the two sides. For finer control, the TEC can be controlled digitally using a *Pulse Width Modulation* (PWM) wave. This is a square wave signal generated from a microcontroller where the gaps between the high rises and the lows determine the amount of time that the signal is 'on' (Figure 4.5). Gap size can be reduced by increasing the duty cycle of the PWM. If the PWM is set at a 100% duty cycle, then the output in the figure will be 5V. If the duty cycle is 0% then the output will be 0V. If the duty cycle is set at 50% then the output will be interpreted as 2.5V by the TEC, as the switching happens at a fast-enough frequency that the TEC will interpret it as a continuous voltage. For the TAD, this power signal was pulsed at a frequency of 490.20 Hz, as it produced the most stable temperature behaviour compared with other frequencies attainable on the Arduino, such as 31.37 kHz, 3.92 kHz, 980.39 Hz, 245.10 Hz, 122.55 Hz, and 30.64 Hz.

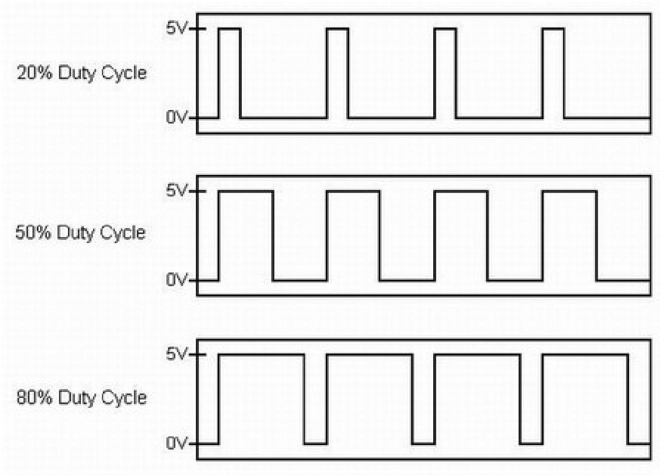


Figure 4.5: Three types of PWM waveforms.

Figure 4.6 shows the schematic view of the first prototype circuit. The circuit on the left side of the Arduino is used to detect the temperature. The circuit to the right of the Arduino controls the TEC module using a transistor and a power supply. As an Arduino can only supply 40 mA of current to the TEC module from its output pins, a BD137 NPN transistor was used to moderate the switching of the 12V power supply to drive the TEC at a higher load. A 10 Ohm resistor was placed between the base of the transistor and ground to protect the Arduino from voltage spikes caused by the switching.

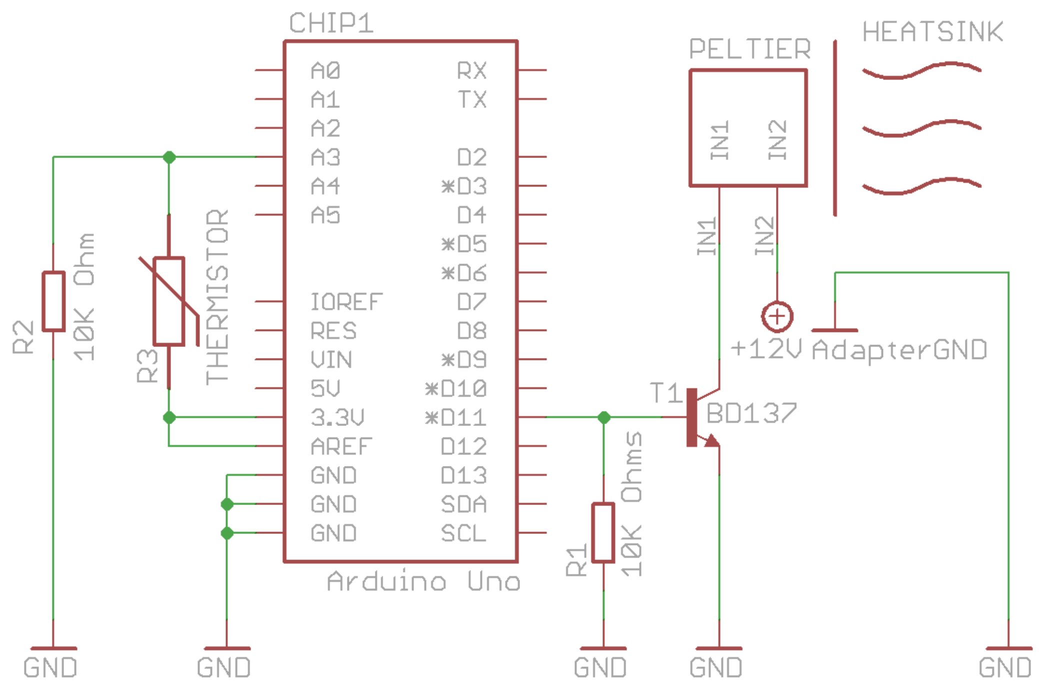


Figure 4.6: Schematic view of Prototype 1.

The thermistor *R3* was placed between the Arduino's 3.3V output and the analog input pin *A3*. A 10K Ohm resistor, *R2,* was connected to the output of the thermistor and ground. This completed the *voltage divider circuit* which divided the 3.3V between *R2* and *R3* when the thermistor's resistance changed. The voltage was fed into the analog pin *A3* of the Arduino which converted the varying voltage to a 10-bit value ranging from 0 to 1023. On the firmware, the *Steinhart-Hart* equation was used to convert the raw 10-bit value into degrees Celsius. Using the 5V line as the reference voltage produced noisy temperature readings, so the 3.3V line was used instead.

As TECs themselves do not process a polarity, reversing the voltage across a TEC swaps the direction in which heat is pumped, making the side that had previously emitted heat absorb it and vice versa. Reversing voltage direction is a very valuable control parameter, so the transistor from Prototype 1 was replaced with a *motor driver carrier* that acted as the switch. This was a breakout board for an *H-Bridge Controller*, a type of circuit that allows a voltage to be applied across a load, in this case the TEC, in both directions.

Figure 4.7 shows the modified schematic. The 12V power adapter was directly connected to *CHIP2*, the motor driver carrier (MC33926, Pololu). Between *Peltier* (the TEC module) and *CHIP2* was the *choke inductor*, *L1*, which protected the motor carrier from dangerous voltage spikes as the TEC turned, as well as smoothed out the voltage to make it appear as a DC current. On the Arduino, the 5V pin was connected to the VDD of the motor carrier to supply it with power for controlling the logic needed to determine which direction to drive the TEC (hot or cold). The Arduino interfaced with the motor carrier via several pins. The enable pin, *EN*, turned on and off the motor carrier. The input pins, *IN1* and *IN2,* were used to control the direction of the TEC, by setting one pin low and the other high. If both were turned high or low the chip shut off power to the TEC. *D2* was used to control the duty cycle of the TEC, which was used to moderate the intensity of the temperature. Pin D1 was set to low as it was not used.

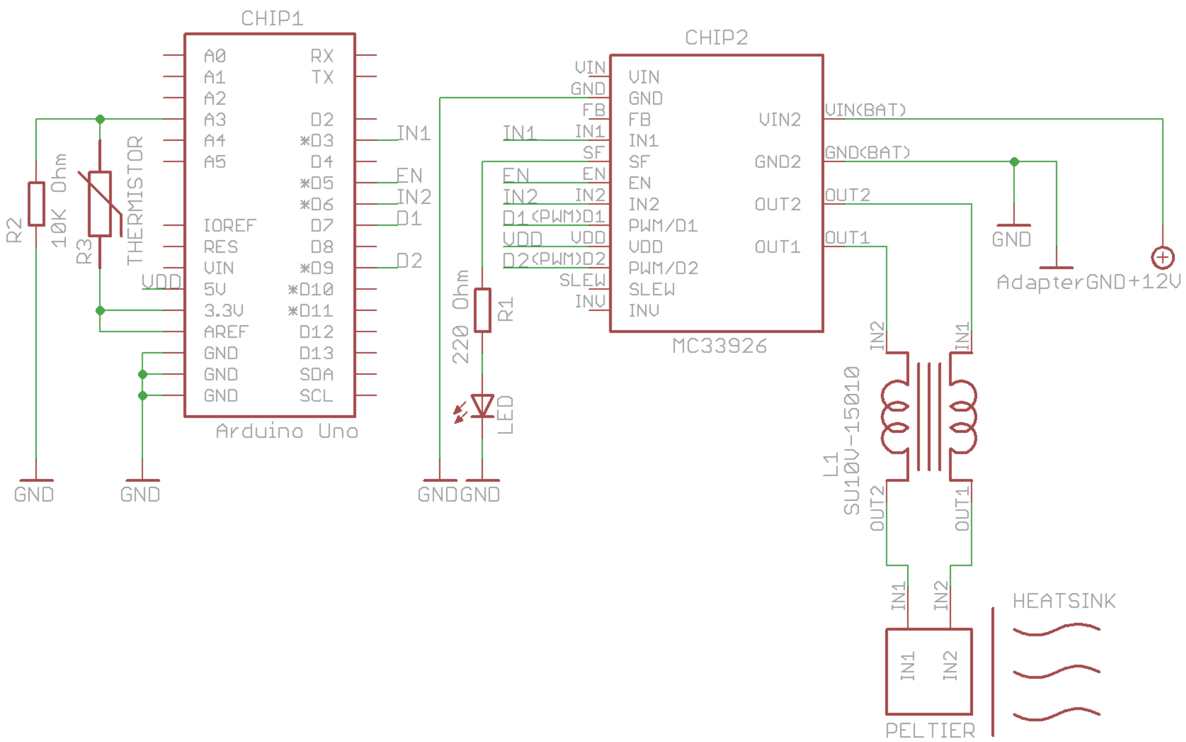


Figure 4.7: Revised schematic for Prototype 2.

The last step was to control several TECs at once. Figure 4.8 and Figure 4.9 show the new schematic. An array of three TEC devices was added, each with their own motor driver carriers, inductors, and temperature sensing circuits. The schematic in Figure 4.8 shows the Arduino, temperature control circuits, and the power supply, and the schematic in Figure 4.9 shows the TEC control systems. An Arduino Mega 2560 replaced the Arduino Uno as more pins were needed to drive all the TEC modules. Also shown are direct current (DC) fans, which will be discussed in the stimulator design section (Section 4.4.2). Additional circuitry for controling the 5V DC fans using BD137 transistors were added. The fans were powered using a 6V voltage source, separate from the voltage source used to power the TECs, as additional current draw was needed.

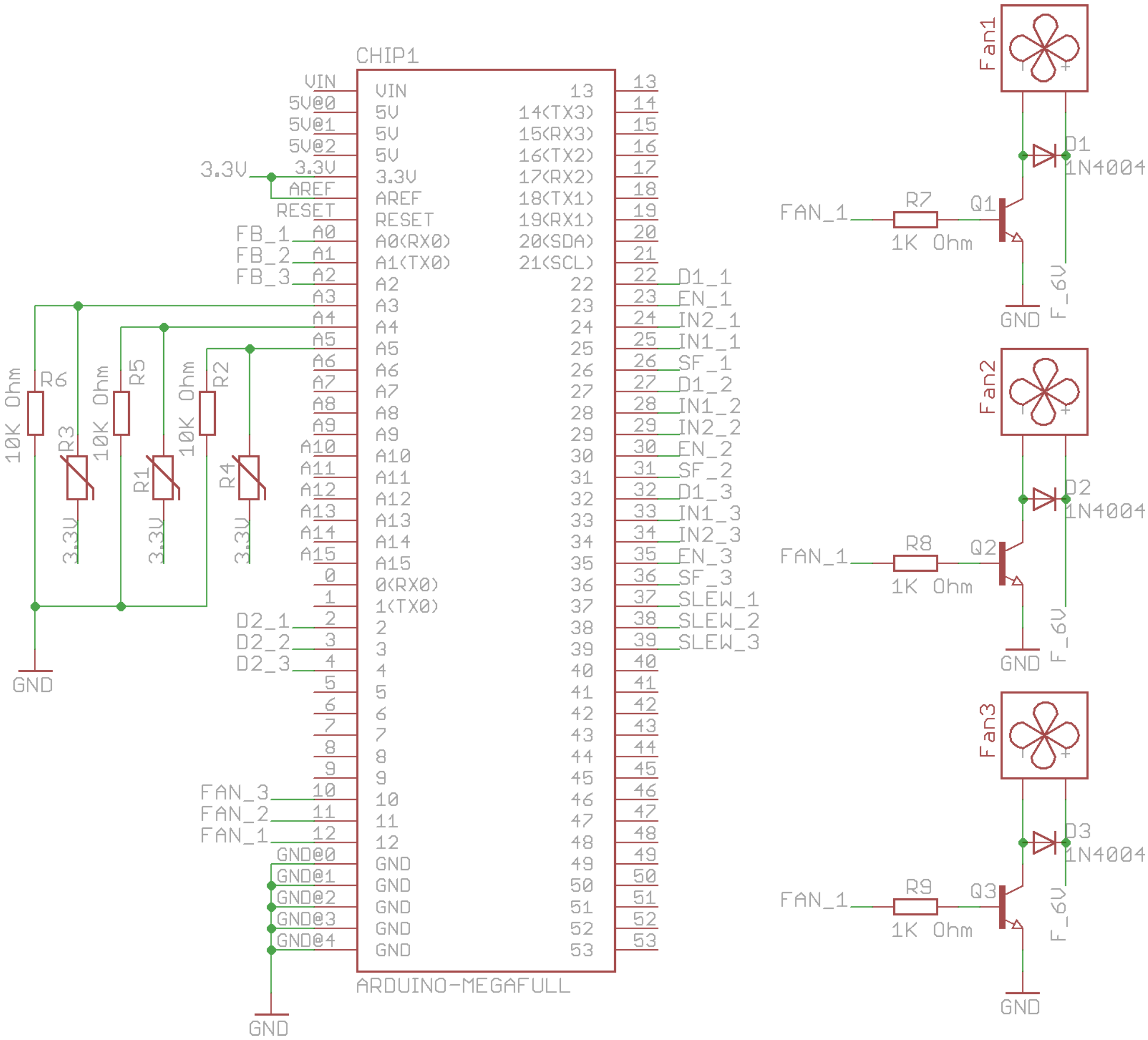


Figure 4.8: Final hardware schematic (MCU, temperature sensors, and fans).

The focus after this point became the safety and performance of the system. Smaller TECs were chosen as their power requirements meant they generated less heat and were safer to use. However, more amperage for these devices was needed. A larger power supply, a 30V, 10A bench supply, replaced the 12V laptop adapter that was used in the first prototype. Since the newer TECs were more reliant on current instead of voltage to drive them, the circuit itself heated up considerably, as more amperage passed through it. This caused the temperature controller on the chip to activate, which would shut down the power supply to the TECs, causing their performance to degrade over time. Because of this, heat sinks were added on all motor drivers and a desk fan was used to drive the heat away from them.

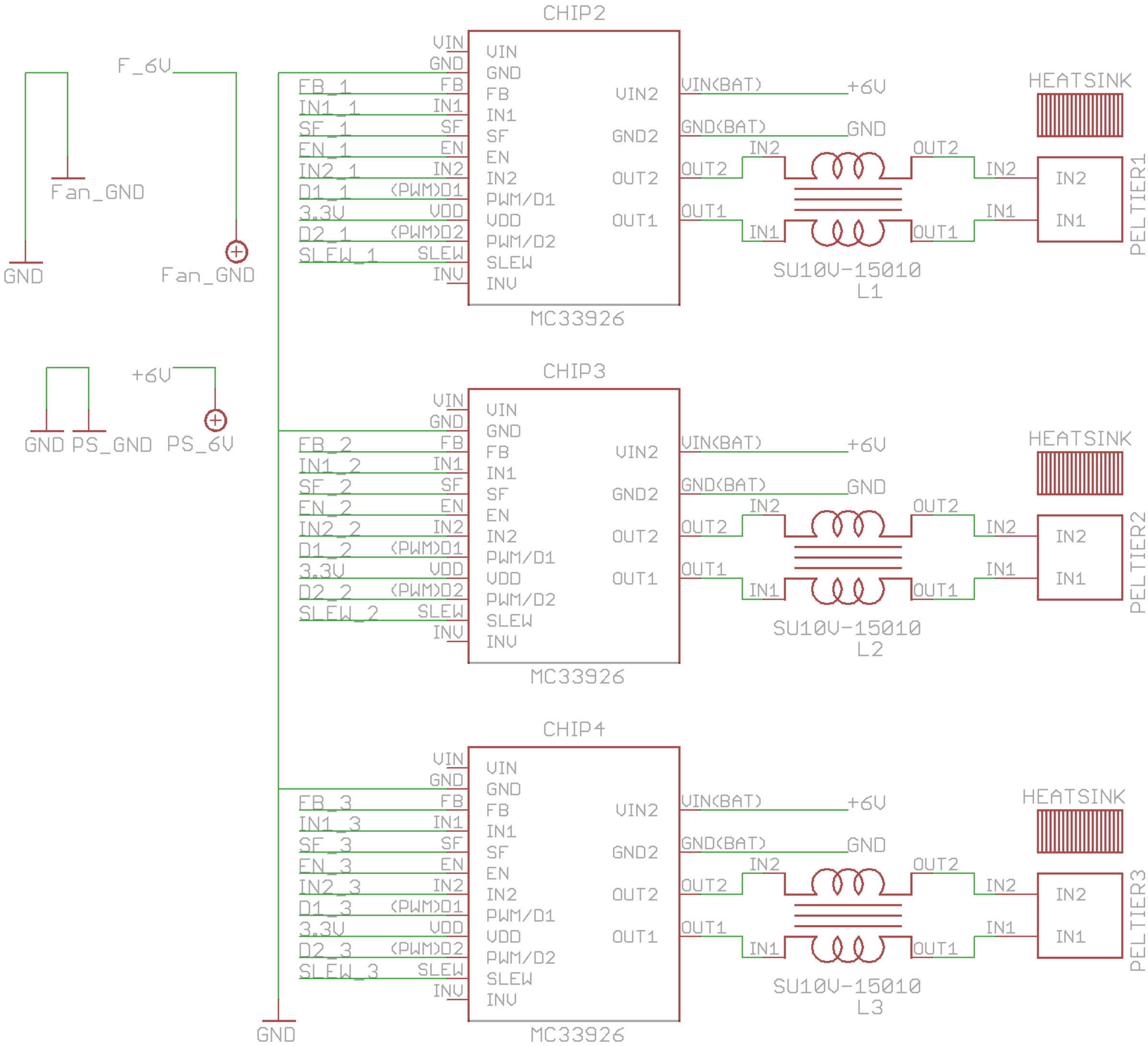


Figure 4.9: Final hardware schematic (TECs, motor drivers, and power supply).

Figure 4.10 shows the completed physical hardware, using three, 4cm x 4cm TECs, the motor drivers, and the Arduino Mega 2560, which replaced the Uno from the early prototype shown in Figure 4.3 due to the need for more pins.

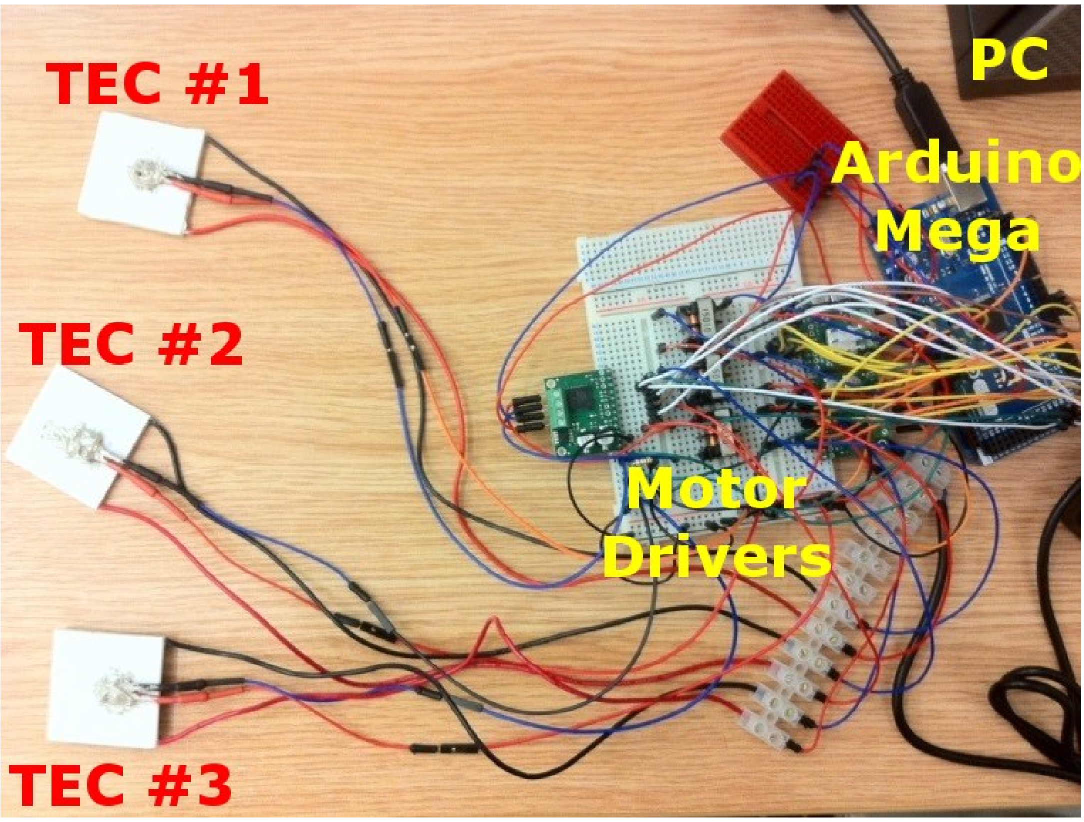


Figure 4.10: Finished breadboarded hardware, using an Arduino Mega 2560 connected to a PC via USB, motor drivers, and three TEC units.

4.4.2 Stimulator Design

The image in Figure 4.10 shows three TEC units, each measuring 4cm x 4cm. This size was selected at first as they were more accessible on the marketplace due to being a common TEC size. Smaller TECs are more specialised and had to be purchased from more obscure retailers such as Farnell Electronics (in the UK). Because of this, they are more expensive and are not as easily replaceable if one broke during testing due to stock shortages. As such, 4cm x 4cm size TECs were selected and tested before examining other size TECs.

To apply a thermal stimulus to the skin, the design of how the three TECs were to be attached to the user had to be considered, along with the sensors and other peripherals, such as fans to aid in ventilating the heat from the TECs. This section will describe the design of the stimulators, which contained the above peripherals, and how they were prototyped to aid in the final design.

To measure the surface temperature of each TEC, which was necessary for the PID controller to function (see Section 4.4.3), thermistors were mounted to the side of each of the TECs which contacted with the skin. Silver epoxy was initially used to bind the thermistors to this contact side, and heat sinks were mounted on the other side of the TECs to displace the heat generated as a by-product of the Peltier Effect, as was described in Section 4.4.1. To allow the device to be worn, Velcro was cut into strips and then wrapped around the arm and the TEC stimulators, as shown in Figure 4.11. After some tests, it was determined that despite addition of the heat sinks, the TECs still overheated after a few minutes of use and posed a safety concern to the user. A redesign of the stimulators was needed to overcome this.

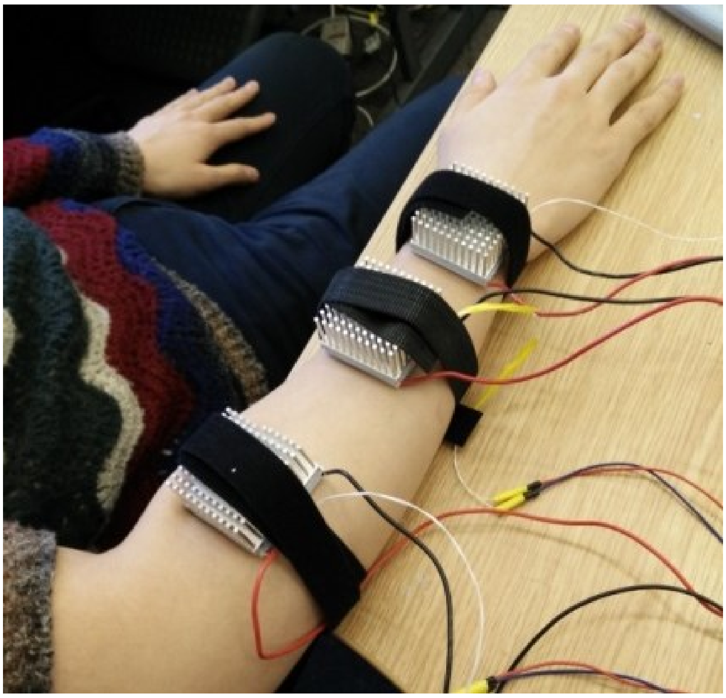


Figure 4.11: TECs worn on the user's arm using Velcro strapped around the stimulators and the arm to hold them in place.

Figure 4.12 shows the improved stimulator design. The first design proved to be potentially hazardous, especially when the power was suddenly turned off, due to heat flow reversing. This could have caused the side of the TECs in contact with the participant's skin to heat up considerably in a short amount of time. For safety reasons, smaller, 10.3W TECs (MCPE1-01708NC-S, Multicomp) were chosen for the new design. They consumed significantly less power and required less heat dissipation, though heat sinks were still used. To prevent user contact with the heatsink, cardboard was attached around the TECs, as suggested by Wilson *et al.* (2011). Smaller and more accurate thermistors (MC65F103A, Amphenol Sensors) were chosen to minimize the area of the TECs in contact with the skin. The thermistors were mounted in the corner of each TEC using a heat conductive epoxy. However, this reduced comfort when wearing the device and left a mark on the user’s skin.

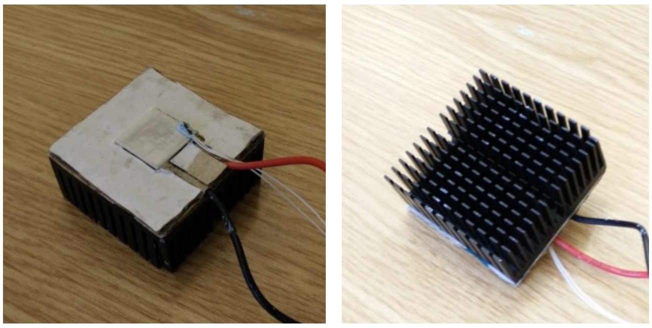


Figure 4.12: Second stimulator design. Left - The contact side of the stimulator with the exposed TEC, the white square in the middle of the surrounding cardboard, with the thermistor mounted with blue thermal epoxy in the lower left corner of the TEC. Right - The bottom side of the stimulator, with a mounted heatsink attached to the TEC.

The simulators were therefore further redesigned to be more comfortable and safer to use, as the design required more elaborate methods of driving the heat away from the user. Figure 4.13 shows the completed prototype as it was worn on the underside of the arm. The stimulators were attached to the arm using two narrow pieces of Velcro which were mounted on the stimulators. Each stimulator was equipped with a fan to blow out the exhaust heat from the heat sink and used a copper pad for delivering the temperature to the skin.

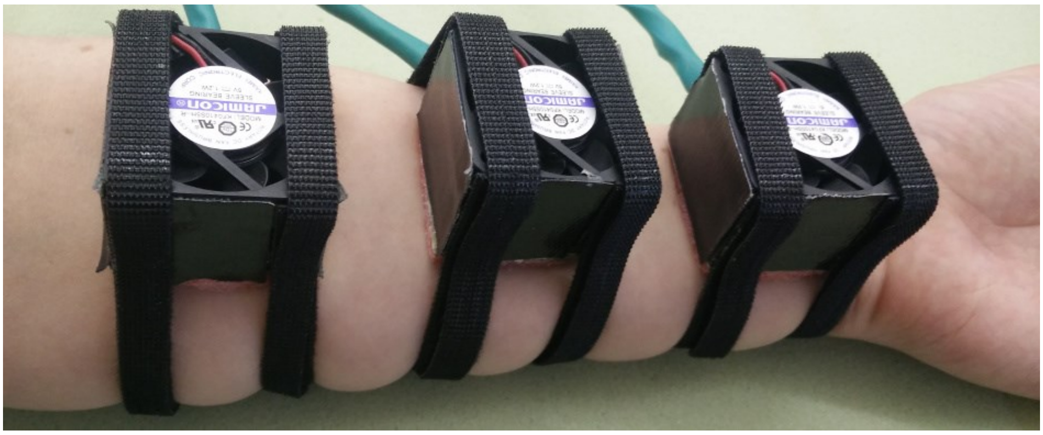


Figure 4.13: Final design of the stimulators being worn on the underside of the arm.

The thermistor in the previous design made the stimulator too uncomfortable to wear as it produced a pain sensation. It was sharp and pushed into the skin, and left users perceiving the pain as burning or heat. It also took up precious space on the contact area of the TEC which was only 15 mm² in area. The thermistor, in fact, takes up more space than its own area size since the skin must deform around it. This lead to a less perceptual area than what the TEC could provide, since the top of the thermistor was not as hot as the TEC's ceramic surface. Exposing the thermistor to the ambient temperature in this manner also resulted in slower readings, as it took longer to settle at a 'setpoint' (see Section 4.4.3) due to an averaging effect between the skin and the TEC. Skin temperature should not significantly influence the stimulator temperature during an experiment. Therefore, a method that incorporated the thermistor within the stimulator itself was investigated.

Using heat sink pads as a transfer point between the stimulator and the skin were experimented with first by inserting the thermistor into the pad. This made wearing the device more comfortable. However, the pads were not heat conductive enough to transfer the temperature from the TEC to the skin adequately. The pad was also too malleable, and after repeated use, tears in the pad appeared which caused the thermistor to fall out, even when sealed with epoxy. A more solid pad was needed to prevent tears, which could also transfer the heat more efficiently to the skin.

To remedy this problem, a technique from Oron-Gilad *et al.* (2008) was used. They mounted a drilled piece of aluminium to the TEC's surface, which in turn transferred the heat to the skin. They inserted a temperature sensor into the aluminium plate so that the sensor did not make contact with the skin of the user directly, resulting in a more reliable measurement. In the TAD design, a copper alloy, C101 copper, was used instead since it offered an even higher thermal conductivity value (385 W/m· K) than aluminium (205 W/m· K). This meant it could conduct heat almost twice as fast as aluminium, resulting in a faster response time to reach the desired temperature. This in turn, reduced some of the latency of the system, resulting in a faster rate of change of temperature permissible with the TAD. A sheet was ordered with 3 mm thickness, which was cut into 15 mm^2 pieces to match the area of the TEC. A 1.7 mm Ø hole was drilled into one of the 4 lateral sides to house the sensor. A fabricated piece is shown in Figure 4.14.

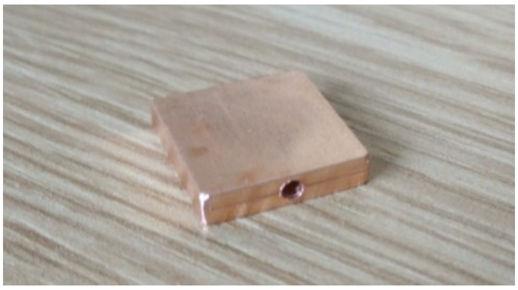


Figure 4.14: Copper plate fabrication.

The temperature sensor was installed into the copper pad, as shown in Figure 4.15. To prepare the temperature sensor for insertion, yellow insulation tape was wrapped around the pad to ensure that its surface remained clean. Heat shrink tube was applied around the sensors' delicate wires to re-enforce them, as one broke due to bending in an initial prototype. The hole was filled with thermal grease (MX-4, Artic) to fill gaps between the interior of the hole and the sensor probe's head. After insertion, grease residue was cleaned and superglue was applied to seal it. Though heat conductive epoxy was used initially, it proved too weak when mixed with the grease. It also took too long to cure as opposed to superglue which bonded in minutes. After curing, both the pad and TEC surfaces were cleaned, and then the pad was mounted on top of the TEC using double-sided thermal tape.

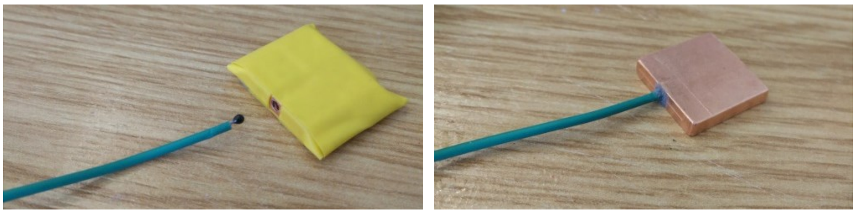


Figure 4.15: Installing the thermistor into the copper pad. Left - Preparations before insertion. Right - After insertion with the thermistor sealed.

The other remaining challenge was fixing the heat disspation problem. In the previous stimulator design, shown in Figure 4.12, the other side of the TEC was mounted to a heat sink (BGA-STD-115, ABL) using double-sided thermal tape. However, even with a heat sink, the TEC performance still degraded in early trials, as the entire TEC unit slowly warmed without a means of channelling the heat away effectively. This affected temperature readings, as the rate of change no longer became steady due to the device gradually becomer warmer, irrespective of the desired setpoint given to the PID controller. This in effect also posed a potential safety issue, as eventually the tempeature rose beyond the safety theshold without intervention using the software failsafe.

The solution was to attach a 40 mm^2 5V DC fan on top of the heat sink using gorilla tape. The user was insulated from the heat sink using a panel of cardboard and Styrofoam glued together, which were cut in the middle to accommodate the TEC and copper pad. Even after sustained usage of an hour, the TEC temperature did not increase, verifying the effectiveness of the fans in conjunction with the heat sink on dissipating the heat waste from the TEC.

To allow the stimulator to be worn easier, double-sided Velcro was glued to both sides of the heat sink. This allowed participants to wear the stimulators by strapping them around their arm. Two strips of velcro were cut in half vertically and attached to both sides of the stimulator with super glue. The construction of both the top and bottom of a simulator is shown in Figure 4.16.

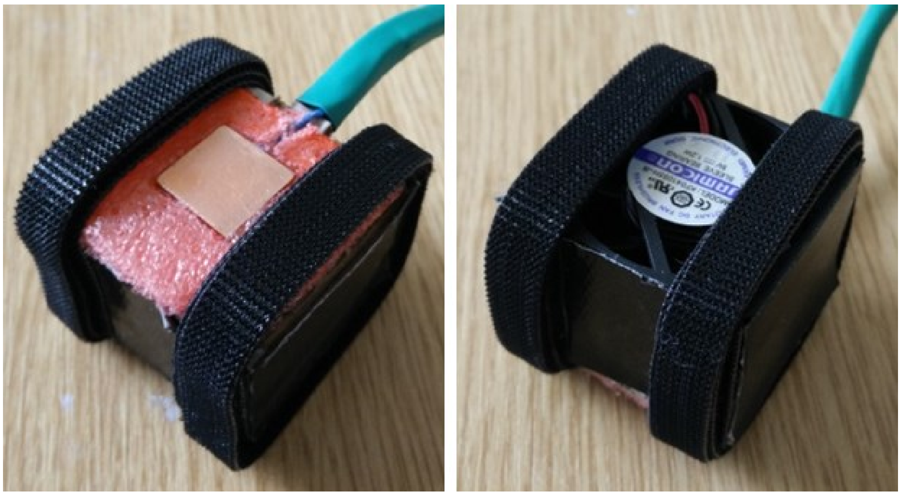


Figure 4.16: Final stimulator design. Left - Bottom side, showing the copper contact plate. Right - Top side showing the DC fan on top of the heatsink.

4.4.3 Software

A feedback control loop known as a *Proportional-Integral-Derivative* (PID) controller was used to control the speed and direction of the motor carrier, which was subsequently used to control the direction and intensity of the temperature using the TECs. To control a TEC continuously from the software involved specifying a desired target temperature, known as a *setpoint*. The system calculated an error value, which was the difference between the present temperature of the TEC, measured using the temperature sensor attached to the side of the TEC that stimulated the skin, and the specified setpoint. The PID controller then attempted to compensate for the calculated error in temperature by driving the TEC via the motor driver using the two parameters of direction and speed until it reached the specified setpoint. The formula for calculating the error is given below in Equation 1, where *SP* is the *setpoint* and *PV* is the *process variable*, or the current temperature reading. Once the setpoint was reached, the PID controller acted to maintain it until a new setpoint was received.

$$error = SP - PV$$

Equation 1: Error Formula

The PID formula is shown in Equation 2. The output of the PID controller, $u(t)$, was calculated with each iteration of the Arduino software loop. This output was an integer in the range of -255 to 255. The sign of the output was used to determine which direction the motor driver should spin the TEC, that is, whether the TEC surface facing the skin should heat or cool. When the sign was positive, the surface would heat, and when the sign was negative, the surface would cool. *e* was the error value calculated in Equation 1 and *t* was the current time. There were also three tuning parameters used to control the output: K_p was *Proportional Gain*, which affected how the PID reacted to the current error value, K_i was the *Integral Gain*, or how the PID reacted to errors over time, and K_d was the *Derivative Gain*, or how the PID reacted to a change in error.

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{d}{dt} e(t)$$

Equation 2: PID equation

There were many proposed methods and algorithms in control theory research on how to tune PID controllers, for instance, the method proposed by Ziegler and Nichols (1942). However, no perfect solution exists for determining the optimal tuning parameters (Choe, 2013). An attempt using an auto tuning algorithm to automatically find these tuning parameters based on the relay method (Wilson, 2005) was used initially. However, the parameters it produced were unable to keep a steady temperature near the desired setpoint.

Instead, a manual process of finding the values via trial and error was used with the assistance of a software tool. The user interface for this tool is shown in Figure 4.17, which displays a graph of the current and setpoint temperatures of one of the

TECs and allows adjustment of the target temperature in real-time. It also allows for adjustment of the proportional, integral, and derivative turning parameters for the PID. These values were important for the proper control of the TEC, as values that were far from optimal made it difficult to sustain a target temperature and could even potentially have led to safety problems.

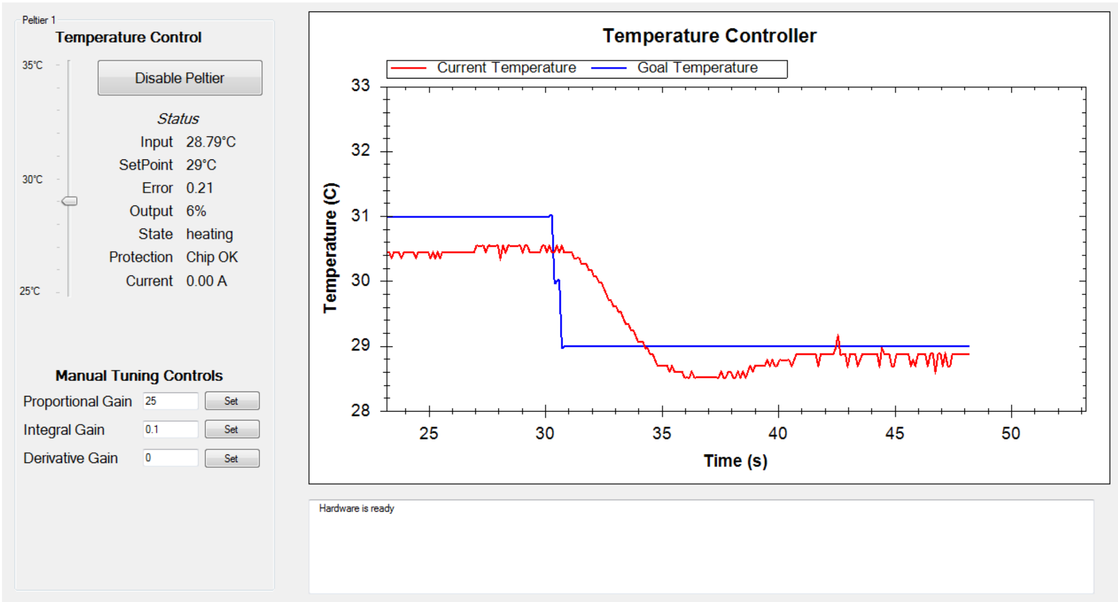


Figure 4.17: Tuner software interface. The graph displays the current reading of the TEC temperature with the red line. The blue line shows the desired target temperature. On the left side of the graph shows the user interface for selecting the setpoint, as well as for changing the tuning parameters of the PID and status reading of the motor driver.

Finding starting point values, or an approximate range of values from which to experiment with, however, proved difficult with guessing. Furthermore, literature in HCI does not often report such tuning parameter values, compounding the issue of which values to use initially. Cheok (2010), however, reported using tuning values of K_p = 20, K_i = 0.1, and K_d = 0 for a thermal feedback device used by children. As such, these values were considered initially in this work.

To simplify the process of tuning these values further to be suitable for the TAD, the Proportional Gain was considered first and foremost, followed by the Integral Gain (Derivative Gain was not altered, as it was set to 0). This is because Proportional Gain allows for control over the rate of change, which, along with direction of change, is one of the most important parameters to consider in thermal feedback design. As discussed in Section 4.1, the rate of change can alter how well subjects can detect the thresholds of thermal stimuli so that they are noticed. After careful tuning, 1°C/s rates of change, on average, were achieved using tuning parameters of $K_p = 50$, $K_i = 2$, and $K_d = 0$, the proportional, integral, and derivative constants, respectively. Figure 4.18 shows a time plot of temperature changes using the control system, first cooled from 35°C to 32°C, and then warmed back to 35°C, using these tuning parameters.

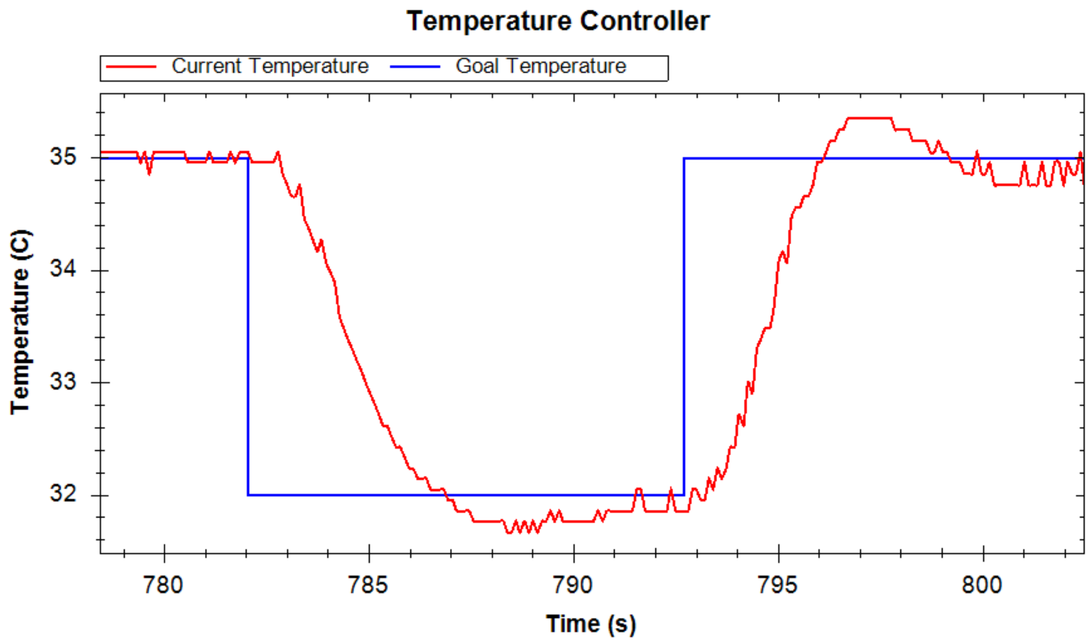


Figure 4.18: Temperature plot of the response time using tuning parameters of $K_p = 50$, $K_i = 2$, and $K_d = 0$ to first cool the stimulator to 32°C and then to warm it back up to 35°C. The red line shows the current temperature reading, and the blue line shows the target temperature the system tried to maintain.

Once the control system was properly tuned, the software used to control three TECs was developed. This software would then be used as the foundation for interfaces used in experiments to automatically control the temperatures of the TAD. These interfaces will be described in more depth in the chapters that follow as they were specific for each experiment. Additionally, configuration files, which automated the selection of which temperatures to use for each TEC, were also created. The software could also generate .txt log files, containing the temperatures of the three TECs presented to the user, as well as user reports (such as Likert scale selections). The data in these files were generated as the test ran and were formatted to allow for easy exporting to data analysis software, such as Microsoft Excel.

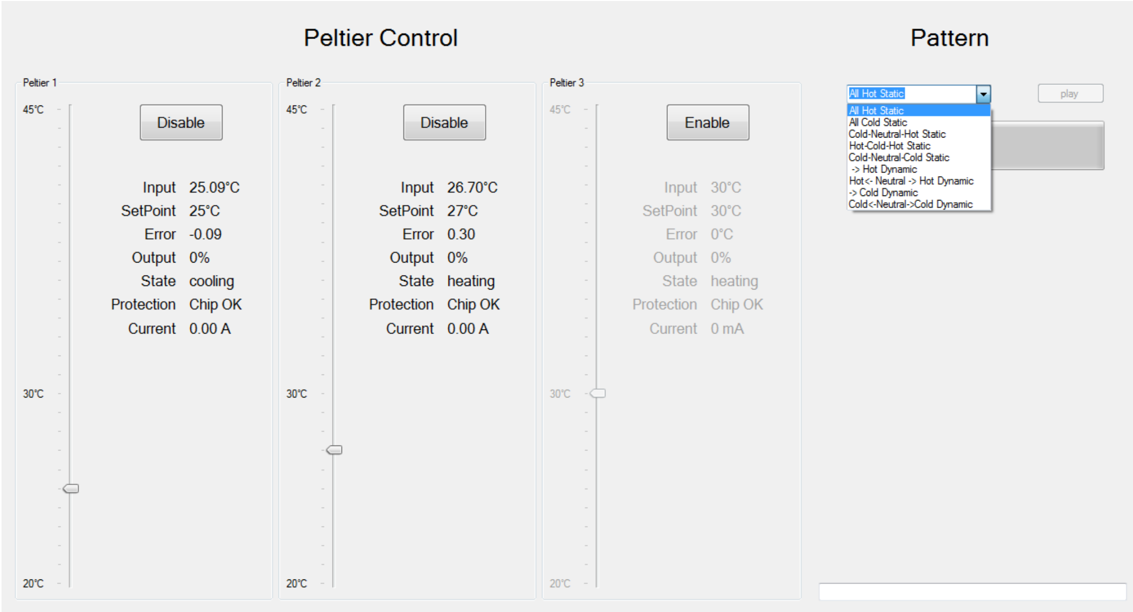


Figure 4.19: Prototype 3 software interface.

To facilitate testing of controlling three TEC units, a Graphic User Interface (GUI) was built to allow for easy changing of the setpoint for each TEC, as well as monitoring each TEC for safety. Figure 4.19 shows this software GUI. This interface uses slider bars to control the TEC devices' setpoints, using a range of temperatures between 20°C and 45°C. Also presented are buttons for enabling and disabling each TEC device individually and useful data about the state of each TEC device. *Input* is the current temperature reading of the TEC device. *Setpoint* is the selected value of the slider bar and is the temperature value specified by the user by which the PID controller would change the side of the TEC facing the skin to. *Error* is the current difference between the input and the setpoint. *Output* is the duty cycle ratio, a value indicating how much power the motor driver should supply the TEC with. This value is displayed as a percentage expressed from 100% (full power) to 0% (no power). *State* is a flag representing if the system is heating up or cooling down, and *Protection* is a safety flag that indicates if the motor driver is overheating or short-circuiting. *Current* is measured in amps (A). The interface under 'Pattern' shows a drop-down combo menu containing pre-defined thermal patterns for use in testing. These patterns will be explained in more detail in Chapter 5 (Section 5.1).

To ensure the wellbeing of participants, several steps were taken to assist in the monitoring of the device while in use. First, an extra PC monitor was added to display the interface shown in Figure 4.19 to the experimenter so that they could observe the temperatures and other outputs of the system while in use. Second, a failsafe was built into the software which shut down the system in case the current temperature went outside the safety thresholds of 20°C and 45°C, respectively. The upper threshold was taken from NASA's Man-System Integration Standards: "The maximum allowable surface temperature for continuous contact with bare skin shall be 45°C (113°F)" (NASA, n.d). The experimenter could also shut down the system by disabling all three TECs using the interface in 4.19 if the system was, for example, unable to cool down due to improper air ventilation.

In the firmware, a TEC library was created which encapsulated the functionality of each TEC device, along with its own PID controller, to make it easier to create further instances of TEC modules. The cmdMessenger library was used to facilitate serial communication with the PC. This allowed for easy serial port access along with the ability to create serial commands for each TEC device and type of control, for example, sending the setpoint from the PC and reading the temperature back.

4.5 Chapter Conclusion

There are limits to human performance in perceiving temperature and its rate of change. The cutaneous sense of temperature is carried on nerve endings that have slow response times. The body's poor ability to localize temperature results in sensory illusions. Finally, the intensity of thermal signals needs to be sufficiently large, otherwise they may be too difficult for users to perceive them correctly, if at all.

The thermal displays investigated in this chapter were examined from two perspectives. First, virtual reality displays were used to model how humans discriminate material objects in the real world so that the materials' thermal-tactile qualities could be reproduced in virtual reality environments. On the other hand, human interaction displays sought to reveal other kinds of information and purposes which could be conveyed with temperature. These included conveying emotion, regulating user behaviour, and augmenting other kinds of media using temperature. This chapter examined array-based thermal displays, which have investigated the human limits of perceiving temperature by studying thermal illusions, such as referral and synthetic heat. Limited work has addressed the concern of whether humans can discriminate thermal patterns based on these factors to convey qualities like emotion and other useful information.

This chapter proposed a novel, array-based thermal feedback system to answer the research question "*Can a wearable array of thermal stimulators be constructed to provide information using temperature?"* Section 4.4 highlighted the major challenges of its development. First, it discussed how TEC units could be driven using simple, off the shelf, electronic components. The final design of the stimulators considered the comfort and safety of the user, particularly regarding the problems of heat ventilation and the location of the temperature sensors. Section 4.4.3 discussed how a PID controller could be used to control the temperature's setpoint in the system's control software and examined methods of tuning PID controllers for thermal feedback. The resulting implementation was an array-based thermal display that could output information, such as temperature patterns of warm, cool, and neutral temperatures.

The next chapter will assess the TAD implementation in two user studies to discover the benefits of a multi-stimulator design. The first study will investigate the effectiveness of using the TAD to communicate thermal-spatial patterns that can be discriminated by human subjects, an area that HCI has not yet explored. The hope is to develop a 'thermal tactile language' for use in HCI, which could be used to communicate more complex information that could not be possible with a single stimulator design. The second study will then examine several ways that temperature states could be reliably signalled with multiple stimulators using spatial summation as a parameter. This study compared the user's ability to sense these states with the condition where the user wore only one stimulator.

Chapter 5

Discrete Signalling of Temperature Feedback

This chapter will investigate how the Thermal Array Display (TAD), developed in the previous chapter, can be used to communicate information not possible with single stimulator designs. Two studies, a pilot study and a main experiment, were conducted to investigate the research question: *what are the benefits of using an array of thermal stimulators over a single stimulator design?*

The pilot study (Section 5.1) will examine using the TAD to communicate thermal-spatial patterns, which are simultaneous heat and cool stimuli presented using multiple stimulators at once that can discriminated by human subjects. A 'thermal tactile language' will be proposed to illustrate how such thermal patterns may be perceived. A small, pilot study was conducted to examine if users could identify patterns of the three stimulators set to warm, cool, or neutral temperatures using the TAD. The hope was to use the thermal tactile language to communicate more complex information that could not be possible with a single stimulator design. However, the results revealed the difficulty of human subjects to accurately discriminate such patterns due to non-linear interactions, such as synthetic heat and referral discussed in Section 4.1, which makes accurate temperature discrimination of thermal-spatial patterns difficult. This reduces the feasibility of using thermal-spatial patterns provided by the TAD to encode information for communication.

Section 5.2 then proceeds to discuss some ways the TAD can be used to signal thermal states using spatial summation as a parameter. This is possible as multiple stimulators also increase the skin area that is stimulated, making it easier for participants to perceive the thermal state. The study in this section investigated how well participants could identify different thermal states communicated using the TAD using three approaches: Single, where only one stimulator in the array was used, Amplification, where all stimulators were set to the same temperature, and Quantification, where some or all the stimulators were set to an extreme temperature. In all cases, the temperature state was reset to a neutral temperature and paused before a new thermal state was signalled, which this thesis will refer to as 'Discrete Signalling', to differentiate it from other methods of signalling temperature which will be discussed in further detail in Chapter 6.

5.1 Pilot Study

In this section, the idea of a thermo-tactile language will be proposed and assessed in a small pilot study using the TAD implementation. The taxonomy of the language and the design of patterns will be discussed in Section 5.1.1. This will be followed by a description of the pilot study procedure (Section 5.1.2), analysis of the data (Section 5.1.3), and a discussion of the results (Section 5.1.4).

5.1.1 Stimuli Design

A challenge in developing a pattern-based, thermal-tactile language are the temperature effects caused by stimulating areas in close proximity with one another that Green (1977) observed, as was discussed in Section 4.3.2.4. These effects, particularly referral, can be undesirable, since they can interfere with the perception of individual stimuli. However, the interaction of these non-linear effects might potentially give rise to a more complicated tactile language not possible with single stimulator designs.

Two types of thermal patterns were conceived initially. 'Static' patterns were those that remained constant throughout the duration of the stimulus and did not change temperature. In this case, only the position within the sequence, as well as the temperature at each position, were used as parameters. 'Dynamic' patterns, on the other hand, changed from one 'static' pattern to another within a time interval. This was an idea originally suggested, but not tested, by Wilson (2013), who discussed the ideas of using an array for 'thermal pulses' or 'waves', like unidirectional vibrotactile rhythms (Shin *et al.* 2007). However, for simplicity, the initial study will focus exclusively on just using static patterns. They are easier to design and therefore test, as dynamic patterns are essentially time varying static patterns. Some dynamic patterns were conceived however, like a countdown 'pulse' of warmth that begins at the elbow and 'crawls' down the arm: this idea became the inspiration for the Quantitative Method that will be described in more detail in Section 5.2.2.3.

To categorise the static thermal patterns by their sequence of temperatures in the array, a taxonomy was devised which did not exist in the current literature. The taxonomy describes a pattern by how it should be perceived by the user wearing the TAD, the *perceived sequence*, and not by its *literal sequence*. Table 5.1 illustrates the difference between the two sequences: the literal sequence, in the second column, shows the positions of the three stimulators on the arm. These are colour coded: red denotes a warm temperature, blue denotes a cool temperature, and white denotes a neutral temperature. Heat and cool temperatures were kept constant at 38°C and 22°C, respectively, with a neutral temperature of 30°C, as was used by Wilson *et al.* (2015) The perceived sequence, on the other hand, was colour coded differently, to illustrate how a user might perceive the literal sequence displayed to them by the TAD. The perceived sequences were influenced mainly by the four physiological illusions described in Section 4.3.2.4: 'enhancement', 'referral', 'synthetic heat', and 'de-enhancement'. The hypothesised perceptions were also influenced by the anticipated 'spatial directions', or the directions that the temperatures would perpetuate down the arm, based on the ordering of their pattern's literal sequence. This idea was discussed in Section 4.3.2.4 regarding the findings of Watanabe *et al.*, (2014).

As such, two parameters were used to design the patterns: the direction of the temperature (warm, cool, or neutral) and the stimulators' position on the arm in the sequence (near the elbow, the middle of the forearm, or the wrist). As the TAD used three stimulators, 27 patterns were achievable using warm, cool, and neutral temperatures. To simplify designing patterns at this stage of the work, this research only considered one temperature each for warm and cool. It did not consider different intensities of each, such as a warm temperature and a very warm temperature.

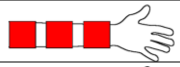
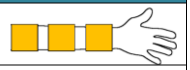
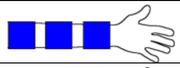
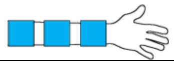
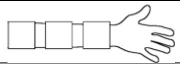
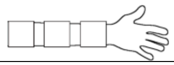
ID	Literal Sequence	Description	Perceived Sequence
1		Enhanced Hot	
2		Enhanced Cold	
3		Neutral	

Table 5.1: Enhanced patterns. The 'Literal Sequence' column on the left shows the true temperatures given to the stimulators by color (red = warm, blue = cool, white = neutral). The 'Perceived Sequence' column is color coded by how the user should have felt from perceiving the pattern (gold = hot or burning, light blue = cold or freezing). The 'Description' column provides a short name for the pattern based on what physiological illusions it embodied, as well as the direction of change.

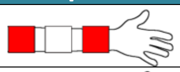
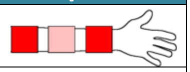
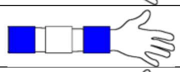
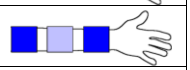
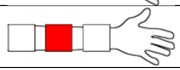
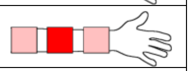
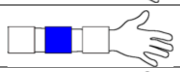
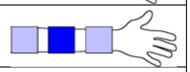
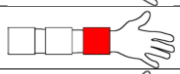
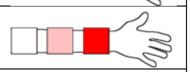
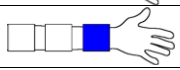
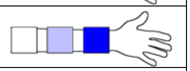
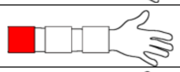
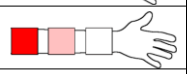
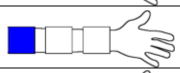
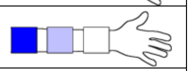
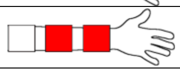
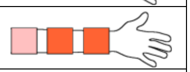
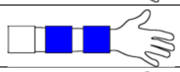
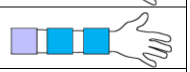
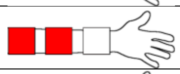
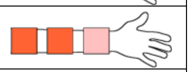
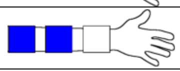
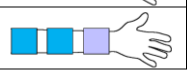
ID	Literal Sequence	Description	Perceived Sequence
4		Inward Referred Hot	
5		Inward Referred Cold	
6		Outward Referred Hot	
7		Outward Referred Cold	
8		Distal Referred Hot	
9		Distal Referred Cold	
10		Proximal Referred Hot	
11		Proximal Referred Cold	
12		Distal Enhanced Referred Hot	
13		Distal Enhanced Referred Cold	
14		Proximal Enhanced Referred Hot	
15		Proximal Enhanced Referred Cold	

Table 5.2: 'Referred' patterns. The colour coding for the 'Literal Sequence' column followed the same rules as Table 5.1 (red = warm, blue = cool, white = neutral). The 'Perceived Sequence' column's color coding was also similar (red colors are warm, blue colors are cool). Gradients indicated intensity of these temperatures. Orange and light blue colors indicated enhanced warm and cool temperatures, respectively.

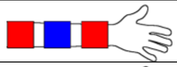
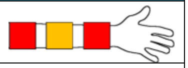
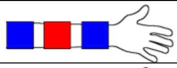
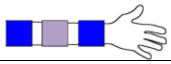
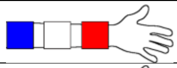
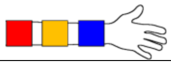
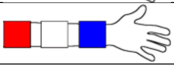
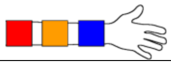
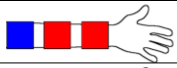
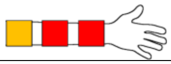
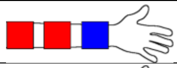
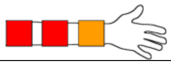
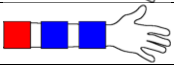
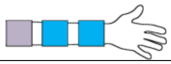
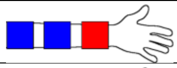
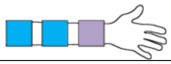
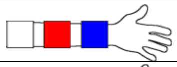
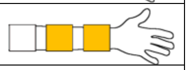
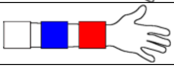
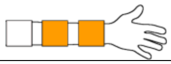
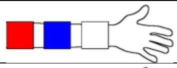
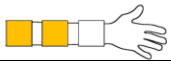
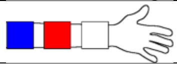
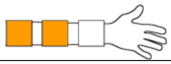
ID	Literal Sequence	Description	Perceived Sequence
16		Synthetic Heat	
17		De-Enhanced Heat	
18		Optimal Referred Synthetic Heat	
19		Suboptimal Referred Synthetic Heat	
20		Optimal Enhanced Synthetic Heat	
21		Suboptimal Enhanced Synthetic Heat	
22		Suboptimal De-Enhanced Heat Enhanced Cold	
23		Optimal De-Enhanced Heat Enhanced Cold	
24		Distal Optimal Synthetic Heat	
25		Distal Suboptimal Synthetic Heat	
26		Proximal Optimal Synthetic Heat	
27		Proximal Suboptimal Synthetic Heat	

Table 5.3: 'Synthetic' patterns. Again, the color coding for the 'Literal Sequence' column was the same as Tables 5.1 and 5.2 (red = warm, blue = cool, white = neutral). The 'Perceived Sequence' column also followed the same color coding scheme as seen in Tables 5.1 and 5.2 (with gold and orange indicating hot or burning sensations and light blue indicating cold or freezing). The grey colors indicated a de-enhanced warm or cool sensation, or possibly a neutral sensation.

Patterns were split into three categories based on their predominant physiological illusion. 'Enhanced' patterns (Table 5.1) were simple patterns where all three stimulators were set to the same temperatures, providing the most enhanced feedback in the taxonomy. 'Referred' patterns (Table 5.2) were predominantly based on the effects of referral on neutral stimulators. 'Synthetic' patterns (Table 5.3) used a combination of heat and cool to produce the unique perceptual effects of synthetic heat and de-enhancement. They were presumed to have more variability in their makeup, which may make them more challenging to discriminate.

The patterns shown in Tables 5.1 - 5.3 are described by the illusions: enhancement, referral, synthetic heat, and de-enhancement. The direction of the dominant temperature also plays a role (warm, cool, and neutral), in that two stimulators set to the same temperature should dominate over the other stimulator if its temperature was different. The position of the temperatures within the sequence also determines the pattern's *optimal perception.* For example, warm applied on the far-right and cool on the far-left should lead to an *optimal* synthetic heat state, as warm travels better towards the centre of the body and cool travels better towards the peripheral, as was discussed in Section 4.3.2.4. This should lead to a more intense synthetic heat effect. If the warm and cool stimulators were swapped, however, the effect should become diminished in comparison. This taxonomy refers to this state as *sub-optimal*.

Each pattern in Tables 5.1 - 5.3 are assigned an ID and a description. They are also assigned a literal sequence, or the true temperatures as actuated by the TAD, and a perceived pattern sequence hypothesis that illustrates what the participant may expect to experience. The difference between the two sequences are due to the interaction effects caused by the illusions of the enhancement, referral, synthetic heat, and de-enhancement, and how optimal the sequence configuration was. The colours in the tables are explained in more detail in the tables' captions.

5.1.2 Study Procedure

After designing the possible patterns the TAD could output to the user, a pilot study was designed to test if users could discriminate them. As testing all 27 combinations from Tables 5.1 – 5.3 above would have been too overwhelming for a pilot study, eight patterns were selected. These were pattern IDs [1], [2], [3], [5], [16], [17], [18], and [19].

There were several reasons for testing these particular eight patterns. First, testing all three enhanced patterns [1], [2], and [3] was used as a benchmark, as they had the least variability and should therefore be easiest to identify. Second, the referral pattern [5] was tested to observe if it would be confused with the 'Enhanced Cold' pattern [2]. Third, was a desire to test variations or "configurations" of synthetic heat, so classic configurations were selected: 'Hot-Cold-Hot' [16] and its inverse 'Cold-Hot-Cold' [17]. In addition, was a desire to test variations of synthetic patterns where referral plays a role in their perception of synthetic heat, by setting the middle stimulator to neutral and the others to either hot or cold. Hence, this is why the 'Cold-Neutral-Hot' [18] and 'Hot-Neutral-Cold' [19] patterns were tested. The synthetic patterns were believed to be difficult to discriminate, as the sensation produced is usually described by the literature as a "pickling" or "burning" sensation (Green, 1977). It was unclear, however, if subjects could discriminate variations of it against the enhanced patterns.

Three people participated in the pilot study. Participants were asked to sit down in front of a desktop PC monitor. They wore the TAD device on their non-dominant arm and used their other hand to control a computer mouse to interface with the UI. Participants were shown instructions preceding the test (Appendix G.7), while the lab monitor sat on a desk opposite the participant to monitor the safety of the TAD.

After the device sent a pattern, participants were shown a screen depicting graphical representations of the patterns on their arm. They were instructed to select the pattern they thought they were experiencing, like the UI presented in Figure 5.1. Note that the pattern numbering in the UI does not necessary correspond with the pattern IDs in Tables 5.1 – 5.3, as this was done to randomize the appearance of each pattern on the screen (the ordering placement as shown in Figure 5.1 was the same for all subjects for all trials though). The order of the patterns presented by the TAD was randomized and each pattern was given to each participant twice, for a total of 16 trials per subject. Subjects were told that they may feel the same patterns displayed again during the study. Patterns were presented for 5 seconds, and then the UI shown in Figure 5.1 was presented. Patterns would continue to display for another 15 seconds until the user made his or her choice, otherwise the system would move on to the next pattern. Therefore, participants had 20 seconds total to make a decision of the pattern they thought they were perceiving, and the time available was displayed in the upper-right corner of the screen, as shown in Figure 5.1.

After the participant pressed the button under the pattern they believed to be perceiving, they were shown another screen with a 7-point Likert scale to record how confident they felt their choice of the pattern they selected was. The scale ranged from 0 (not confident at all) to 6 (very confident). No time limit was given to the Likert scale screen to rate their confidence.

After rating their confidence, the system reset their arm temperature to neutral for 20 seconds before sending a new pattern to their arm. This process, called *re-adaptation*, will be discussed in more detail later in this Chapter in Section 5.2, as it is an important distinguishing parameter of how temperature could be signaled to the user. For now, this section will simply note that this was done to return the skin temperature a physiological zero point, as was discussed in Section 4.1. As a reminder, this is the temperature which feels neither cool nor warm to the subject.

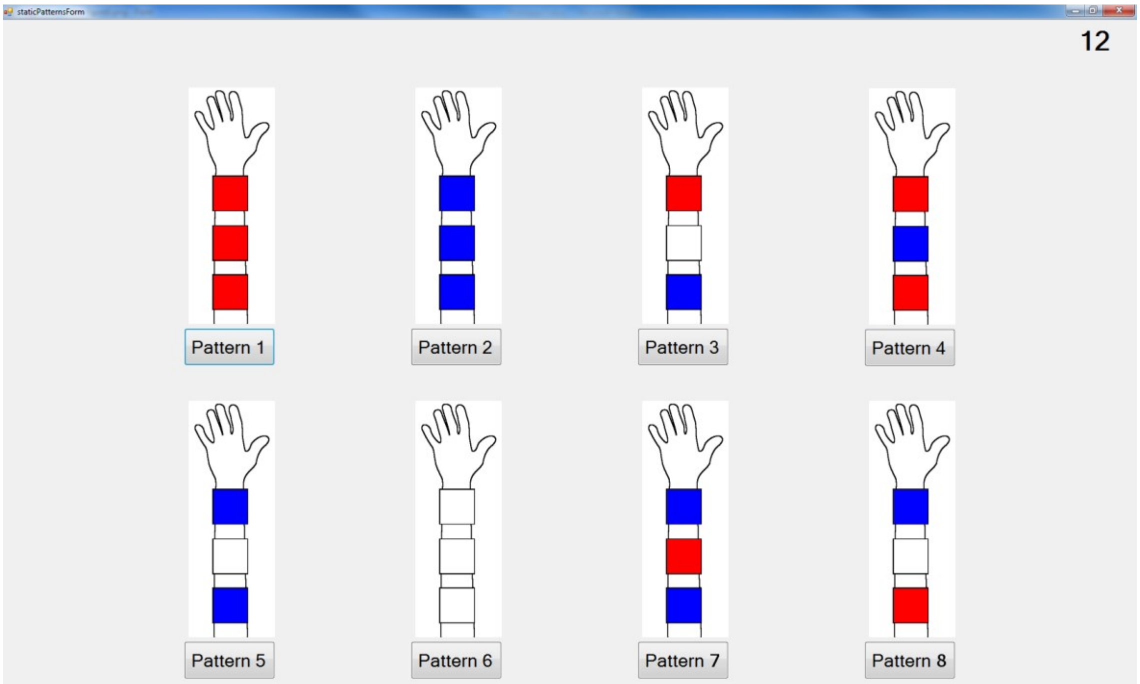


Figure 5.1: Pilot test user interface for selecting the eight patterns. Each pattern was given a colour coded graphic depiction of its literal sequence (red = warm, blue = cool, white = neutral), along with buttons directly underneath them used to select that pattern when the user perceived a temperature. The number in the upper right corner depicted a countdown timer in seconds to alert the user to make a selection within the time limit.

To summarise the procedure:

- Participants wore the TAD on their dominant arm and were shown visual representations of eight thermal patterns.
- Participants were instructed to select the one they believed was being 'displayed' to them.
- Participants were also asked to rate how confident they were of their selection of the pattern.
- The temperature of the device then reset to neutral for 20 seconds as the re-adaptation time before the next pattern was displayed.
- Each pattern was repeated twice for a total of 16 trials per subject.

5.1.3 Results

The raw data, illustrating the patterns presented to subjects, can be referred to in Appendix C.1. The results of the pattern selections are shown in the confusion matrix in Table 5.4. As a reminder, 3 subjects rated each pattern twice for a total of 48 trials. However, there were two occurrences where subjects ran out of time which were marked as incomplete, hence, why the dark green, ‘overall’ cell in the bottom right only shows 46 occurrences. The eight patterns are abbreviated as ‘Pat 1-8’.

		Truth Data								Classifier Overall	Precision
		Pat 1	Pat 2	Pat 3	Pat 4	Pat 5	Pat 6	Pat 7	Pat 8		
Classifier Results	Pat 1	1	2	1	0	1	0	0	1	6	16.7%
	Pat 2	1	0	0	2	1	0	0	0	4	0%
	Pat 3	0	1	1	0	0	0	0	2	4	25%
	Pat 4	3	1	2	0	2	1	5	1	15	0%
	Pat 5	0	0	0	0	0	0	0	1	1	0%
	Pat 6	0	0	0	0	0	3	0	0	3	100%
	Pat 7	0	1	2	2	1	2	0	0	8	0%
	Pat 8	0	1	0	2	1	0	1	0	5	0%
Truth Overall		5	6	6	6	6	6	6	5	46	
Recall		20%	0%	16.7%	0%	0%	50%	0%	0%		

Table 5.4: Confusion matrix showing the results of the eight patterns selected by each of the three participants. Each pattern was displayed to each participant twice.

As can be seen in Table 5.4, the overall accuracy was quite poor, with only 10.87% correct detections. Pattern 6 (Neutral [3]) was detected correctly 50% of the time with the highest precision of 100%. Pattern 1 (Enhanced Hot [1]) was detected correctly only 20% of the time with a precision rate of 16.7%. Pattern 3 (Optimal Referred Synthetic Heat [18]) was detected correctly only 16.7% of the time with a precision rate of 25%. There were no correctly answered selections in any of the Pattern 2 (Enhanced Cold [2]), Pattern 4 (Synthetic Heat [16]), Pattern 5 (inward referred cold [5]), Pattern 7 (De-Enhanced Heat [17]), and Pattern 8 (Suboptimal Referred Synthetic Heat [19]) patterns. This illustrates that none of the participants could discriminate any of the synthetic patterns well, including the referred pattern [5], and the enhanced pattern [2].

The frequency of which patterns were selected, regardless of whether they were correct, can be seen under the 'Classifier Overall' column. Pattern 4 (Synthetic Heat [16]) was reported the most with 15 occurrences of subjects selecting it, though none of these were selected when the pattern was actually presented to the subjects. Pattern 5 (Inward Referred Cold [5]) was responded to the least, with only 1 instance of it being reported, and not when it was actually presented. There were also two instances of when a subject (Participant 1) ran out of time to give an answer (Pattern 1 and Pattern 8), as can be seen in the "Truth Overall" row: these two patterns had frequency responses of 5 instead of 6.

Participant	Pat 1	Pat 2	Pat 3	Pat 4	Pat 5	Pat 6	Pat 7	Pat 8
P1	0	5	4	4	5	5	3	0
	N/A	4	4	2	2	5	4	3
P2	3	4	4	3	5	3	1	4
	4	5	1	1	N/A	5	3	4
P3	3	5	1	5	1	5	3	4
	4	1	N/A	4	5	4	3	2

Table 5.5: Results of the 7-point Likert scale ratings for the eight patterns as rated by each of the 3 participants. The scale range was from 0 (no confidence in their ability to discriminate) to 6 (high confidence that they discriminated the pattern correctly). Each rating here corresponds with one of the two trials for each pattern, as each pattern was repeated twice in the pilot. Cells marked with N/A were due to a glitch in the software not recording a response.

Finally, all confidence ratings, using the Likert scale data shown in Table 5.5, were analysed. All participants had a median and mode of 4, with standard deviations of 1.68 (Participant 1), 1.4 (Participant 2), and 1.5 (Participant 3). The global descriptive data on the entire dataset also suggests that participants rated confidence differently (σ = 1.49, both median and mode = 4), however, the median and modes indicated that they were neither not confident, nor confident of their responses. Ratings fell within the range of 3 – 5, and no other choices on the scale were made. Finally, a Friedman test was run to compare any difference in ratings across the eight patterns. This produced $p = 0.54$ ($H = 5.54$, $df = 7$), indicating that there was also no significant difference amongst any of the patterns in terms of confidence ratings. In other words, participants felt the same level of confidence for all patterns.

5.1.4 Discussion

Participants had great deal of difficulty in discriminating thermal patterns, and were unable to even match visual representations of temperature patterns with what they were experiencing. This was despite the simplicity of the patterns used here, which consisted of only three stimulators within the pattern sequences. Most of the selections on the screen made by the participants appeared to be by chance, and the only pattern with 50% correct discrimination was the neutral pattern. This was surpassing as some subjects were confused with feeling synthetic patterns when presented with the neutral pattern, as evidenced by the other selections made when the neutral pattern was presented.

Even more striking were the confidence reports. Participants reported to be neither not confident, nor confident in their ability to discriminate patterns, and no significant differences in their confidence in discrimination ability were found across the patterns. Subjects appeared to be indifferent, or even confused, to how well or decisive they were able to discriminate temperature patterns, regardless of the patterns' literal sequence.

Little work has examined how well human subjects can discriminate linear array sequences of thermal patterns, and no previous work had attempted to link visual representations of thermal patterns to what subjects were perceiving. Oron-Gilad *et al*. (2008) setup and ran a trial study of two stimulator array sequences. However, very little detail was given of the outcomes other than that synthetic heat was perceived differently to setting the stimulators to all hot or cold (similar to what this thesis referred to as enhanced hot and cold). Sato and Maeno (2012) investigated a related area using a small 2 x 2 matrix of micro-TECs. They found that their participants could also not easily identify the temperature and positions of individual TECs when participants were asked to do so by touching the matrix with their finger and reporting on what they felt. In other words, even within such a small sequence (in Sato and Maeno's experiment, a grid rather than a linear array), participants still could not discriminate patterns well. The results of this section's study also found similar results, in that participants could not discriminate what they were perceiving, even when presented with graphic depictions of all possible outcomes on a screen in front of them.

One may argue why this research did not consider displaying the perceived sequence images from Tables 5.1 - 5.3 on the screen instead of the pictures from the literal sequence columns. The reason was that the perceived sequence images were mainly used here for the purposes of illustrating how temperature *might* have interacted with the surrounding areas, based on the known literature of the illusions discussed in this chapter as well as the preferred direction of how the temperatures might 'flow' to these areas based on their position in the sequence. Using these pictures might have confused the subjects, as they would not have been familiar with ideas of synthetic heat or referral. In addition, using these pictures would have required the participants to undertake significant training to map these illusions to the colours in the perceived sequence images. On the other hand, users could understand how the colour mapping scheme worked in the literal sequence pictures, as it was easy to explain what blue, red, and white were and how the mapping worked. As this study was concerned with how users could discriminate temperatures without the need for such training, the literal sequence images were used instead. Nevertheless, participants were not able to discriminate the patterns with the literal sequence images. As such, it would have been even less likely they could have mapped such patterns to a more complicated colouring scheme.

One possible venue that this research did not explore was training. Training might had helped subjects become familiarised with the stimuli and admittedly, its absence could be seen as a limitation. Additionally, the idea of training was influential for future experiments in this thesis to familiarise users with thermal stimuli.

Discrimination of senses is important, as it allows humans to identify what they are perceiving so that they can map the perception to a meaning. Using thermal patterns in this manner for use in communication may appear to be novel, however, it is unlikely that human subjects can accurately discriminate such patterns due to the myriad of different factors discussed in this section. The illusions of referral, enhancement, synthetic heat, and de-enhancement caused non-linear interaction effects which significantly impeded with the perception of which temperatures were conveyed in the sequences. The optimal direction of temperature, namely how warm temperatures spread toward the body's centre and how cool temperatures spread out towards the peripheral, added to this complexity. Lastly, of course, were the parameters of the temperatures themselves, such as their intensities, their rates of change, and their directions (warm or cool). These factors made it difficult for users to consistently discriminate temperatures, as even the simplest patterns in Table 5.1 were difficult to discriminate. All the above factors reduced the feasibility of using thermal patterns to encode information for communication, hence this chapter turned its attention to other venues to explore using the TAD implementation.

5.2 Main Experiment

As was discussed in Chapter 4 and this chapter so far, a challenge in HCI has been to ensure that users can discern different thermal signals, which is constrained by both human and technological factors. These are due to both skin thermo-receptors having a low resolution and the non-linear 'illusions', like synthetic heat and referral, which makes accurate temperature discrimination of thermal patterns difficult. Thermoelectric coolers (TECs) can also suffer from high latency, with noticeable temperature changes occurring in the order of seconds, depending on the kind of TECs used, as well as risk of overheating due excessive heat dissipation, which limit their usefulness for real-time thermal feedback applications.

This section will discuss some ways that a multi-stimulator thermal display can mitigate these common issues by demonstrating how the TAD could be used to signal thermal states. Individually, the TAD's stimulators can be heated and cooled over a small temperature range, but as a group, they could alternatively be used to signal a wide thermal span. This has a direct effect on latency, or the time taken for the stimulators to warm or cool the skin to a specified setpoint, or target temperature, since the stimulators only need to change their temperatures slightly using several stimulators, instead of a more distant setpoint using only one stimulator, to achieve the same perception of intensity. This is because of spatial summation, discussed in Chapter 4, as multiple stimulators also increase the skin area that is stimulated, making it easier for participants to perceive the thermal signal. No thermal display in HCI research has examined this idea experimentally, though the idea was originally proposed by Wilson (2013).

This remainder of this chapter will present this novel technique of reducing the perception latency of signalling temperature with the TAD device, referred to as *Discrete Signalling*. To test this approach, participants were asked to identify seven thermal stimuli, ranging from Coolest (29°C) to Warmest (35°C), using three methods:

- *Single*, where only one stimulator in the array was used as a control condition.
- *Amplification*, where all stimulators were set to one of the seven temperature stimuli.
- *Quantification*, where the target temperature was represented by setting one, two, or all three stimulators to the warmest or coolest temperatures.

In all these methods, a thermal stimulus was presented to the participant, and then there was a pause of several seconds to re-adapt the skin back to neutral before presenting a new cue.

5.2.1 Background

No studies have examined the feasibility of using spatial summation as a parameter to present thermal states to users using an array of stimulators like the TAD. Wilson (2013) proposed that an array could use spatial summation as a parameter, by turning on and off the individual stimulators in the array to allow for stronger sensations without the need for increasing the temperature. However, he did not pursue this as he deemed that the size of such an array would be impractical for mobile use to be effective. He also proposed that an array could be used to generate thermal pulses, which could be identifiable as information. Additionally, the length of the pulses could also be used as a parameter along with the position of each stimulus within the sequence. However, he did not pursue this either due to concerns of the temperatures' comparative nature. For example, he stated that warming the skin from 32°C to 35°C would feel like warming, but decreasing the skin's temperature back to 32°C may be perceived as cooling instead of returning to a neutral temperature. He also stated there where technological issues, as such technology would require fast rates of change in order to be effective. However, he did not conduct studies to verify these claims.

Sato and Maeno (2012)'s work showed that multiple stimulators could address the problem of latency attributed to technology. Their device consisted of a small 2 x 2 matrix of TECs that participants placed their fingertips on. The authors created six thermal patterns which consisted of a pre-heating/cooling phase that was displayed for 5 seconds, followed by 1 second of no stimulation, and then the main stimulus, which was displayed for another 5 seconds. Two of the patterns used their proposed method of setting two stimulators to either warm or cool, and the other two stimulators to the opposite temperature during the pre-stimulus phase and the middle phase for one second, to prepare the skin for the main stimulus phase, which consisted of inverting the pattern from the pre-stimulus phase. The participants were then asked to rate the perceived intensity of the main stimulus on scales from 1 to 3, and their response times were automatically recorded. The results demonstrated that the proposed method lowered detection response times compared to the other four patterns, which did not use less intense variations of temperature in the first and middle phases. Their proposed method also increased the intensity perception of the main stimulus.

The only other significant work of using multiple stimulators to address latency was the work of Akiyama *et al.* (2012). In their approach, two TECs were placed side by side, and placed under the participants' hand to 'prime' the skin with a pre-stimulus of warm or cool before sending a hot or cold stimulus. The authors claimed to be able to reduce the detection times by up to 28% for hot stimuli and 24% for cold stimuli using this technique, compared to the condition where the stimulator was initially off at the beginning of the stimulus.

The remainder of this chapter will present a technique for thermal feedback that uses the TAD to signal thermal states to the user. It will demonstrate how the TAD can be used to increase a users' ability to identify temperature states better than using only a single thermal stimulator by using spatial summation as a parameter. The next section will discuss how the thermal stimuli were designed using three approaches to signalling the thermal states.

5.2.2 Stimuli Design

Three parameters were considered when designing the seven temperature stimuli: the neutral temperature, the temperature range, and the temperature difference between stimuli. Each will be discussed in this section and then the process in how temperature was signalled using the TAD will be described afterward.

Section 4.3.2 provided an overview of the previous work in HCI regarding thermal displays. As discussed, many prototypes existed for displaying heat to users to convey various information. However, few researchers examined how the key parameters of temperature discussed in Section 4.1, like intensity and rate of change, could be used to create more structured thermal feedback for practical means.

Significant work in this area began to emerge in recent years by researchers such as Graham Wilson, Martin Halvey, and Stephen Brewster. Wilson *et al.* (2011) first examined the key parameters of intensity, rate of change, and temperature direction, and how well users could perceive stimuli designed with these parameters in a static use case environment (such as being seated in an office space). The authors noted that 1°C/sec rates of change were more appropriate for ambient temperature displays and did not produce any less discernible stimuli than 3°C/sec changes. 1°C change magnitudes, on the other hand, were harder to detect than 3°C and 6°C changes and resulted in longer time-to-detections. A follow up study then compared using the same stimuli with the users wearing the authors' thermal display in a mobile setting. The authors discovered that participants found it harder to detect the thermal changes when walking as opposed to the static use case when the user was seated.

Wilson *et al.* (2012) also looked beyond the simple, binary (yes or no) detection of thermal cues and combined them with vibrotactile feedback to produce *intra-modal icons*. These icons consisted of tactile rhythms produced with vibration motors worn on the wrist with accompanying thermal stimuli that the user felt with their palm of the same hand. Furthermore, Wilson *et al.* associated different intra-modal icons with various kinds of email messages, by mapping parameters of each modality in the icons to the importance and subject matter of the emails. They found that temperature cues, by themselves, could be detected with an 82.8% mean accuracy. However, when combined with vibrotactile icons, this accuracy was increased to a mean accuracy of 96.9% to convey the same information.

Wilson *et al.* (2015) subsequently examined other potential scenarios of how users could discern thermal stimuli to rate activities based on the user's subjective interpretation of temperature accompanying the activity. In one study, users were presented with an application that displayed a phone contact list. When they clicked on a contact in the list, they perceived an accompanying temperature. They were then asked to rate how long ago the contact posted on social media using the thermal feedback as a guide. Users associated cool temperatures with older social activity and warmer temperatures as recent activity. The authors also presented similar studies, such as asking users to rate the activity level of thermal augmented door knobs (users reported that warm temperatures indicted the occupant was extremely busy, while cool temperatures indicated that the occupant was currently out of the office), application usage on a PC (warm was equated to heavy usage, while cool was associated with low usage), and reviewing restaurants (warm was associated with positive reviews, and cool was associated with negative reviews). While the results revealed that users could detect the various levels of temperature, it was not clear, indeed doubtful, if those levels could be discriminated accurately, however.

Other work that has investigated the parameters of thermal feedback rigorously is that of Martin Halvey, who investigated environmental effects on thermal feedback and, as will be discussed in further detail in Chapter 7, media augmentation using temperature. Halvey *et al.*, (2011) conducted a study that examined the effect of clothing on thermal feedback using thermal stimulators placed on top of cotton or nylon clothing, as well as directly on the skin as the control condition. The results showed that wearing clothes below the thermal stimulators reduced the perceived intensity of the stimuli, however, wearing clothing also made the stimuli feel more comfortable. Halvey *et al.*, (2012b) also examined the effect of environmental variables, such as the effect of humidity and ambient temperature on human perception of cutaneous thermal stimuli on the wrist and the thenar region of the palm. They found that ambient temperatures significantly affected detection and perception of temperature stimuli, but humidity did not.

These works greatly contributed to the stimuli design used in this chapter for examining how temperature could be signalled with the TAD. In particular, Wilson *et al.* (2015) used a temperature range of 22°C to 38°C, with 2°C as the smallest difference between two stimuli in this range. Within this range, was found to be a safe and comfortable zone of temperatures appropriate for thermal feedback.

However, the use of such a wide temperature range also required significant time for the hardware to warm or cool the stimulators. For example, the most intense temperatures at the extrema of this range (22°C for the coolest stimulus and 38°C for the warmest stimulus), would have required a full 8 seconds for the TAD to warm or cool the skin from the neutral temperature, 30°C, in their study (Wilson *et al.* 2015). This is because the TAD has a maximum operating rate of change of about 1°C, which results in significant latency attributed to the hardware, the time it takes for the stimulators to reach a new designated temperature setpoint. Therefore, it is paramount to use a smaller range for the TAD to minimise the effect of latency, to reduce the time taken for the TAD to change temperatures.

In contrast, this section suggests seven temperature stimuli in the narrower range of 29°C to 35°C, and a reduction of the intervals between stimuli to 1°C as opposed to the 2°C intervals used by Wilson *et al.* (2015). These two changes both reduce the time taken to change signals from a neutral temperature, as well the time needed for participants to complete a study. The smaller step changes make it harder for participants to discriminate adjacent temperature stimuli in this range, for example, the difference between 29°C and 30°C or between 33°C and 34°C. However, this also forms a better study design to validate the novelty of using spatial summation as a parameter to increase the perceived intensity of weaker thermal stimuli. This in turn, provides a stronger argument for using the TAD as a better apparatus for testing the fine discriminability of stimuli using multiple thermal stimulators as opposed to employing just one stimulator.

Since skin adapts to stimulation of temperature, there was also careful consideration of which temperature to use as the neutral stimulus or baseline temperature. Discussed in Section 4.1 as the physiological zero, this neutral temperature varies from person to person, but it is thought to be in the range of 20°C - 40°C (Jones and Berris, 2002). Within this range, the skin will adapt itself to the presented temperature. As the skin adapts to the stimulation, the stimulus will slowly feel less intense until full re-adaptation has taken place, when the user no longer feels any sensation. Temperatures closer to the middle of this range are easier to adapt to than at the extremes (Halvey *et al.*, 2013). Beyond this range, temperatures will feel persistently cold or hot (Kenshalo and Scott, 1966). Such extreme temperatures are not commonly used as they are uncomfortable and even painful. Therefore, this research decided to choose a conservative temperature of 32°C for the neutral temperature as was used in the work of Wilson *et al.* (2011; 2012) and Halvey *et al.* (2012a).

To examine how the TAD could use spatial summation as a parameter for usage in discrete thermal feedback, participants were asked to identify the seven thermal stimuli as unique thermal states, or descriptions of how intense the perceptions felt, from 'Coolest' to 'Warmest' on a 7-point Likert scale. This was done using three approaches to provide the signalling. The first approach, called simply the *Single*

Method, used only one stimulator, which was set to any of the seven thermal stimuli. In this case, a point, or thermal state, on the Likert scale was also one of the thermal stimuli. The second method, the *Amplification Method,* set all stimulators in the array to the same temperature, which was any of the seven stimuli. This method was basically the same as the Single Method, except all three stimulators were used in the array. The final method, the *Quantification Method*, was fundamentally different from the other methods, in that instead of setting the stimulators to one of the seven stimuli to represent a thermal state, the state was instead represented by setting one, two, or all three of the stimulators to the warmest or coolest temperature, which was either 29°C or 35°C.

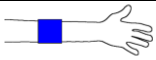
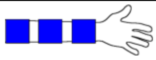
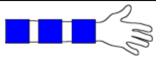
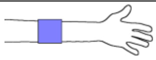
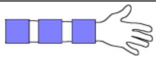
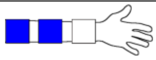
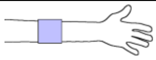
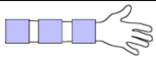
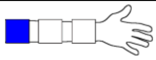
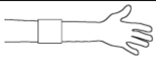
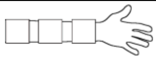
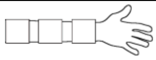
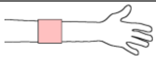
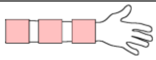
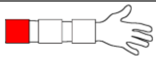
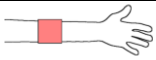
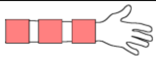
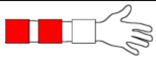
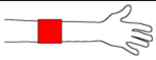
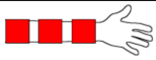
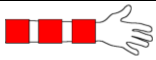
Name	Single	Amplification	Quantification
Coolest			
Cooler			
Cool			
Neutral			
Warm			
Warmer			
Warmest			

Table 5.6: Experimental stimuli for the Single, Amplification and Quantification tests. Red colours indicate warm temperatures, the white colour indicates the neutral temperature, and blue colours indicate cool temperatures. Darker colour gradients indicate stronger intensities.

Table 5.6 shows how temperature was signalled in each test. The squares represent stimulators, where the left, middle, and right squares represent the wrist, middle, and elbow stimulators, respectively. Colours denote whether the stimulus was warm, cool, or neutral using red, blue, and white, respectively. Neutral does not mean off, but was rather an ambient temperature that was not perceived as either warm or cool (32°C). There were three states for warm and cool, which could be thought as three separate intensities for warm and cool in both the Single and Application methods, where the colour gradient in Table 6.1 indicates the thermal state. However, in the Quantification method, stimulators were either on or off, and were set to the coolest (29°C) or warmest (35°C) temperature, and not to a particular intensity, like 32°C or 34°C.

5.2.2.1 Single Method

This method used only the middle stimulator, which was chosen to prevent biasing effects from using either the elbow location, which would have made warm sensations feel more intense, or the wrist, which is the direction cold sensations spread better towards (Watanabe *et al.*, 2014). Other stimulators were not worn as it eliminated the decision of whether to leave them on (at the neutral temperature) or off, and further eliminated the possibility of confusing the user into thinking the other stimulators were in use. Participants were asked to identify which of the seven stimuli was presented. Stimuli differed by 1°C increments with 'Neutral' at 32°C. Hence, 'Warm' was 33°C, 'Warmer' was 34°C, and 'Warmest' was 35°C. 'Cool' was 31°C, 'Cooler' was 30°C, and 'Coolest' was 29°C.

5.2.2.2 Amplification Method

This method set all stimulators to the same temperature to indicate the thermal state. All three stimulators were worn, and the participants were asked to identify the combined stimulus as a whole. As with the single test, temperature states differed by 1°C increments with 'Neutral' at 32°C. The temperature value was applied to all three stimulators, using the same temperatures from the Single Method. Hence, 'Warm' was 33°C, 'Warmer' was 34°C, and 'Warmest' was 35°C. 'Cool' was 31°C, 'Cooler' was 30°C, and 'Coolest' was 29°C.

5.2.2.3 Quantification Method

The idea for the Quantification Method came from the 'dynamic patterns' proposal from the previous pilot study in Section 5.1. One of the ideas was a countdown timer that the user would feel as each temperature stimulator activated sequentially in the array, which would give rise to a (presumably) more intensive stimulation of heat and cool. In this design, stimulators were activated that were directly adjacent to one another. Though the ideas of the countdown timer and 'dynamic' patterns were discarded, they inspired the Quantification Method proposed in this section, and how it may be used as another approach for increasing perception of thermal states using multiple stimulators and decreasing the thermal latency.

In the Quantification Method, participants were asked to discriminate thermal states wearing all stimulators like the Amplification Method. However, unlike the Amplification Method, the Quantification Method used only three temperatures: 29°C for cool stimuli and 35°C for warm stimuli. In this method, it was the number, or *quantity*, of active stimulators that determined the felt intensity, rather than a specified temperature setpoint in degrees. Stimulators that were not set to either 29°C or 35°C were left at 32°C, the neutral temperature. For example, the thermal state of 'Warm' is the state above the neutral point. In the other two methods, the stimulators were set to 33°C. However, in this method, only one stimulator is set to 35°C, with the other two stimulators remaining at neutral. For the next state, 'Warmer', two stimulators were set to 35°C, and the other stimulator was set to neutral. Finally, for the state 'Warmest', all stimulators are set to 35°C. This same pattern was applied to the cool states: 'Cool' had one stimulator set to 29°C, 'Cooler' had two stimulators set at 29°C, and 'Coolest' had all three stimulators set to 29°C, with the unused stimulators left at neutral. The 'Neutral' state was simply all three stimulators set to 32°C.

5.2.3 Procedure

The purpose of the experiment was to test which method of signalling temperature resulted in the best discrimination of the seven thermal states. Specifically, the experiment tested whether the null hypothesis was true or not: whether the signalling methods (Single, Amplification, and Quantification) and the rates of error were independent. If the signalling methods did have a significant effect, then one would reject the null hypothesis on the grounds that the variables of signalling methods and the frequency of errors were dependent. In other words, accepting the alternative hypothesis that there was a relationship between how many errors participants made and which method was used to signal the temperature states.

Twelve participants, ten males and two females, were recruited from City, University of London. While it has been argued, as discussed in Section 4.1, that gender could influence perception of temperature, the most recent paper by Wilson *et al.* (2016) showed no differences in perceiving temperature, and thus the issue of gender for this study was abated. Each participant received £10 for their time, in line with standard practices at the institution. The experiment was approved by the school ethics board in advance, and subjects were given the participant information sheet shown in Appendix H.3 before the study. The consent form they signed before they were allowed to participate can be found in Appendix H.4.

To ensure both the wellbeing of participants and the efficacy of the study, certain exclusions had to be made. Individuals could not participate if they had medical problems that could have impeded with temperature perception, such as over-sensitive skin, or where exposure to temperature could have caused discomfort or harm.

Participants wore the TAD on their non-dominant arm, following the practice of previous studies, such as Wilson *et al.*'s work (2015). Each participant took approximately one hour to complete the experiment, including induction and completion of all tests. There was no time limit imposed on participants, thus the experiment lasted until they submitted their selections for each trial. Participants, however, were instructed not to dwell on answers and to move on as quickly as they could.

The entire experiment was automated. Tests were separated by five-minute breaks to allow participants to relax their arms. Participants were told to read the instructions on the screen (Appendices G.8 to G.12) and complete the tests by recording their perception of the signalled temperature on a 7-point Likert scale, as shown in Figure 5.2. Each point denotes one of the temperature states, colour coded from 'Coolest' to 'Warmest', with 'Neutral' in the middle. The seven stimuli were presented three times in random order for each test. Furthermore, the order of the three tests was randomized by counterbalancing beforehand, so that only two subjects were given the same order of tests (this allowed all order arrangements to be explored with 12 subjects).

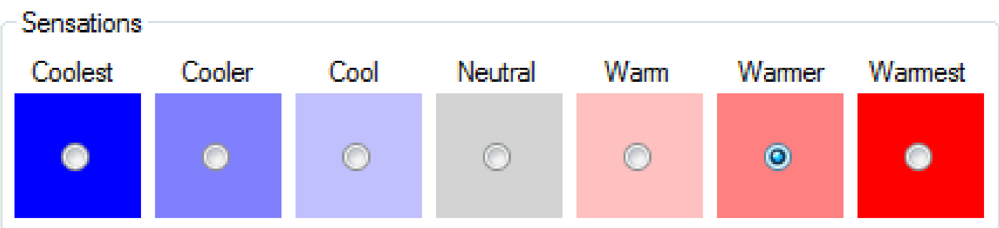


Figure 5.2: User interface for the main experiment, showing the 7-point Likert scale used for recording the temperature state the user believed they were perceiving.

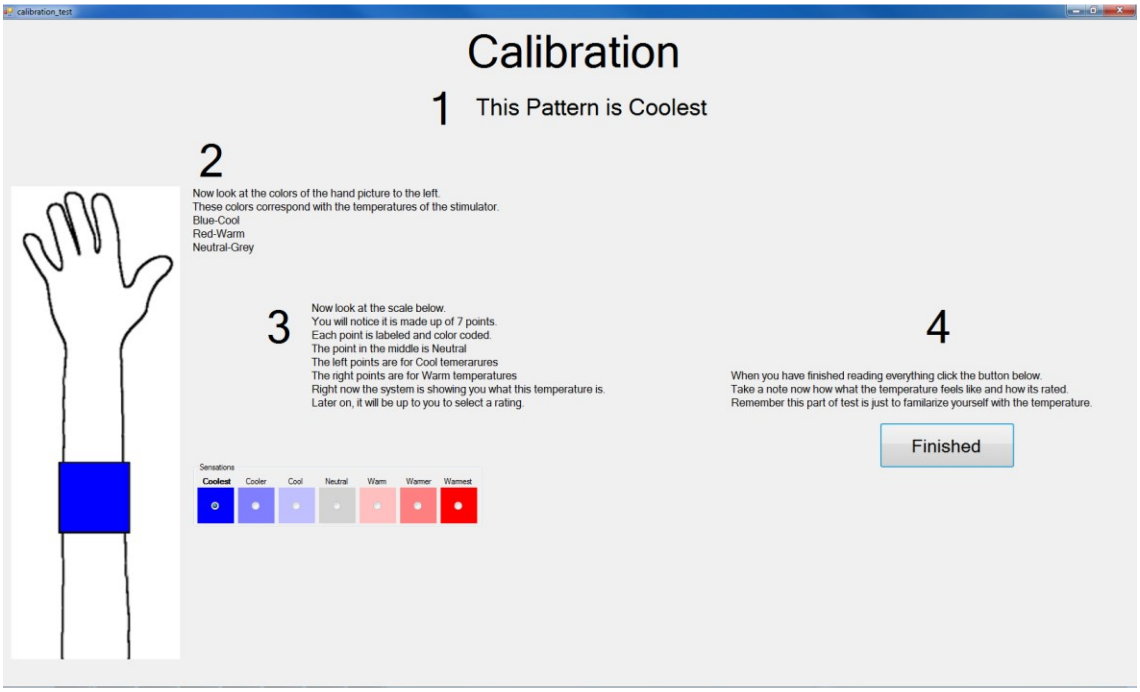


Figure 5.3: Calibration user interface, showing that the current thermal state/pattern 'Coolest' is presented to the participant.

Preceding each test was a calibration session to familiarise participants with both the seven thermal states presented in the test and the interface that the participants would use to record their responses. The calibration session was nearly identical to the real tests that followed, but with the Likert scale pre-selected with the correct response. Additional, color-coded graphics depicting stimulators across the arm were shown in the user interface (Figure 5.3), with instructions on how to navigate the interface (Appendices G.9 to G.11), along with the name of the selected thermal state (or 'pattern' as it was referred to as in the instructions), such as 'Very Warm' or 'Neutral'.

Between each thermal state was a short delay of ten seconds to allow participants' skin temperatures to re-adapt back to the neutral temperature. This time took place from when the user pressed either the 'Finished' button (Figure 5.3) or the 'Next Pattern' button (Figure 5.5), which indicated their readiness for the next stimulus, to when the system presented the next stimulus, and includes the time taken to reach 32°C (neutral temperature) from the previous stimulus. To inform the participant of this process, a screen consisting of a progress bar was presented to the participant using the UI shown in Figure 6.3 - *Left* below. After re-adapting the skin, the next thermal state was presented for three seconds, which was also notified on the screen, as shown in Figure 6.3 - *Right.*

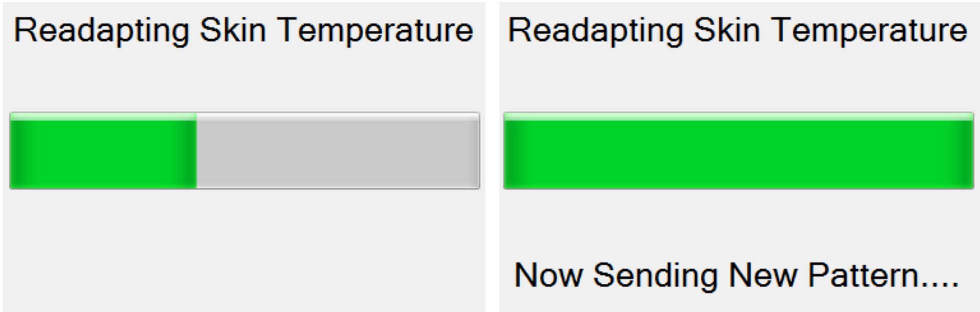


Figure 5.4: Re-adapting user interface. Left - In-progress. Right - Completed.

Re-adaptation, discussed in Section 4.1, is used to ensure participants can discern the next thermal state without bias from the most recent thermal state, by establishing the reference temperature used to judge subsequent thermal states. Previous studies have used inter stimuli delays of between ten seconds (Wilson *et al.*, 2015) to two minutes (Halvey *et al.*, 2011) for re-adaptation. This thesis chose the short time of ten seconds due to time constraints of the study. As the temperature range used in this study (29°C to 35°C) was smaller than the range used by Wilson *et al.* (2015) in their work (22°C to 38°C), this time was deemed acceptable, since the skin did not need to adapt from using more intense temperatures, hence the time could be shorter.

After three seconds had passed, the UI with the Likert scale from Figure 5.2 was displayed on screen. This full UI (for the Single Test) is shown in Figure 5.5. At this point, the participant would still feel the thermal pattern, which would be sustained by the TAD until the participant made a choice. Once the participant made a choice, the 'Next Pattern' button would become active. At this stage, the participant could either make a new choice on the scale if they changed their mind, or they could proceed to the next thermal state/pattern by clicking the 'Next Pattern' button. After the participant pressed the button, they were presented with either the re-adapting screen again, shown in Figure 5.4, or the completion message if they reached the end of the test.

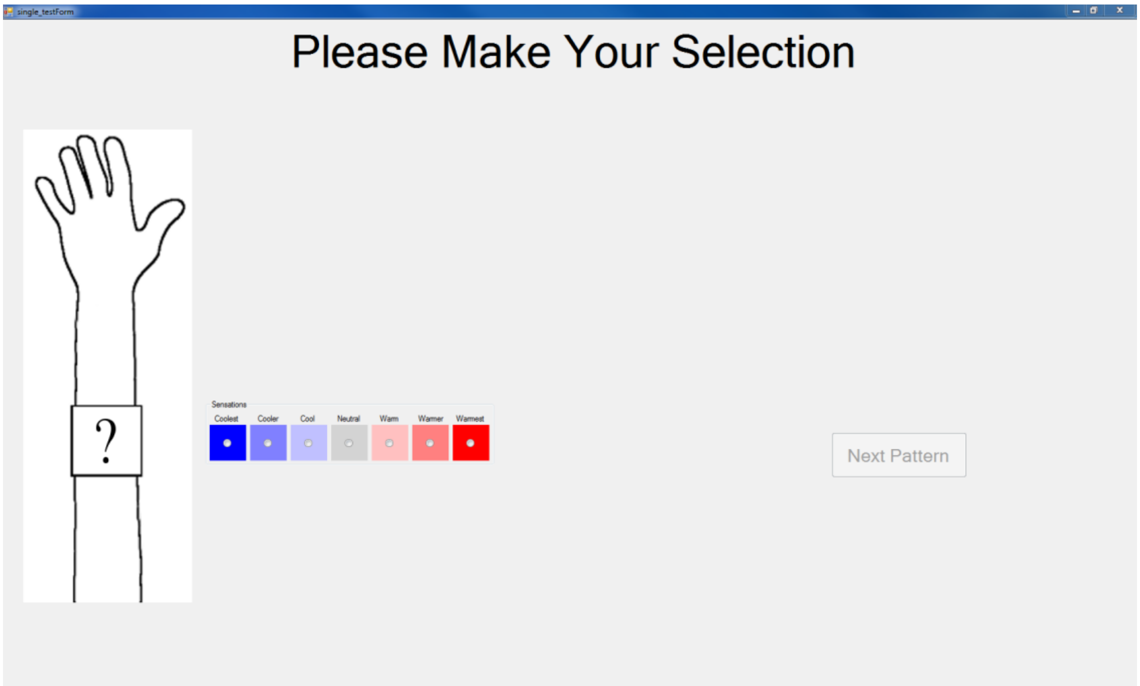


Figure 5.5: Selection user interface for the Single Test.

To summarize the experimental procedure:

- The experiment consisted of testing three different methods of signalling temperature with the TAD: the Single Method, the Amplification Method, and the Quantification method.
- Each of these three tests was presented in randomised order.
- Each test had a calibration session beforehand to acquaint participants with each of the seven temperature states used in that test.
- During each test, the seven temperature states were randomly presented three times each, for a total of 21 trials for each test.
- Participants made selections on a 7-point Likert scale.
- After the user made a selection, the skin temperature returned to neutral before the next temperature state was presented.
- There was a five-minute break in between each test.

5.2.4 Results

The raw data for all three tests is presented in Appendix D.1. Table 5.7 shows descriptive statistics for each test: the means and standard deviations of the users' Likert scale ratings across all seven thermal states. From this table, several observations can be made. First, the mean ratings appear to increase in line with the perceived temperature of the thermal states: cooler states are rated less than warmer states, and ratings increase steadily as the temperatures increase. Second, the standard deviations of the two multi stimulator methods (Amplification and Quantification) appear to be smaller than those of the Single Method. This implies that users were more precise when rating the multi-stimulator methods.

Test	Stat.	Coolest	Cooler	Cool	Neutral	Warm	Warmer	Warmest
Single	$\bar{x}$	2.4	2.8	3.7	4.2	4.5	4.9	5.8
	σ	1.6	1.4	1.2	1.2	1.1	1.4	1.2
Ampl.	$\bar{x}$	1.8	2.5	2.9	3.9	4.3	5.8	6.7
	σ	1.3	1.3	0.8	0.7	0.8	0.9	0.5
Quan.	$\bar{x}$	2.0	2.6	3.5	3.8	4.9	5.7	6.1
	σ	1.1	1.2	1.1	0.8	1.1	1.0	1.1

Table 5.7: Means ($\bar{x}$) and standard deviations (σ) of all seven temperature states for each of the three tests (Single, Amplification 'Ampl.', and Quantification 'Quan.').

To illustrate these observations better, box plots were generated of the Likert ratings for the Single (Figure 5.6), Amplification (Figure 5.7), and Quantification Tests (Figure 5.8). A linear relationship can be seen in all three tests: as temperature increased, the ratings also appeared to increase. This relationship appears to be stronger in the multi-stimulator methods: the means of the boxes appear to align on a straight line better than in the Single Test results. Finally, there appears to be less variance in both multi-stimulator results: the whiskers in Figures 5.7 and 5.8 do not extend as far as the whiskers in Figure 5.6. There is also very little variance in how users rated the neutral thermal state for both multi-stimulator methods. These figures support the view that the multi-stimulator methods were better than the Single Test in terms of how well participants were able to map the thermal state with the correct Likert scale rating. However, further statistical testing needs to be done to verify this claim and to find whether the Amplification Method or the Quantification Method was better than the other.

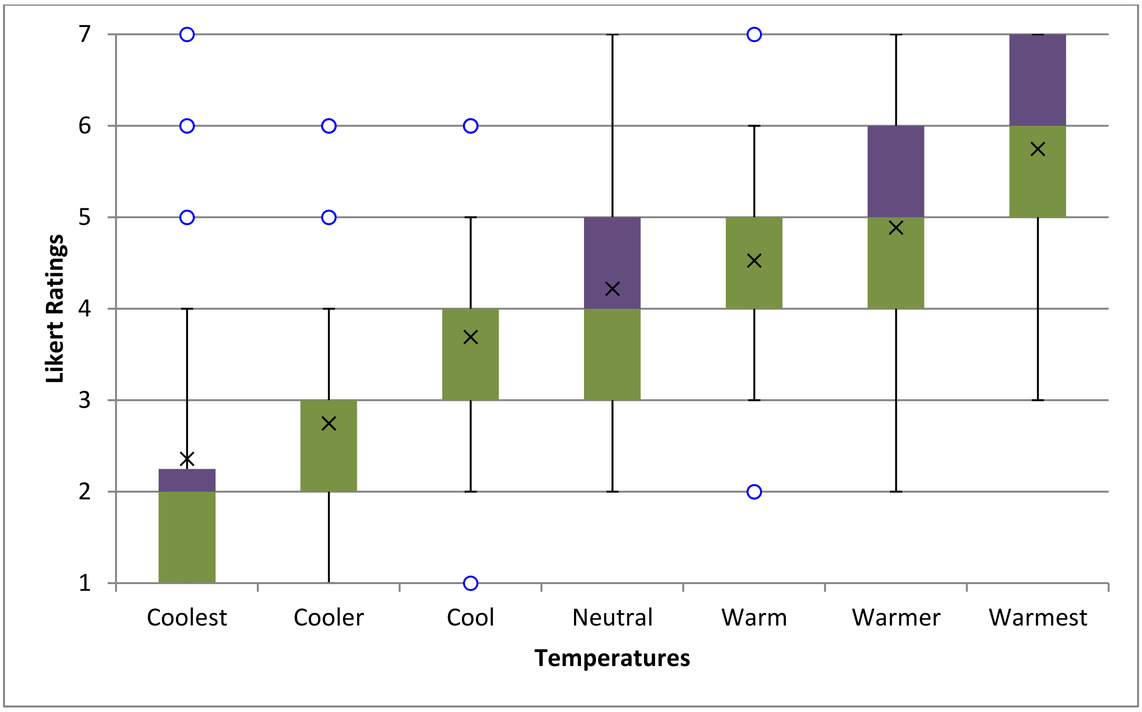


Figure 5.6: Single Test box plots of the user Likert ratings for the seven thermal states listed on the 'Temperatures' axis.

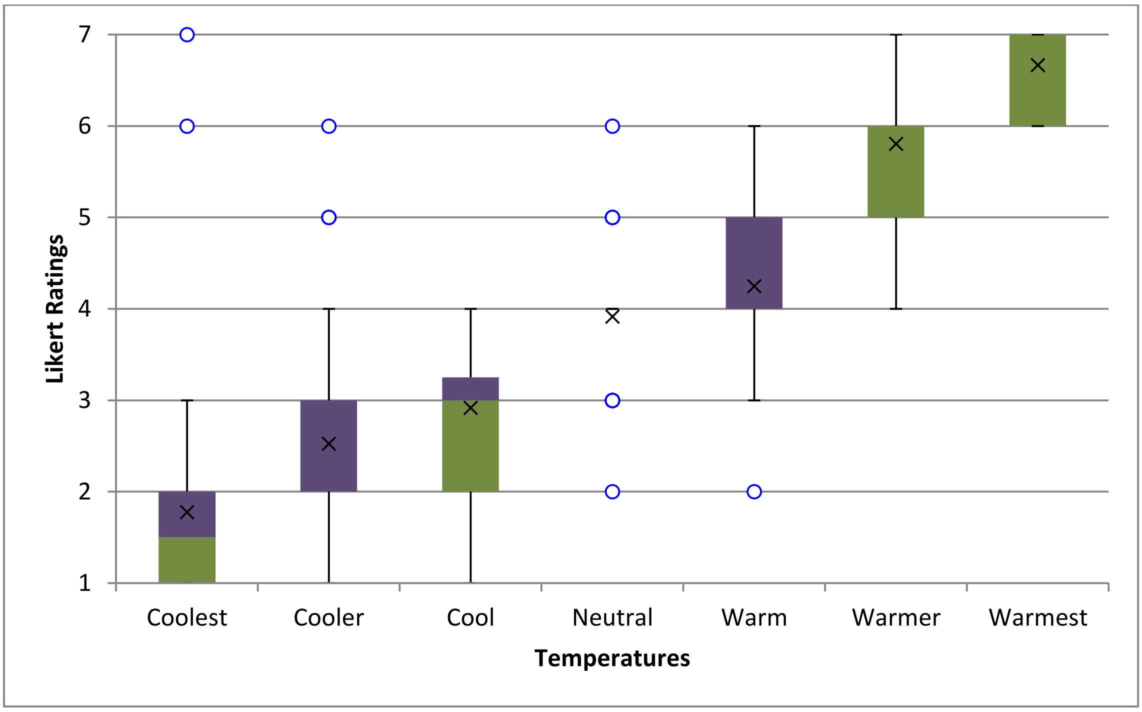


Figure 5.7: Amplification Test box plots of the user Likert ratings for the seven thermal states listed on the 'Temperatures' axis.

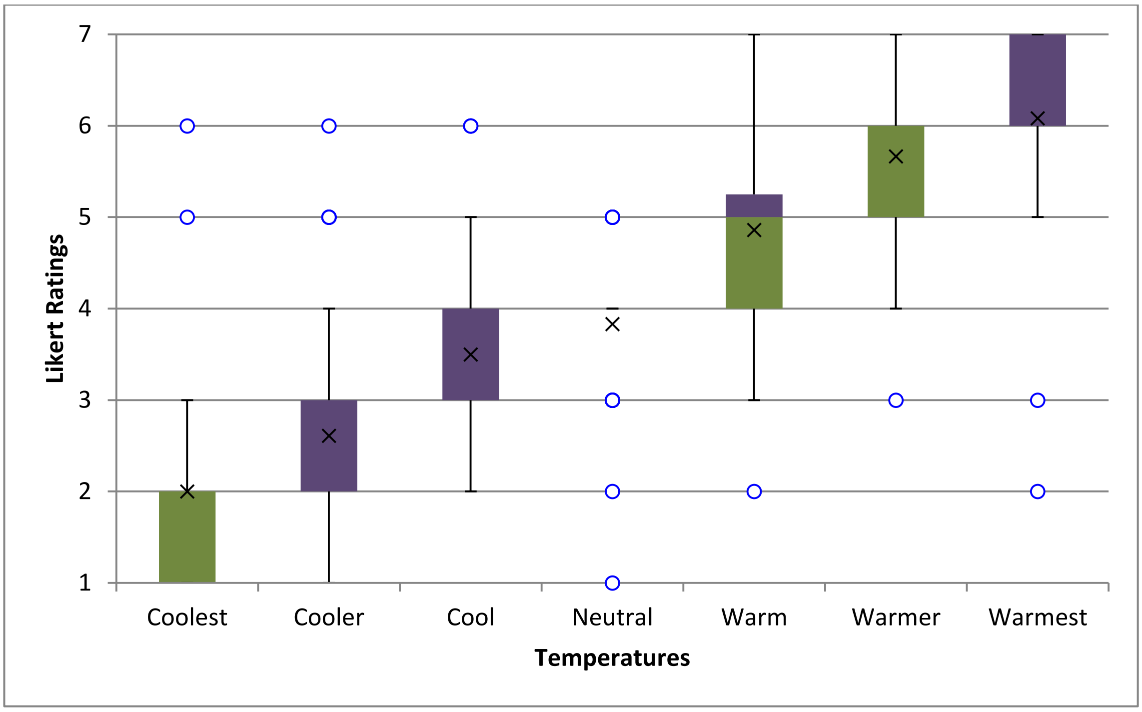


Figure 5.8: Quantification Test box plots of the user Likert ratings for the seven thermal states listed on the 'Temperatures' axis.

The error rate was first calculated for all three signalling methods. Error rate is defined as the frequencies of whether or not the participants correctly mapped the temperature state felt to the correct thermal scale rating on the Likert scale. These frequencies of correct vs incorrect responses for each method were then analysed. As the data was not normally distributed, ANOVA was not used to analyse the data, so non-parametric methods were employed instead.

The simple error rate using a chi-squared test produced p = 0.004 (χ^2 = 10.89, df = 2). As this p-value was very small, it could be presumed that whether the participants answered correctly or not depended on the signalling method used to present the thermal state, and thus, the null hypothesis was rejected (the two variables were not independent). The Single Method provided the worst outcome, with only 34.9% correct responses, while the Amplification Method and Quantification Method produced 49.2% and 44.4% correct results, respectively. Subsequent testing for which of the two multi-stimulator methods provided the most accurate outcomes produced an advantage for the Amplification Method (χ^2 = 4.51, df = 1, p = 0.036). Thus, in terms of error rate, the Amplification Method produced the best results.

The degree of error, or the absolute difference between the true thermal scale rating and the participant's rating, was tested next. The degree of error was measured separately from error rate, as non-significance in either test would have led to rejecting the alternate hypothesis that there existed a relationship between error responses and signalling method. A Kruskall-Wallis test on the degree of error between the three methods produced $p < 0.001$ ($H = 22.59$, $df = 2$). Again, both multi-stimulator approaches proved superior to the single stimulator method. However, there was no significant difference in the relative degree of error between the Amplification Method and the Quantification Method.

The alternative test for the population distribution of errors using a chi-square test also proved significant and produced $p = 0.001$ ($\chi^2 = 20.55$, $df = 8$). This examined degrees of errors ranging from 1 (the subject picked an adjacent selection on the Likert scale such as, for example, 'Cool' when they should have picked 'Cooler') to 6 (the subject picked the 'Coolest' scale instead of the 'Warmest' scale, or they picked 'Warmest' when they should had picked 'Coolest' instead). These differences were calculated from the error formula above. Thus, the Amplification Method and Quantification Method both gave more accurate detections and resulted in lower degrees of error than the Single Method.

Surprisingly, the three methods produced no significant difference on how fast subjects were able to assign ratings for each scale. The mean times for each method were 6.57 seconds (Single Method), 6.59 seconds (Amplification Method), and 7.19 seconds (Quantification Method). The standard deviations for each method were 4.11 seconds (Single Method), 4.19 seconds (Amplification Method), and 4.81 seconds (Quantification Method). As the data was non-normal ($p = 0$, $W = 0.72$), a Kruskal-Wallis test was used instead of ANOVA to compare the median time responses of the three signalling methods. This produced $p = 0.259$ ($H = 2.7$, $df = 2$). This indicated that there was no significant difference between the three signalling methods regarding how quickly participants were able to perceive and rate the thermal states on the Likert scale.

5.2.5 Discussion

Overall, the data suggests that the Amplification Method was the most promising method for signalling thermal states, but as the advantage over the Quantification Method was low-power, both multi-stimulator approaches are better suited for signalling temperatures than the traditional single stimulator method.

The analysis compared the three signalling methods by examining error rate and the degree of errors made. The Single Method, which used only one stimulator to display the scales, had the worst error rate and degree of error when comparing the participants' Likert scale responses to both the Amplification Method and the Quantification Method. Both of the latter methods significantly improved the perception of the thermal states: the Amplification Method set all TECs to the same temperature to indicate the state, and the Quantification Method indicated states by setting the number of active TECs within the array to either very warm (35°C) or very cool (29°C). When comparing the effectiveness of either multi-stimulator methods to indicate the thermal states, error rate was statistically significant, but not the degree of error. The Quantification Method resulted in significantly higher error rates than the Amplification Method, but no significant difference in degree of error was found between the two methods.

The choice of whether to use the Amplification Method over the Quantification Method depends of the circumstances of usage. While the Amplification Method may result in better appreciation of thermal states, the Quantification Method could be novel in situations where power is a constraint. This is because the Quantification Method uses less stimulators to designate states that are less intense. The Amplification Method, on the other hand, requires all stimulators to be turned on, regardless of the thermal state being presented. This may have applicable usage in mobile situations, where battery life may take precedence over the performance of the system. On the other hand, a constraint of using either multi-stimulator method may be limited stimulation area or location of stimulation. As Wilson (2013) discussed, "In order to use body location or spatial location as a parameter, the locations would best be on the same part of the body, for example the forearm or the upper arm. Were they to be on different areas of variant perceptual fidelity, the same feedback stimuli may be perceived differently, such as feeling less or more intense" (pg. 156).

The TAD did not reduce the time taken by participants to detect and discriminate the thermal states. This was surprising, as it was thought that, since the TAD signalled the thermal states to feel more intense when more than one stimulator was in use, participants should had perceived the thermal states easier. This was believed to also allow them to discriminate the thermal states quicker than when compared with the Single Method. However, this was not the case: the TAD only effected the perceptual accuracy and not the time for subjects to perceive a change and discriminate the thermal state when the TAD was used to signal temperatures discretely.

5.3 Conclusion

This chapter examined the research question: "*What are the benefits of using an array of thermal stimulators over a single stimulator design?*" To answer this question, this chapter proposed several methods of utilizing an array-based thermal display to present thermal stimuli to participants discretely, by requiring temperatures to reset to neutral before presenting another thermal state. Developing a thermal tactile language (Section 5.1) posed significant challenges which undermined the TAD's usefulness to convey information with thermo-spatial patterns. A pilot study was run which examined the feasibility of whether thermal patterns displayed by the TAD could be discriminated by users. The results showed that the users struggled to discriminate any of the patterns used in the pilot, including even the simplest patterns. This confirmed the difficulty of discriminating thermal patterns, due to participants' poor discrimination of the location of the stimulators when worn on the arm. This in effect reduced the novelty of using thermal patterns for further investigation, such as developing a thermal tactile language to communicate information.

However, the array design of the TAD still provided an advantage for thermal communication not yet explored in previous research. As discussed in Section 4.1, changing the amount of skin stimulated has a proportional effect on the temperature intensity perceived by the participant. As suggested by Wilson (2013), an array-based thermal display, like the TAD, could use spatial summation as a parameter, by turning on and off the individual stimulators in an array to allow for stronger sensations without the need for increasing the temperature. The TAD could follow up on this idea of using spatial summation as a parameter to improve the ability of users to accurately identify a single temperature state over using just a single stimulator.

The second section of this chapter proceeded to test this idea of using the TAD for conveying thermal states of temperature (Section 5.2). The results showed that participants were able to utilize the TAD to reliably discriminate seven distinct thermal states better than just one stimulator. The Amplification Method (Section 5.2.2.2) provided the most reliable way of conveying the different states of warmth and cool, with the Quantification Method (Section 5.2.2.3) being slightly less effective. The

Single Method (Section 5.2.2.1), however, produced the worst results in terms of error rates and the degree of error. Neither multi-stimulator method had any significant effect on the latency, or the time taken to perceive and rate the changes, compared to the Single Method. Nevertheless, this demonstrated the benefit of using an array of thermal stimulators over a single stimulator design: the potential of using spatial summation as a parameter in thermal feedback, as the TAD enabled better accuracy in discrimination of thermal states than with a single stimulator. This is despite using a tighter thermal range (29°C to 35°C) than what has been used in prior studies that utilised discrete thermal states of warmth and cool, such as 22°C to 38°C (Wilson *et al.* 2015; 2016), 20°C to 40°C (Narumi *et al.*, 2009b), 17.9°C to 29.9°C, 27.5 °C to 39.5°C (Salminen *et al.*, 2013), and 26°C to 38°C (Akazue *et al.*, 2016).

A limitation of discrete signalling, as was done in both studies in this chapter, is that temperature states can only be sent one at a time, and then there is a need to return to a neutral temperature and pause for tens of seconds before a new thermal state can be signalled. There is a question of how useful thermal feedback can be with these limitations, especially if the feedback needs to be more urgent, for example, to guide user behaviour. In the next chapter, this thesis will present an alternative technique of signalling temperature called *Continuous Signalling* to address these concerns. The next chapter will furthermore demonstrate the utility of continuous signalling with a study that provided thermal feedback to guide user navigation.

Chapter 6

Providing Information Using Continuous Thermal Feedback

Chapter 5 examined the effectiveness of utilizing the TAD to convey thermal states using different quantities of stimulators. However, in both studies in Chapter 5, as well as significant work in thermal related HCI research (Wilson *et al.* 2015; 2016; Narumi *et al.*, 2009b; Salminen *et al.*, 2013; Akazue *et al.*, 2016), thermal cues were typically used to communicate single temperature states one at a time, and then there was a pause of tens of seconds to allow the skin to re-adapt to a neutral temperature before sending another signal. This was referred to in the previous chapter as *Discrete Signalling*. Therefore, Discrete Signalling may not be appropriate for applications that require constant feedback from the user if the temperature must be reset each time a new thermal state is presented, such as guiding real-time behaviour or to monitor a system process.

This chapter will explore a situation (spatial navigation) where information presented by the TAD could be used to guide users in a meaningful way by using a different approach to signalling temperature. The situation constraints were that:

- It had to be in real-time.

- It had to continuously guide user behaviour without slowing down or stopping to pause.
- It had to take into consideration the *latency* of temperature, as thermal perception is not instantaneous due to the slow rate of change of the TAD and the slow nature of human thermoception.

Considering these constraints, this chapter will propose a new method of signalling temperature to users referred to as *Continuous Signalling*. In contrast to Discrete Signalling, the TECs are not reset to a neutral temperature in between signals, so it could potentially be used for continuous feedback to guide ongoing behaviour. While this thesis is not the first to suggest continuous feedback, it is the first to evaluate continuous feedback in a controlled experiment within a context. The proposed study will answer this chapter's research question "*Can continuous feedback provide reliable information from a thermal display?"* by demonstrating how continuous feedback significantly improved user performance in a 2D maze navigation task.

This chapter will be as follows. First, it will review similar work in HCI which has suggested similar feedback (Section 6.1). The experiment design will be discussed (Section 6.2). Section 6.3 will describe how the continuous feedback was trialled using two pilot studies (Section 6.3.1 and 6.3.2). The main experiment procedure will be provided (Section 6.4.1) and its results (Section 6.4.2) will then be discussed (Section 6.4.3). The remainder of Section 6.4.3 will then discuss how continuous thermal feedback could be used for real world navigational tasks.

6.1 Literature Review

Some work has investigated the effectiveness of using vibrotactile feedback (VTF) in navigation tasks. An in-situ evaluation of PocketNavigator (Pielot *et al.*, 2012), for instance, identified several issues using VTF for navigation. Participants often found VTF irritating and they had to learn how to interpret the VTF cues. Although visual distraction was reduced, participants still looked frequently at their mobile displays: "our results confirm that distraction is a challenge" (Pielot *et al.*, 2012*,* pg. 7 - 8). Another example is Jacob *et al.*'s work (2011), where they created a tactile pedestrian navigational system that used four algorithms to convey direction to the user using the built-in vibration alarm in a mobile phone to provide the VTF. However, the authors did not conduct a study to verify which of the four methods was the most effective. Furthermore, user preferences for feedback can vary by location and situation, and while VTF is effective in many situations, it is not appropriate in noise-sensitive environments, such as libraries, and is also less effective in loud and bumpy environments, like trains (Hoggan *et al.*, 2009).

On the other hand, there is the possibility of using temperature to provide similar anticipatory signals in situations requiring ambient attention, particularly within a navigational context. Thermal feedback, unlike VTF, can be silent, depending on the technology used (Wilson, 2013), and it does not require users' full attention, making it a more suitable modality for ambient displays. In addition, the TAD device developed in this thesis is what could be referred to as an 'Ambient Display' (Wisneski, 1999), which has the properties of low resolution, a slow refresh rate, and a specific form factor. Such objects do not demand significant focused attention from the user, but allow access to information presented in a non-cognitively intense manner.

Ambient displays could be deployed in environments that contain many streams of constantly monitored information, such as aviation cockpits and cars (Wisneski *et al.*, 1998). In the cases of an airplane or a car, navigational information that does not require the pilot's or driver's immediate attention, such as stalling or braking, could be presented to the user outside of their peripheral, such as guiding them towards a location. Information provided by a car's GPS system using satellite navigation, or satnav, for example, have traditionally provided this kind of information with interactive maps and audio feedback. However, this demands focused attention from the user, which can be distracting or even dangerous as this information is provided constantly. Alternatively, this information could be presented ambiently using a different modality, like temperature, to reduce the cognition needed to guide user navigation.

Some researchers have proposed that temperature signals could be used to guide navigation. Wettach *et al.* (2007) argued that temperature could be a good interaction modality for communicating ambient information, particularly in the domain of navigation, as thermal signals could provide "a rough clue about the intensity of a certain signal or entity" (pg. 183). The authors designed a handheld thermal device that functioned like a compass with five levels of heating. When the user was aligned with the goal, the device would heat up. When the user was not walking straight towards the target, the device cooled down to one of the other four levels, each of which was mapped to an angle of deviation from the goal. However, no outcomes were reported from their study other than “the user was able to find her way to the destination…” (pg. 184).

Several prototypes had been developed with blind users in mind. However, no controlled studies were carried out to evaluate their effectiveness. For example, Lécuyer *et al.* (2003) proposed a device that used heat from lamps surrounding the user to indicate the direction of the sun to visually impaired users in a virtual world. The results of their informal study showed that very few subjects could perceive the temperatures. However, the authors attributed this to the uncontrolled nature of their study, in that the ambient temperature was too high and that the virtual environment experience was not the same from subject to subject, as the sun deactivated when the subject walked into a virtual building. The authors also did not evaluate the potential of using both heat and cool cues to guide navigation. Balata *et al*. (2013a) proposed that thermal devices could instead be worn on the hand by visually impaired users to navigate real-world spaces. However, no studies were performed, and only a non-functional prototype was built.

Some research had investigated using thermal cues to guide navigation for video game applications. However, these did not perform controlled studies, and results were under-reported. *Quido* (Balata *et al.*, 2013b) presented thermal feedback to navigate the player towards a goal in a 2D maze. The authors claimed that adding temperature feedback was beneficial, as it improved player performance. However, this claim was ambiguous, as tactile feedback was also used in conjunction with the thermal feedback, so it was unclear which modality contributed the most to performance. They also failed to detail the game mechanics, especially how finding the goal contributed (or not) to the scoring used. *Hiya-Atsu* (Nakashige *et al.*, 2009) featured another spatial navigation game where users searched for an object hidden on a computer screen with a temperature augmented computer mouse. While all participants found the hidden objects, no details were reported about how the device was evaluated.

Thermotaxis (Narumi *et al.*, 2009b) demonstrated that temperature could orient users in a real-world space by using hotspots to transmit intangible characteristics within a real-world environment. The authors partitioned a real space into areas of warmth and cool and had participants wear an earmuff-shaped device outfitted with TECs that could display the warm and cool temperatures to the users' head as they walked around. The authors found that users tended to stay in areas that provided comfortable, warm temperatures: "Due to the variations of desired conditions and surrounding environment such as the air temperature, different positions are found to be comfortable by different visitors. For example, on a cold day in winter, a comfortable place would be warm unlike a summer day. People who have a similar preference would gather together" (pg. 358). However, this may had been because the experiment was conducted outdoors in the cool season.

A caveat with how thermal displays, particularly those used in HCI, signal temperature is that they require resetting temperature to neutral, the physiological zero point discussed in Chapter 5, before sending another signal. This raises some questions as to how useful thermal feedback can be if it requires resetting temperature each time a new signal is sent. Since this process of resetting can take tens of seconds to accomplish, it further raises the issue of latency in thermal feedback design. Therefore, a new feedback methodology needed to be investigated to mitigate these concerns. This demanded an alternative method of signalling temperature changes instead of Discrete Signalling, to provide more *continuous* and constant information that is not distracting to the user.

The idea of *continuous* thermal feedback had been suggested by some researchers, but none had tested the idea in situations with controlled studies. Halvey *et al.* (2013) suggested continuous or 'dynamic' interactions with thermal stimuli and experimented with different starting points with users. They found that the starting point did not significantly affect comfort but did affect the perceived intensity. They suggested that a minimum of 3°C changes should be used for continuous interactions, and that stimuli should begin with a starting point of 32°C ± 4°C to maximise the intensity.

Salminen *et al.* (2011; 2013) examined several ways of signalling thermal feedback to the user. One method, which they called 'dynamic' feedback, was similar to the Discrete Signalling used in Chapter 5, where users placed their hand on a stimulator as it warmed or cooled from a neutral point. The authors also explored 'pre-adjusted' feedback, a more adaptive feedback where the stimulator was already set at the target temperature before the user was allowed to touch the stimulator. Afterwards, the device would then adapt the stimulator to maintain the veridical temperature as heat was transferred from the user to the device. Their work will be discussed more in Chapter 7, as they mainly collected information of how users emotionally rated the stimuli rather than the perceived intensities.

Thus, a gap remains in the literature: *Can continuous feedback provide reliable information from a thermal display*? This chapter will investigate this question by proposing a controlled, laboratory-based study to examine different methods of providing continuous thermal feedback. This chapter proposes that such continuous interactions can be used to guide navigation: in the study that will be discussed for the remainder of this chapter, subjects used the feedback provided by the TAD to navigate 2-dimensional mazes displayed on a screen. Both quantitative and qualitative data were collected to evaluate the effectiveness of the continuous thermal feedback to guide the users.

6.2 Experiment Design

In the children's game 'Hot-and-Cold', a temperature metaphor is used to guide players towards the location of a hidden object. The hypothesis tested in this study was that actual temperature changes on the skin could provide similar proximity information in a navigation task: increasing heat could indicate getting closer to a goal; conversely, increasing cold could let a user know that they are moving further away. To test this hypothesis, a 2D maze navigation task was designed and, in a controlled experiment, user navigation performance with and without thermal feedback was compared.

A player (the participant playing the game) was represented by a red dot in a 2D maze displayed on a computer display (Figure 6.1). In the game task, the player controlled their position by moving from one path block to an adjacent one, using the keyboard arrow keys. Participants were instructed to make as few moves as possible and to try and find the goal within a time limit of ten minutes. The goal, represented by a green dot on the screen, was hidden somewhere inside the maze, and only the local area around the player's current position was visible: the rest of the maze was blacked out. Figure 6.1 shows a 3x3 block section of a maze visible to the user on screen, with the surrounding area left semi-transparent in the image—rather than blacked out—to show the maze.

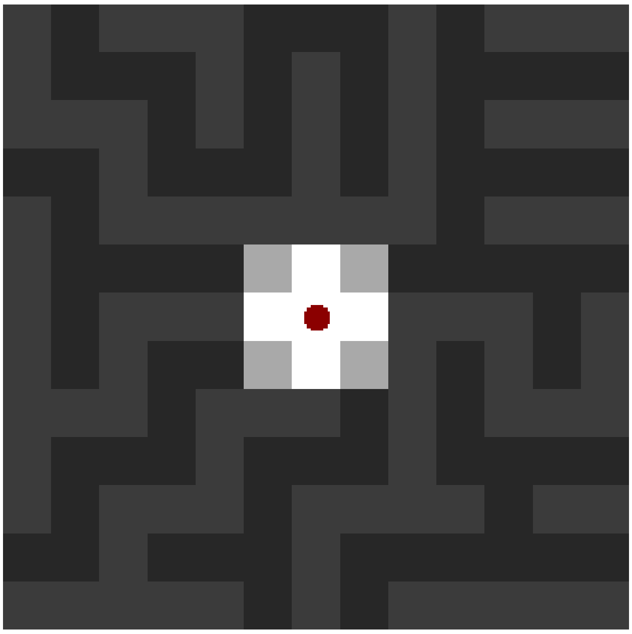


Figure 6.1: Participants (represented by a red dot) could only see the maze in the immediate area around their current position and the rest of the maze was blacked out (left semi-transparent in this image to show the underlying maze design).

Several maze designs were explored to determine an appropriate size and complexity for the study: the height and width of the mazes and the number of moves needed to go directly from start to finish. Four mazes of 40 x 40 units, as shown in Figure 6.2, were chosen, with their path solutions highlighted in blue. Each block is a single move up, down, left or right. These dimensions were chosen based on the average length of time it took pilot participants (to be discussed in Section 6.3) to complete a maze without thermal feedback (317.8 seconds, σ = 167.9 seconds). This meant participants were able to complete four mazes within an hour session. Four mazes were designed by hand, assisted by an on-line generator (http://www.billsgames.com/mazegenerator). Each maze design contained no loops, meaning there was only one solution to the goal and that the paths did not converge after branching. All mazes had a single, optimal path from the start point to the goal (global shortest path) of 245 moves.

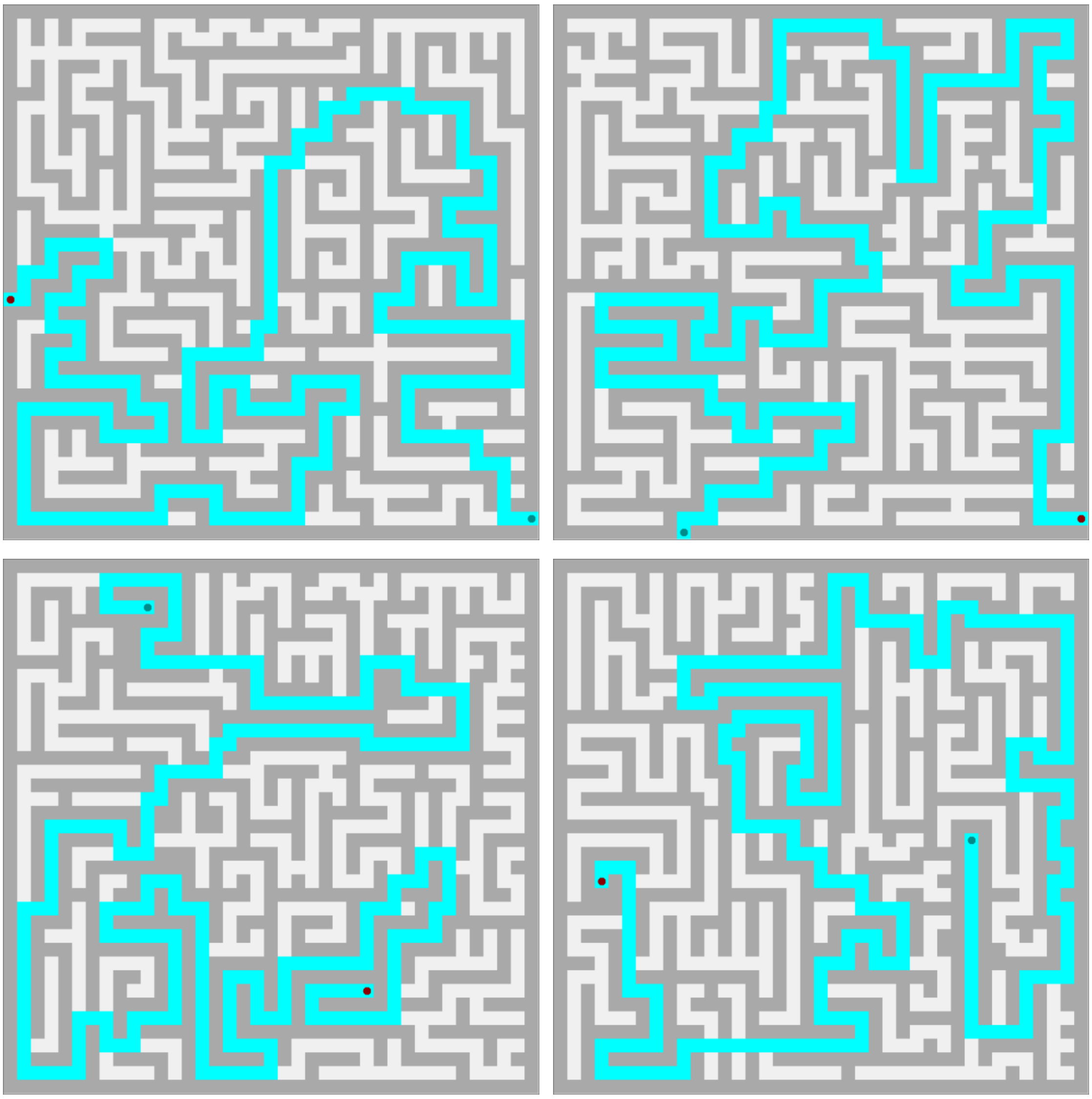


Figure 6.2: Maze 1-4 designs and solutions (denoted by the light blue path). The red dot shows the player's start position and the green dot shows the goal.

6.3 Pilot Studies and Feedback Design

To design effective thermal feedback for maze navigation, different techniques for correlating temperature changes with a participant's location relative to the goal were explored in pilot studies. This thesis experimented with both (1) what was being signalled and (2) how it was mapped to temperature changes. This was done across two pilot studies, each with three participants. This allowed fast prototyping of ideas which could be quickly changed and re-tested again.

6.3.1 Pilot 1: Testing Thermal Resolutions

As discussed in the last chapter (Section 5.2.2), Wilson *et al.* (2015) used a temperature range of 22°C to 38°C, a safe and comfortable zone of temperatures appropriate for thermal feedback. The main experiment in Chapter 5 (Section 5.2) used a smaller range of 29°C to 35°C. Using all three stimulators set to the same temperature, known as the Amplification Method in the last chapter (Section 5.2.2.2), resulted in the best thermal state detections. As such, the Amplification Method was reconsidered to minimize the time taken for the TECs to reach the target temperatures for this study, using the same range of 29°C to 35°C, with 32°C designated as the neutral temperature, the same neutral temperature used in the previous chapter's main experiment (Section 5.2).

This study began trialling the mapping mechanism of assigning thermal feedback to player behaviour in the mazes by using the seven thermal states from Section 5.2.2.2. These thermal states were mapped to the distance the player was from the *global shortest path*, the optimal path between the player's starting position in the maze and the end goal's position. This global shortest path was calculated once at the start of the game using a breadth-first search algorithm to solve the maze (mazes were checked beforehand when they were designed to ensure they were solvable). This path is illustrated in Figure 6.3 below as a blue path. Participants were continuously provided with the 'Warmest' thermal state (35°C) when they remained on this path, to indicate positive, or desired behaviour.

However, to indicate undesirable behaviour once the player left this path, negative feedback using cool temperatures was introduced to inform the player to alter their movements. This feedback was dependent on the *local shortest path*, the distance the player was from nearest point on the global shortest path. Figure 6.3 illustrates this as the pink path. In this case, the player deviated from the global shortest path by 20 steps. The negative thermal feedback functioned by mapping the magnitude of the deviation to one of the seven thermal states ('Coolest', 'Cooler', 'Cool', 'Neutral', 'Warm', 'Warmer', and 'Warmest'). For example, when on the global shortest path, the user deviated 0 steps, which was mapped to the 'Warmest' state. When they moved off the path, the number of steps deviating from global shortest path determined which of the other six states the TAD would be set to. This would continue as long as the player kept deviating from the global shortest path, until the player deviated enough to receive the ‘Coolest’ thermal state. However, if the player altered their direction and began to return to the global shortest path, the number of steps would begin to decrease, and the feedback would become warmer until the player was once again on the global shortest path.

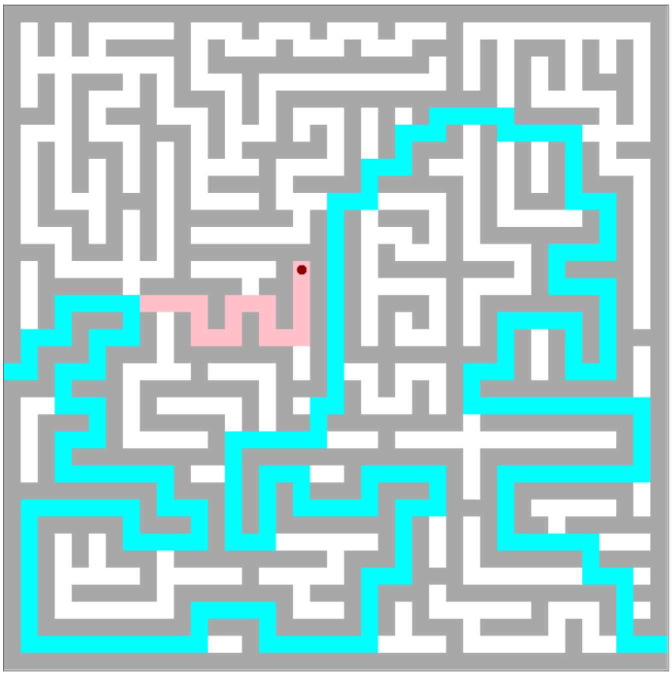


Figure 6.3: Highlighting the global shortest path (blue) and local shortest path (pink).

To map the length of the player’s deviation, the local shortest path, to the appropriate thermal state, scale factors were introduced by multiplying the length of the current local shortest path by a constant scale factor. The value produced by this calculation fell into one of seven ranges of values, each of which corresponded to one of the seven thermal states. Three scale factors were used: 1x, 2x, and 3x. A fourth, 0x scale factor was also used for the control condition of not feeling anything at all. In this case, the temperature remained neutral. These scale factors determined the resolution of the thermal feedback, or *thermal resolution,* which was the interval number of moves needed to change to the next thermal state. For example, the 3x scale changed the thermal state in intervals of three moves: if the user moved three steps away from the global shortest path, they would feel the ‘Warmer’ state, and after six moves they would feel the ‘Warm’ state, etc.

To examine the effectiveness of thermal resolution on how well participants could find the maze goal, a pilot study was run using three participants. The effectiveness of thermal resolution was judged by measuring the number of moves made and the time taken for the participants to reach the goal for each maze. It was hypothesised that the control condition (where temperature did not change) would result in taking the longest times to complete the mazes and the most number of moves. In addition, the larger the thermal resolution (2x and 3x), the longer the participants were expected to complete each maze and were expected to take more moves than the shorter thermal resolution (1x). For this pilot study, there was no time limit given to reach the goal. Though maze order was randomized, the order of scale factors was always the same for each subject in that they received the control condition first, followed by the 1x, 2x, and finally, 3x scale factors. Participants were instructed to always wear the device, including for the control condition where the neutral thermal state was always presented, regardless of the participant's behaviour within the mazes. The results of the pilot study are summarised in Table 6.1, and the raw data can be referred to in Appendix E.1.

Scale Factor	Participant 1			Participant 2			Participant 3		
	Maze	**Time**	**Moves**	**Maze**	**Time**	**Moves**	**Maze**	**Time**	**Moves**
X0	3	460.4	1220	1	533.9	2204	4	1134.4	3530
x1	4	308.6	572	2	124.8	473	1	1054.7	658
x2	1	2631.9	6572	3	120.2	512	2	635.4	677
x3	2	NA	NA	4	171.6	708	3	NA	NA

Table 6.1: First pilot results, showing the time in seconds and number of moves made by each of the three participants for the four mazes. Mazes were presented in random order, and the order for each participant is shown under the 'Maze' columns. The mazes are ordered by thermal resolution, which is shown in the 'Scale Factor' column.

Observations of this data revealed some unexpected outcomes. Participant 1 (P1) had the best performance in terms of both time and moves made when the scale factor was kept to a minimum, though the 2x scale factor resulted in worse performance than the control condition. P1 also encountered a technical glitch on the last maze and thus was not able to complete it. The second participant's (P2) results were in line with expected observations: without temperature feedback, P2 took the longest time to complete the maze given and made the most moves compared to the conditions with 1x, 2x, and 3x scale factors. The 1x scale factor produced the best results in terms of number of moves made, with 2x and 3x thermal resolutions providing progressively worse results. Participant 3 (P3)'s results revealed difficulty navigating both the control condition and the 1x scale factor condition, as they required over 10 minutes to complete each maze, though they improved on the subsequent 2x trial. Unfortunately, they voluntarily withdrew from the last maze as they could not complete it due to an error in the software. P3 also reported not trusting the temperature initially, as it took them a while to get used to the feedback's mechanism.

From observations of the participants' behaviour, it was clear that thermal resolutions greater than 1x were hard to interpret and trust. These often resulted in participants getting stuck in regions of the mazes, causing them to traverse over the same area instead of relying on the feedback to guide them back towards the global shortest path. Given the difficulties participants had with this method of providing thermal navigation cues, changes were made to the thermal feedback to see if a more effective way of guiding navigation could be found.

6.3.2 Pilot 2: Testing Local Shortest Path

Based on the first pilot results, several alterations were made to simplify the thermal feedback. First, the 2x and 3x scale factors were removed, as it was hypothesised that having longer scale factors would reduce player performance in comparison to the 1x feedback condition. Longer latencies appeared to confuse 2/3 of the players in the first pilot to the point where no feedback resulted in better performances for them. Additionally, mapping each player's movement to only an adjacent thermal state, which is what the 1x scale factor signified, kept the study design simple, as this feedback was only compared against the control condition (no feedback) for the second pilot.

The second change from the first pilot was that players did not wear the device for the control condition. This was done to mitigate any concern of effects caused from simply wearing the device. Wearing the device may had caused some confusion as some users in Pilot 1 reported that they felt a temperature, since it was kept at neutral and the fans ran, and thus believed they were given feedback. Another reason for removal of the device for the control condition was to reduce unnecessary fatigue of the users during the study, as they needed to keep their arm outstretched for up to 10 minutes while wearing the TAD.

The third change was that players were given a time limit of 10 minutes to complete each maze. If they failed to complete the maze in the time limit, their time was recorded as 600 seconds and they moved on to the next maze. The four mazes used in the second pilot study were presented in a random order unique to each player. However, the ordering for the control and experimental conditions were the same for all players, in that the first two mazes were presented wearing the TAD, and the last two mazes were presented without the player wearing the TAD to guide them.

The results of the second pilot study are shown in Table 6.2, and the raw data can be referred to in Appendix E.2. Three new participants were recruited to participate. Participant 1 could not complete the second and third mazes within 10 minutes, however, they were able the first maze as well as the fourth, the latter of which was provided with thermal feedback. Participant 2's results were in line with the expectation that having thermal feedback would reduce the completion time and moves made vs the control condition where they did not wear the TAD. Participant 3's results, however, were the opposite: they performed worse with thermal feedback than when they did not wear the TAD device, and they also failed to complete one of the mazes using thermal feedback within the 10 minute time limit.

TAD On?	**Participant 1**			**Participant 2**			**Participant 3**		
	Maze	**Time**	**Moves**	**Maze**	**Time**	**Moves**	**Maze**	**Time**	**Moves**
No	2	418.3	1510	3	167.3	696	2	196	636
No	1	600.0	2069	1	200.7	852	3	324.4	1130
Yes	4	600.0	2219	4	156.8	538	1	600.0	1676
Yes	3	281.2	732	2	106.5	398	4	348	976

Table 6.2: Second pilot results. Only two conditions were tested: the control condition where the player did not wear the TAD, and the experimental condition, where they did wear the TAD. This is shown in the 'TAD On?' column. The 'Time' column shows the length of time in seconds each player took to complete each maze. 600.0 seconds signified that they ran out of time. The 'Moves' column shows the number of steps the player took reaching the goal or time limit.

The results suggests that Participants 1 and 3 may had been confused by the feedback presented. This may have been due to the mapping of the thermal states to the behaviour of the players, as the changes were dependent on how quick the players traversed the mazes when they deviated from the global shortest path. In such cases, the changes going from one state to the next may had been too perceptually subtle to be effective. There were some instances where players would often become stuck in the same corner of the map. A major issue though was that once they returned to the path, they sometimes headed back towards the start rather than towards the goal if they lost orientation, since the feedback only indicated how far they had strayed from the path rather than giving them directional information about the location of the goal. In summary, the participants found the subtle temperature changes and slow rate of change confusing, and their performance was not improved. In some cases, performance was worse than if they had not worn the TAD at all.

The idea of using thermal feedback to indicate deviation using a local shortest path was discarded, as this was too complex for players to understand. Instead, the feedback was redesigned to indicate direction by using only two temperatures. One was the 'Warmest' thermal state (35°C), which was used to indicate that the player was on the *current shortest path*. The current shortest path was the optimal maze solution to the goal calculated from the player's current position in the maze each time they took a step. The other temperature used was the 'Coolest' thermal state (29°C), for when they left the current shortest path.

Previous research had investigated a similar manner of providing feedback to successfully guide a complex real-time behaviour using vibrotactile feedback (VTF) (van der Linden *et al.*, 2011). Specifically, the authors used the bowing action of children learning the violin to map their actions to vibration motors worn on the upper body. When their bow left the desired trajectory, these motors would then 'buzz' the subjects to correct their posture. A key difference with their work is that their subjects relied on the absence or presence of feedback to guide their behaviour (the vibration motors used in their study were set to either on or off), rather than a modality like temperature which can take on a continuous range of temperature values from cold to hot. Using their idea, the thermal feedback was redesigned so that if the player remained on the path, the feedback remained very warm. A change in temperature only occurred if the player had left the path to indicate a correction needed to be made.

The new hypothesis was that this could allow players to finish the mazes faster and with less moves than without feedback. As a reminder, the latency is a crucial issue as the TAD requires 6 seconds to cool from 35°C to 29°C, given that the maximum rate of change is only 1°C/sec. The study would therefore determine, even with the high latency, and additionally, the lack of re-adaptation used in discrete signalling and ambient style feedback, that continuous signalling of temperature changes could improve navigation in a controlled experiment using 2D mazes.

6.4 Main Experiment

6.4.1 Procedure

The main experiment used a within-subjects design. Unlike the previous two pilot studies, the order that participants experienced the control condition and the thermal feedback conditions was counterbalanced. 12 participants, 9 males and 3 females, all students in the engineering school of City, University of London (mean age 31.7 years, σ = 6.3 years), were split into two groups. Group 1 wore the device for the first two mazes (feedback condition) and then removed it for the other two (the control condition). Group 2 did not wear the device for the first two mazes and then wore it for the last two. In the control condition, a participant had to reach the goal location without any guidance, and thus had to rely on their memory and chance to choose the correct path. In the feedback condition, they were provided with thermal cues that informed them whether they were on (very warm) or off (very cool) the current shortest path. Mazes were completed in a pre-determined, randomized order, unique to each participant. Subjects were given the participant information sheet shown in Appendix H.3 in advance, and they signed the consent form in Appendix H.4 before they were allowed to participate.

Before navigating any mazes, participants were given oral and written instructions (Appendix G.13) to ensure that they understood what the thermal feedback signified and how the controls worked. Participants wore earplugs due to the audible sounds from the inductors, as confirmed in the pilots. Before each of the two mazes in the feedback condition started, their skin was re-adapted to a neutral temperature (32°C). However, re-adaptation only occurred before participants started each maze and not while they were navigating the maze.

The time taken to reach the goal and the number of moves made were recorded for each maze. If a participant did not complete the maze within the time limit, they were 'timed out' and a cap time of 10 minutes (600 seconds) was used. Every move was logged so that heat maps could be generated of participants' behaviour with and without thermal feedback. After the four mazes were completed, each participant was interviewed about their experience with the thermal feedback.

6.4.2 Results

The raw data can be found in Appendix E.3. The mean time to complete mazes with thermal feedback was 249.0 seconds (σ = 115.6 seconds); in the control condition, it was 358.5 seconds, (σ = 165.3 seconds). The mean number of moves taken with feedback was 593.5 moves (σ = 321.4 moves); the control condition mean was 1396 moves (σ = 577.7 moves). On average, participants made over twice as many moves without feedback, and despite the latency, they performed about 30% faster when they had temperature to guide them. Each maze required 245 moves to complete, so no thermal feedback guidance resulted in about 5.7x as many moves to reach the goal, compared with 2.4x as many moves with the feedback condition. Participants tended to slow down when using thermal cues: on average, 2.4 moves per second (mps) were made in the feedback case, whereas 3.9 mps were made in the control condition.

As the data were non-normal, a Mann-Whitney non-parametric test was used to compare performance in the two conditions. This produced $U_a = 413.5$, $z = -2.58$, $p = 0.005$ (one tailed) when comparing times. Applying the same test to the number of turns taken produced $U_a = 537$, $z = -5.12$, $p < 0.001$ (one tailed). Thermal feedback, while of relatively long latency, strongly reduced the maze solution time. The low time-out rate across the two conditions did not permit a valid statistical comparison, but the relative counts of 5 (control) versus 1 (thermal) were consistent with the improved performance of using thermal feedback.

In interviews, every participant reported that they understood the thermal feedback and found it easier to find the target with the temperature cues: "the temperature feedback helped me to predict where the target was" [Participant 11]; "it's like a guide to the right path" [Participant 6]. All participants reported that the temperatures were comfortable, Participant 12 said “it was at a level that lets you just feel it”. Participants used temperature changes, rather than the absence or presence of feedback, to guide their navigation: Participant 3 reported “it’s not too hot or cold but there’s enough of a difference to tell them apart”. The specific responses per participant were recorded in Appendix E.4.

Some participants emphasised it had taken time to learn the feedback. Participant 5 said “once I got used to it, I went a bit slower”. There is statistical evidence of a learning effect between the first and second mazes. Discarding all pairs that included an unsuccessful attempt (timed out), the average time using thermal feedback fell from 265.2 seconds (σ = 55.4 seconds) for the first maze, to 205 seconds (σ = 62.9 seconds) for the second maze; in the control condition, performance actually slowed from 237.9 seconds (σ = 32.1 seconds) for the first maze, to 281.6 seconds (σ = 167.6 seconds) for the second maze. To test the significance of this, pairwise comparisons were made between the first and second mazes for both the feedback and control conditions (again, these are only with the trials that did not timeout). The first and second maze time data, with feedback, were normally distributed ($p = 0.83$, $W = 0.96$) so the two maze treatments were compared using a two-tailed paired sample t-test. This resulted in $p = 0.025$ (t-crit = 2.57), meaning that there was a significant improvement in the time taken to complete the second maze after the subject completed the first maze. Next, the control condition’s first and second maze time data were compared. The data was not normally distributed ($p = 0.004$, $W = 0.7$), so a Wilcoxon signed rank test for paired samples was used instead of a t-test. This resulted in $p = 0.5$ (exact), meaning the difference in times between the first two mazes for the control condition was not significant. Overall, there appeared to be a learning effect with the thermal feedback, as participants took less time to complete the second maze than the first maze when they had the feedback.

Figure 6.4 shows ‘heat maps’ for Maze #2: the start position is bottom right and the target is bottom left. The left image shows Participant 6’s moves without thermal feedback, using a strategy they described as, “just try all available paths – some of the paths, I visited them 3 or 4 times”. Seven participants reported using this ‘exploration’ strategy in the control condition. Two subjects reported that they did this systematically (e.g. always turning the same direction at a junction), while others admitted they were more random. Three participants said they tried to memorise the maze, but Participant 5 admitted, "I tried to remember the junctions but it was too difficult". Figure 6.4 (middle) shows Participant 4 navigating with thermal feedback, which could be compared to the global shortest path shown in blue (right).

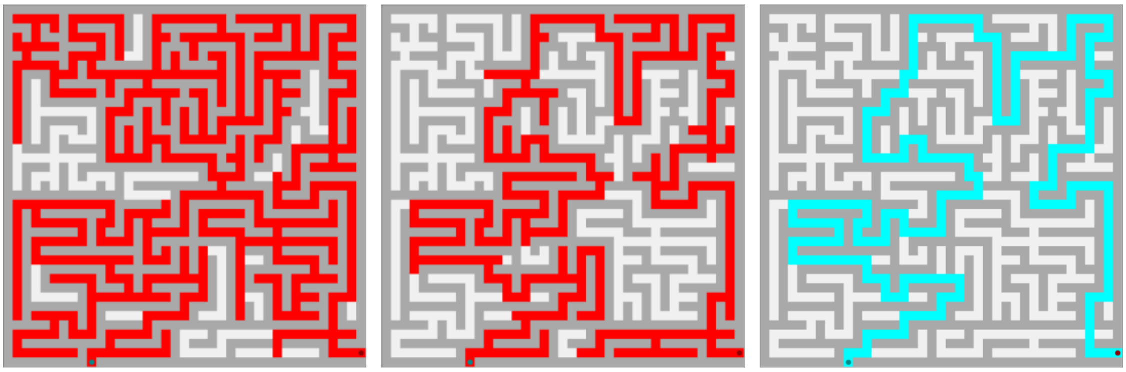


Figure 6.4: Heat maps for Maze #2. Left - Participant 6's moves without thermal feedback; Middle - Participant 4's moves with thermal feedback; Right - the global shortest path from start to end.

Thermal feedback reduced exploration of the maze by indicating when participants left the path and thereby reduced their exploration of blind alleys. However, some participants still turned in the wrong direction at some junctions and took some time to return to the correct path. Participant 8 said "sometimes I couldn't distinguish the difference so I had to continue further to understand is it cold or warm". Participants had to learn to adapt to the latency of the feedback by slowing movements and seeing how the temperature changed when they took a certain path. Participant 10 expressed frustration that they "had to keep turning around" and expressed a preference for navigation cues that more actively guided them, rather than feedback after the path was left. Participant 1 was more comfortable with the ambient feedback, saying "[you] can't always rely just on temperature – it's more of a complementary hint – I still need to trace the maze in my head".

More detailed heat maps were generated to highlight areas of the maps participants frequently visited. An example of this for Maze #4 is shown in Figure 6.5. Areas of the map in darker red indicate paths the participant visited the most frequently. Areas of the map in lighter shades of red indicate paths the participant visited less frequently or only once. Paths appearing as white indicate that the participant did not visit them at all. The case where no feedback was presented features darker red paths than the feedback case, indicating that participants revisited many areas of the maze repeatedly. This is far less pronounced when the participant had feedback. The solutions for the mazes, and the subjects' respective heat maps, can be found in Appendix E.5.

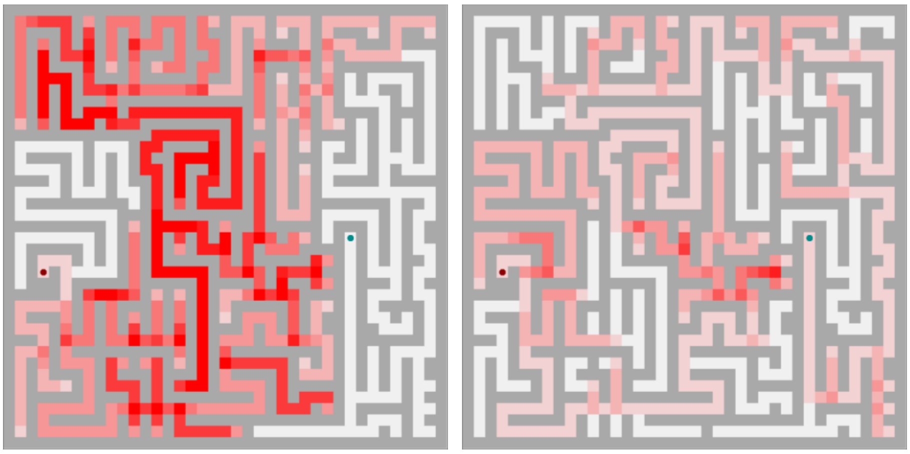


Figure 6.5: Detailed heat maps. Left - Without feedback. Right - With feedback.

Finally, participants were asked if they felt the thermal feedback could be useful for pedestrian navigation. This could be a potential activity that could be leveraged by using slow feedback for guiding navigation, as the issue of latency could be mitigated due to the slower walking speed of pedestrians using the system. All subjects in the study agreed that the Heat-Nav system could be useful for navigating walking spaces in the real world, though the subtlety of the feedback gave rise to differing opinions on how this could work. Three participants suggested that VTF cues might be more effective than thermal cues and one participant stated that, "with this system you will be able to look around" [Participant 3]. Another participant stated that it would be better for the system to guide them in the right direction, since they felt it would be annoying if they had to keep turning around. Two participants said the device would have to be smaller to be practical.

6.4.3 Discussion

Given the high latency of the feedback provided to participants, how were they able to use temperature information to improve navigation? First, the feedback was simple to understand, using a warm temperature to inform participants that they were on the right path and a decrease in temperature only when they left the shortest local path. Second, although it took six seconds for the TAD to change between the warmest and the coolest temperatures, most participants detected the temperature changes before the extremes were reached. Participants all found the feedback useful, but they needed to initially learn how to interpret the temperature changes. Future work could explore how the TAD can provide more complex thermal signals to indicate direction as well as the distance from the optimal path.

The results are particularly relevant for the design of mobile interfaces for pedestrian navigation. Continuous thermal feedback could provide a more ambient manner of suggesting routes to pedestrians for exploration of urban areas than what VTF or glancing at a visual display could provide. For instance, it could indicate both a route to follow and the presence of points of interest while still allowing tourists to focus on their environment, rather than their mobile phones or watches, and also allow the tourist to make serendipitous discoveries along the route (Traunmueller and Fatah gen Schieck, 2013). Given the slower speed that people walk compared to the rate at which participants could move around the maze, the high latency of the feedback may be less of an issue for real-world pedestrian navigation.

Temperature could also potentially provide anticipatory navigational cues for drivers. Satellite navigation (satnav) communication gives a driver a shortest route that will get from them from point A to point B. However, the driver must a keep a conscious auditory channel open to listen to the satnav as well keeping an eye out for visual distractions while glancing at the map when making a turn. Some drivers' seats and steering wheels already have heating elements built in, although it's not immediately clear whether they would be suitable for communicating salient temperature cues. Future work could investigate whether these findings will transfer to noisy and challenging real world environments (Wilson *et al.*, 2011).

More generally, the interview data collected suggests the high potential of using temperature to convey information that is ambient. In other words, the feedback provides a sensory channel that allows information encoded as thermal cues to stay within the periphery of a users' attention and only shifts to their centre of attention when necessary. Whether thermal cues are less distracting than other feedback modalities will need verification, but participants reported barely feeling them.

6.5 Conclusion

Can continuous feedback provide reliable information from a thermal display? The results of this chapter supports the view that it can. The controlled study in this chapter demonstrated the effectiveness of continuous thermal feedback for providing navigational information that was reliable enough to guide the players to the goals. Continuous Signalling differs from Discrete Signalling in that thermal signals can be sent without requiring the system to pause to re-adapt the skin temperature. In contrast to previous work that only demonstrated the *potential* of using temperature to guide navigation, this chapter provided the first experimental evaluation of simple thermal cues for guiding navigation in a 2D maze. Given the latency of the thermal feedback and lack of re-adaptation between signals, it was not clear whether Continuous Signalling would be effective, but the results showed that the thermal feedback enhanced navigation performance of the 2D maze task in terms of time completion and moves made, compared to when there was no thermal feedback given.

So far, various thermal signalling methods have been proposed and tested with the TAD in this thesis. However, a question remains as what kind of qualities can the TAD communicate? The next chapter will present a study that explored whether the TAD could augment the emotional content of social media text messages. This study was similar in scope to the previous work with smell (Chapter 2) and vibrotactile feedback (Chapter 3) presented in the first half of this thesis, with the overarching aim of utilising sensory-based implementations to communicate information, like emotion, in interactions.

Chapter 7

Augmenting Text Messages with the Thermal Array Display

This thesis had examined the effectiveness of utilizing a multi-sensory implementations to communicate information, like emotion. There is the opportunity that temperature signals perceived on the skin using the TAD could be used to convey or augment emotional information, similar to how Chapter 2 investigated the usage of a mobile smell display (Scentee) and Chapter 3 investigated the Ring*U implementation. However, participants struggled with interpreting the emotions conveyed by the messages when they used the Scentee (Section 2.6.4), and the Ring*U was found to neutralise emotions instead (Section 3.6.4). The later effect had been noted by Suhonen *et al.*, (2012): they reported instances where vibrotactile feedback (VTF), such as the TCONs presented by the Ring*U, could be misunderstood emotionally. Alternatively, they claimed that temperature feedback could be used to communicate similar emotional meanings with warmth and coolness, thanks to temperature's bi-directional (warm and cool, not just intensity) and continuous nature (it can take on a fine degree of values), which is an advantage over VTF.

Furthermore, the results of Chapter 5 endorsed the usage of spatial summation as a parameter in thermal feedback design. This is a different approach than what most previous literature discussed so far (Section 4.3.2.1) had used to convey emotion with temperature, as these examples either used a single stimulator or a single temperature state to convey emotion in subjects. It is unclear from the results of these works if the recipient users could appreciate different scales of temperature and how they would map to emotions. A further literature review is therefore necessary to investigate how work in HCI has examined the mapping of temperature perception to emotion. Based on this literature review, this chapter will then present a new study which will investigate the research question: *Can a wearable array of thermal stimulators augment the emotional content of social media messages?*

This chapter overview is as follows. First, controlled studies in HCI which had used thermal states to communicate emotion, as well as those which had examined key parameters of temperature, will be examined (Section 7.1). This chapter will then conduct a series of pilot studies to select the media (text messages) and temperatures based on how they conveyed emotion to users alone (Section 7.2). The final section of this chapter (Section 7.3) will then combine the temperature states and messages selected from the two pilot studies to examine the effect of temperature on augmenting the original perceived emotion of the text messages.

There are three contributions in this chapter. First, temperature displayed from the TAD device was able to elicit emotional arousal, and warm temperatures were perceived as more arousing than cool temperatures when augmenting texts. Second, for valence, the message content was highly effective, and temperature was ineffective, regardless of the thermal state used. Third, while text messages dominated the valence in the absence of a context for interpreting the temperature changes, the TAD consistently augmented the emotional arousal communicated by the text messages, especially those that were rated emotionally neutral. These results demonstrate that a wearable array of thermal stimulators can augment the arousal content of social media messages, but not their valence.

7.1 Literature Review

Giving someone the cold shoulder, and likewise giving them a warm welcome, are popular metaphors used for communicating the abstract concepts of antipathy and affection that humans can harbour toward each other. IJzerman and Semin (2009) argued that there exists a “systemic inter-dependence among language, perception, and social proximity" (pg. 1214), and that more concrete experiences, [such as sensing temperature], could ground these abstract concepts when they are co-experienced together. Thus, temperature may be able to augment the perceived emotions if users can co-experience the events that triggered the emotions along with temperature perceptions.

The link with temperature perception and emotion need not be explained with such abstract connotations however, as the subjective perception of social interactions that lead to emotional reactions have been linked to physical perceptions of temperature itself. Williams and Bargh (2008) described this phenomena in an experiment in which participants were asked to hold warm and cold beverages before meeting a stranger. This technique, called *priming*, exposed subjects to warm and cool temperature stimuli in order to influence their responses to their encounter with the stranger. Williams and Bargh observed that participants who were primed with the warm beverages perceived the stranger more positively than subjects who held cold beverages. They referred to this idea of using temperature to influence, or prime, a person's first impression of others as *Psychological Warmth*.

Similar experiments have demonstrated the effects of temperature stimuli on user perceptions of others, as well as the results of social activity on temperature itself. Warm stimuli can induce greater social proximity towards others, and warmer, ambient temperatures can enable humans to describe social events more concretely (IJzerman and Semin, 2009). Subsequently, cool temperatures can alternatively induce negative perceptions of social experiences, particularly, social exclusion, as the experience of being excluded can feel literally cold to humans (Zhong and Leonardelli, 2008). Zhong and Leonardelli's study, in which certain subjects excluded others in a social exercise, resulted in the excluded subjects giving lower estimates of room temperature and craving hotter foods during the exercise than the participants who were not excluded.

Temperature, like the sense of smell, is processed in the limbic system of the brain, along with human processing of emotion. This link has been showcased in medical literature which has utilized PET and fMRI imaging of brain scans (Craig *et al.*, 2000; Löchtefeld *et al.*, 2014). These scans demonstrated how areas of the brain within the limbic system became excited after stimulation had occurred with the patient using temperature. Intense thermal stimulation, for example, has been demonstrated to activate the anterior cingulate cortex of the brain, which also controls affective reactions (Craig, *et al.*, 1996). Cooling a patient's right hand linearly correlates with brain activity within the insular cortex, which regulates internal feelings such as panic, anxiety, sadness, and sexual arousal (Craig *et al*., 2000). Warm thermal stimulation, on the other hand, activates distributed regions of the brain that are associated with affective responses and processes, such as inner body feelings (Sung *et al.*, 2007). Using varying levels of heating and cooling thermal feedback could hence be used to excite regions of the brain in order to regulate underlining basic emotions and autonomic responses.

Section 4.3.2.1 presented some thermal display prototypes in previous work that were used to communicate emotion. These examples drew on the potential of using temperature cues to transmit states of emotion to recipient users in human-human communication, such as a sender's arousal state (Iwasaki *et al.*, 2010), remembrance for others (Fujita and Nishimoto, 2004), and social presence (Gooch and Watts, 2010). However, most of the literature discussed so far in this thesis had only focused on the exploration of temperature feedback, or the novelty of the form factors to present the thermal stimuli to users. These examples had not used carefully controlled lab studies to examine the role of temperature's effect on emotion thoroughly or to discover key parameters to elicit specific emotions.

Salminen *et al.* (2011) examined two methods for presenting thermal stimuli to subjects for invoking emotional responses: 'dynamic' and 'pre-adjusted' stimuli. In the dynamic method, participants were told to place their finger on a stimulator as it warmed or cooled 4°C from their original (neutral) skin temperature. In the pre-adjusted method, participants placed their finger on the stimulator, but only after it warmed or cooled 4°C from the neutral temperature. Participants then rated the stimulus, regardless of presentation method, using four subjective scales for pleasantness, approachability, arousal, and dominance. Additionally, the subject's physiological responses were recorded using skin conductance response sensors. In both methods, the warming up stimulus was rated as more arousing, more dominating, and more motivational than the neutral (no change) and the cool stimulus. Surprisingly, temperature did not affect ratings of pleasantness (valence) and acceptability in either method, though pre-adjusted stimuli were sensed as more arousing than those presented using the dynamic method. Thus, temperature appeared to invoke arousal in participants, especially when the stimulator had already been adjusted prior to skin contact.

Alternately, Lee and Lim (2010; 2012) utilized a method of allowing users to discover ways of utilising temperature to express themselves in real world situations. This method, which the authors referred to as 'experience prototyping', differed from controlled study methodologies which are better suited for uncovering techniques to control temperature or for understanding more fundamental characteristics of thermal sensations. An experience prototyping approach, on the other hand, allows the researcher to observe how participants can investigate the kinds of information that could be conveyed with heat like, in Lee and Lim's case, a wrist worn thermal device.

Lee and Lim conducted two studies with their experience prototyping approach. In their first study (Lee and Lim, 2010), they asked subjects (mothers and daughters in one group and colleagues in another group) to wear the device in the subjects' own living environment. Subjects were also instructed to log usage of the thermal device when they either sent or received thermal sensations to and from their family or colleagues. From this, Lee and Lim found that thermal feedback only appeared to have a meaning when it took place in a situational context. However, they discovered that thermal feedback could also offer a unique, emotional value that allowed for less obtrusive and more casual ways of communicating with others.

In their second study (Lee and Lim, 2012), Lee and Lim asked four groups of subjects, two families with children and two couples, to wear the devices in their daily lives and to use them for personal messaging. The subjects were also told to log their usage, including the context of the situations when they sent and received feedback to and from each other within their group. The authors found that temperature worked better on a more visceral, unconscious level than being a cognitive mediator for conveying clear information, due to subjects reporting great difficulty with understanding information communicated with temperature, as well as their family's/partner's intentions behind the thermal feedback. The usage of the thermal feedback also differed widely from group to group: some subjects used the devices hundreds of times in the same day, others only for unique purposes such as games. Lee and Lim argue that this is because humans have no legacy of communicating information with heat, and thus have no cultural conventions of informing others with temperature.

In contrast to Lee and Lim's work, Wilson *et al.* (2016) examined thermal responses on emotional valence and arousal using a more controlled study. Participants were instructed to place their palms on a thermal stimulator which presented temperature stimuli in the range of 22°C to 38°C for ten seconds. Subjects then had to select how the emotional content of the stimuli made them feel using two scales for rating both valence and arousal. When mapped to a circumplex emotional model, most of the stimuli were associated with low valence/high arousal and high valence/low arousal emotions, with some appearing in the high valence/high arousal quadrant in the circumplex model. No thermal stimuli, however, were associated with low valence/low arousal emotions. Wilson *et al.* concluded that temperature alone may only be able to communicate emotions within the two dominant quadrants observed, namely, pleasant/calm emotions or unpleasant/exciting emotions. They also observed that warm stimuli were usually perceived as pleasant, and cooling stimuli were usually perceived as unpleasant. As the rate of change or magnitude increased, so did the extent of how strongly subjects rated both the valence and arousal of the stimuli. Both parameters of rate of change and magnitude had the same effect on how the stimuli were rated.

Another method of examining thermal effect on emotion is how temperature can change the emotion of other modalities and media though augmentation, for example, the visual and audio content of images and movies. Hannah *et al*. (2011) used temperature to augment television content by heating up a remote device that users could hold during pleasant scenes. Similarly, the remote could also be cooled down for when the user encountered sad scenes. The authors proposed that information for detailing the cues of temperature presented using the remote could be embedded within the metadata of movie files for more practical applications. Another similar device was AmbiPad (Löchtefeld *et al*., 2014), which was an Android tablet modified with coloured lighting around the frame and TEC elements on the back. Together, these modalities were claimed to enhance the contents that appeared on the screen of the tablet when it played a 3D movie in a custom media player. However, both the remote device (Hannah *et al*., 2011) and AmbiPad were mainly developed for novelty of their form factors: the authors performed no significant studies in relating specific emotions with the stimuli that were presented to users.

Suhonen *et al.* (2012) investigated the use of temperature to augment conversational speech using a wrist worn device. They designed two identical devices, which were worn by pairs of participants for their study. During the study, the subjects were asked to talk about a range of topics, with a duration of five minutes, and then they completed a questionnaire at the end. Using an input device that could understand squeezing and stroking gestures with their hand, each subject could signal thermal and squeeze sensations to the receiver during the discussions. For instance, when they covered the device with their hand, the receiver would feel heat on their arm, and when the sender stroked their input device, the receiver would feel cold. Depending on how long the sender completed each of these actions determined the intensity of the thermal stimulation felt. Suhonen *et al.* found that warmth was typically used to reinforce agreement and was seen as 'positive', while cold was used to signal disagreement and was seen as 'negative'.

On the other hand, Halvey *et al.* (2012a) carried out a more robust study of using temperature to augment media contents, particularly the effect of temperature on subjective perceptions of images and music. In their first study, the authors selected images based on pre-rated valence and arousal ratings derived from the International Affective Picture System database (Lang, 2005). The images were then displayed to participants in combinations with thermal stimuli, which the subjects felt on their palm as they observed the images presented to them. The thermal stimuli consisted of 26°C (cold), 32°C (neutral), and 38°C (hot), and each was altered with either 1°C/sec (slow) or 3°C/sec (fast) rates of change. Subjects were then instructed to rate the combinations on two, 9-point Likert scales for intensity (arousal) and pleasantness (valence). Halvey *et al.* found that images accompanied by warm stimuli usually resulted in higher valence and arousal ratings than images paired with cool stimuli. However, when compared to the neutral condition, where temperature did not change, the authors found that thermal stimuli, regardless of direction, reduced the valence of the images and increased their arousal, with some exceptions. Rate of change also had no significant effect on arousal, but faster rates of change were perceived as more pleasant.

In their second study, happy and sad music pieces, selected based on their volume and dynamics characteristics, were combined with even stronger thermal stimuli: 22°C (cold), 30°C (neutral), and 38°C (hot), which all used a 3°C/sec rate of change. In addition to using these thermal stimuli, which remained constant as the piece played, Halvey *et al*. (2012a) also explored a second method of presenting these thermal sensations to users. This consisted of 'pulsing' the temperature changes as the songs reached specific points, based on volume peaks and troughs. Like the previous study with images, participants were instructed to rate how they felt using two, 9-point scales for valence and arousal. The results of the second study revealed no significant differences between the two presentation methods and the control condition, where the stimulator remained at the neutral temperature. Qualitative data, however, revealed that the participants appreciated the pulsing method and found the constant thermal presentation method as unemotional as the control (neutral) condition. These results are preliminary and admittedly, more work is needed to demonstrate that temperature can or cannot be used to augment emotion with music: Akiyama *et al.* 2013's work, for instance, showed that music experience can be influenced with temperature.

Extending the work of Halvey *et al.* (2012a), Akazue *et al.* (2016) also focused their research on thermal augmentation of images to find which parameters of temperature could be used to augment the emotional ratings of pictures (also taken from the IAPS). Additionally, they performed a second study by experimenting with varying the timing of the presentation of the temperature stimuli: presenting stimuli before, during, or after the images were displayed to the user. In addition to rating valence and arousal, the authors also examined ratings of dominance, and all three emotional dimensions were rated with illustrated 9-point Likert scales, known as Self-Assessment Manikin Scales, or SAM (this rating method will be described in more detail in Section 7.2). The authors also examined ratings from an emotion wheel. In both studies, nine thermal stimuli were used: cooling stimuli (26°C and 29°C), neutral (32°C), and warming stimuli (35°C and 38°C). Both the cooling and warming stimuli were presented with 1°C/sec and 3°C/sec rates of change.

Akazue *et al.* (2016) first examined temperature presented at the same time as the image, similar to the previous work of Halvey *et al.* (2012a). The results of their first study revealed no significant differences with direction of temperature as a parameter (whether the stimulus was hot or cold) and ratings of valence, domination, and emotions selected on the emotion wheel. However, warm temperatures significantly increased arousal and cool temperatures decreased arousal. Stimuli intensity did not significantly affect valence, but did impact ratings of arousal, domination, and the emotion wheel. Finally, rate of change had no significant effect on valence, arousal, domination, and the emotion wheel. Thus, the authors concluded that, when examining the parameters of temperature, both direction and intensity could affect arousal significantly, but not valence.

When examining the effect on images, however, Akazue *et al.* found a significant difference in all four dependent variables (valence, arousal, dominance, and the emotion wheel), when calculating differences between the original emotional ratings of the images and the ratings after they were thermally augmented. In particular with valence, the authors claimed that low valence images could be made more pleasant by augmenting them with thermal stimuli and high valence images could be made less pleasant by presenting them with thermal stimuli. Thermal stimuli also increased arousal for both low arousal and neutral images and reduced arousal in images that were rated originally as highly arousing. Additional qualitative results revealed that thermally augmented images felt more pleasant than those presented without thermal augmentation. The authors noted that this preference may have been caused by the content of the images, as some subjects felt danger from the unpleasant images, preferring the comfort that warmer temperatures provided to sooth them.

In their second study, Akazue *et al.* (2016) examined the effect of presentation timing of thermal stimuli on the same images. They examined four different presentation methods: before the image was presented, after the image was presented, during the image was presented but turned off after 3 seconds, and during the image was presented but turned on after 3 seconds (images were presented for a total of 6 seconds before being switched off). The authors used similar stimuli from the first study but only used a 3°C/sec rate of change for all of them. The results demonstrated that temperature stimulation increased valence in unpleasant and neutral images, and that thermal stimulation reduced the valence of pleasant images. However, no significant differences were found based on the presentation timing of the thermal stimuli in that they resulted in similar ratings of valence, arousal, domination, and emotion wheel selections. However, additional qualitative feedback was gathered which revealed that subjects reported feelings of anticipation with the pre-image presentation method. In general, participants believed that cool stimuli informed them that a pleasant image would be displayed and that warm stimuli signalled that the image would be unpleasant.

To the knowledge of this research, similar work with thermal feedback had not been performed to augment text messages. Thermal Hug Belt (Gooch and Watts, 2010), as discussed in Section 4.3.2.1, examined how temperature could mediate a sense of social presence when subjects used thermal stimulation 'hugs' in instant messenger chats. However, the authors did not examine how temperature could elevate or decrease their valence and arousal, as the text used was not controlled nor emotional assessed using these two dimensions of emotion.

There does exist research, on the other hand, which has examined the emotional content of text messages sent on social media alone. Gill *et al*. (2008) undertook a study in which participants were asked to rate short and long text excerpts from blogs posted online by using an emotion wheel according to "how they perceive the author's emotions" (pg. 1123). The results demonstrated that expert and naïve users could rate blog text messages similarly with each other, and that strong agreement existed for longer texts, especially those that were joyful, disgusting, angry, or signalled anticipation. As such, it may be permissible to find corpuses of pre-rated text messages, similar to the images rated in the IAPS used by Halvey *et al.* (2012a) and Akazue *et al.* (2016), which were pre-rated by valence and arousal (unlike the messages from the text corpus used in Chapters 3 and 4 which were not pre-rated by valence and arousal). Such messages could be used to examine the effect of thermal stimuli on their valence and arousal content which may reveal more insight on how temperature could affect the emotional content of text messages. For instance, can temperatures result in the same effects on messages as they did for reducing and enhancing the valence and arousal of images, as reported by Halvey *et al.* (2012a) and Akazue *et al.* (2016)?

The remainder of this chapter will examine the hedonic characteristics of temperature in more detail. Particularly, it will study how temperature could be used as an augmenting modality for enhancing and reducing the valence and arousal of Facebook text messages. The experiment proposed in this chapter consists of two studies. First, a pilot study (Section 7.2) was conducted to select appropriate texts from an existing corpus of Facebook messages. In addition, the pilot also re-examined the thermal states from Section 5.2.2.2 in the previous chapter, using the Amplification

Method, to evaluate how participants emotionally perceived just the temperature states on their own. After the pilot study, the main study (Section 7.3) then evaluated combinations of the messages and thermal states in pairs to investigate whether temperature could augment the emotion communicated by the Facebook text messages.

7.2 Pilot Study

The pilot study was comprised of two parts and was conducted to verify the valence and arousal ratings of both messages and thermal stimuli appropriate for use in the main study. First, participants evaluated the emotional valence and arousal of text messages from an online corpus, which had already rated the text messages according to valence and arousal on 9-point scales (Preotiuc-Pietro *et al.*, 2016). These messages were retested to verify rating them using SAM scales (which was not used in the corpus). Next, participants rated the emotional valence and arousal of the thermal states selected from Section 5.2.2.2 using the Amplification Method. For both parts of the pilot, subjects rated the valence and arousal of the texts and thermal states using the SAM method, which will be discussed in Section 7.2.2 below.

7.2.1 Stimuli Selection

To study the emotional effect of temperature on text messages, it was first necessary to obtain messages that were pre-rated according valence and arousal ratings. As was previously discussed at the end of the last section, Gill *et al.*, (2008) demonstrated agreement between expert trained (research assistant) users and naïve (non-expert) users when rating the emotional content of blogs according to the Russell circumplex model (Russell, 1980). This model was also used previously in this thesis to analyse the emotion wheel ratings in the studies of Chapters 2 and 3 according to valence and arousal.

However, one of the concerns from the studies in Chapters 2 and 3 was the choice of messages and their translation from English into Japanese. Though the translations were accurate, the translated messages may had carried different connotations in Japanese due to cultural differences, especially since the same message may be used and interpreted differently by male and female participants. Thus, there was concern in how the non-native English speakers rated the British

English texts chosen from the corpus and how valid the responses were. Especially, since the messages were not given within a context, which is important for Japanese speakers. Though the same messages used in Chapter 2 from the corpus (Tagg, 2009) could had been reused and re-tested in this chapter, the outcome of the pilot study in Section 2.4.2 demonstrated the difficulty of obtaining messages that non-expert participants could strongly agree were pleasant and especially unpleasant.

To remedy this, new text messages were chosen from a new corpus and presented only in English. At first, crafting messages based on their emotional tone, or the content within the sentences' structure which would make them be read as pleasant or unpleasant, and arousing or calm, was considered. However, this would not provide a guarantee that participants would agree such messages were strongly emotional according to valence or arousal ratings, due to the experimenter's non-expertise in emotionally rating sentence content, as was done in Gill *et al.*'s research (2008). Instead, a previous study which rated Facebook posts by psychologically trained annotators was used (Preotiuc-Pietro *et al.*, 2016), which had already rated the valence and arousal of the posts. This made suitable text messages easier to identify and re-test for their validity with new subjects in the pilot.

Like the experiment with temperature and images described by Halvey *et al.* (2012a), messages, much like the images used in their study, were selected based around five emotional categories: high valence/high arousal, high valence/low arousal, low valence/high arousal, low valence/low arousal, and neutral valence/neutral arousal. As the Facebook post study by Preotiuc-Pietro *et al.* (2016) rated messages on two 9-point scales for valence and arousal by two expert reviewers, a criteria was established to select the messages in Preotiuc-Pietro *et al.*'s corpus to fit within these five categories. First, any message rated 1-3 on the 9-point scales by both subjects in their study was selected as a candidate for either low arousal or low valence. Messages which were rated 7-9 were candidates for high arousal or high valence. Lastly, messages that were rated 5 for both valence and arousal were candidates for the neutral stimulus. The reason the criteria included a range of 3 was that there were so few messages in their study which were rated 1 or 9 for either valence or arousal by both expert reviewers. Message inclusion was based on how extreme both scores were from each of their expert reviewers. For example, for the high valence/high arousal category, scores of [9, 9] were first included, then scores of [9, 8], [8, 8], [8, 7], and finally, [7, 7]. This selection process continued until 25 messages; five for each valence/arousal category, were selected.

Along with text messages, the thermal stimuli used in the experiment from Chapter 5 were selected for evaluation. As the Amplification Method provided the best feedback in terms of error rate and degree of error, its method of presentation was selected for the pilot. All seven of the thermal states used in the study in Section 5.2 were re-used: 'Coolest' (29°C), 'Cooler' (30°C), 'Cool' (31°C), 'Neutral' (32°C), 'Warm' (33°C), 'Warmer' (34°C), and 'Warmest' (35°C).

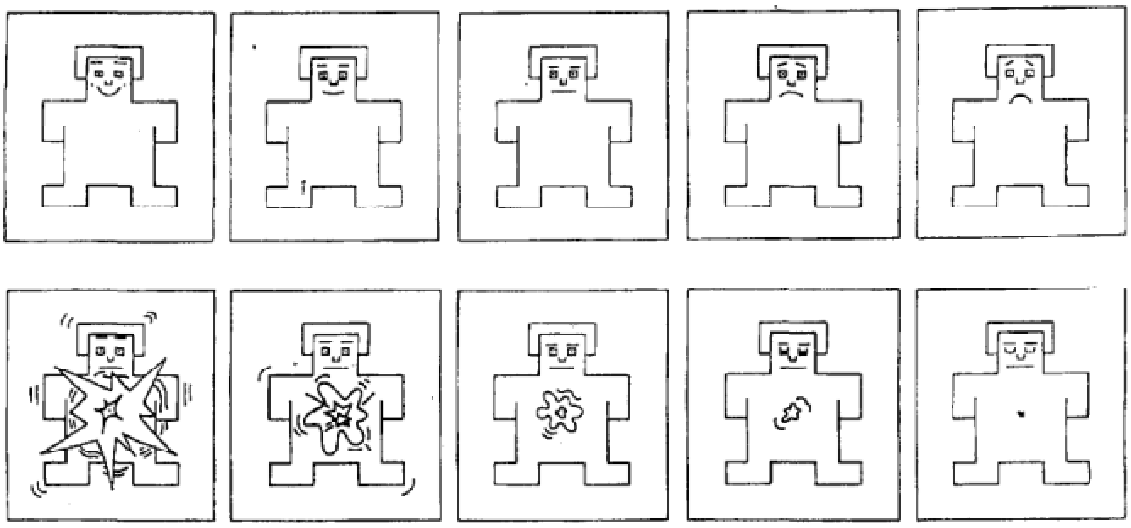


Figure 7.1: Self-Assessment Manikin (SAM) illustrations (Image from Bradley and Lang, 1994). The top row indicates 5 points of valence, from a state of happiest on the left to unhappiest on the right. The bottom row indicates 5 points of arousal, from a state of excitement on the left to calm on the right. The third point in each row indicates a state of neutral. Standard SAM scales can also be composed of 7 or 9 points, or pictures.

For recording responses, a Self-Assessment Manikin (SAM) technique (Bradley and Lang, 1994) was employed to capture the participant's valence and arousal ratings of the message and thermal stimuli. In this method are Likert scales, each representing a dimension of emotion such as valence and arousal, such as those shown in Figure 7.1. Each point on the scale is represented by a graphical depiction of the degree of affective state along the scale. Standard SAM scales typically range from 5 to 9 points and usually show two rows (for valence and arousal) or three rows (dominance, in addition to the other two). The benefit of the SAM approach is that it is easy to understand for untrained users to select which manikin they think best represents their current emotional state after exposure to a stimulus.

The SAM is another standard method for collecting emotion data, and was selected over the emotional wheel used in Chapters 2 and 3. There were several reasons for this switch from the emotion wheel:

1. The SAM method is simple to understand, and there are standard instructions available.
2. The SAM scales present the concepts of valence and arousal in a more illustrative manner to users, whereas on the emotion wheel, the selections are illustrated as just button selections.
3. The implementation of the emotion wheel used in Chapters 2 and 3 was quite complicated. This may had caused confusion in users because of the overwhelming number of possible selections they could had made (57 bubble selections total).
4. The use of the emotion wheel is redundant for capturing just valence and arousal information. Use of the wheel in this manner required converting user selections in an extra step. With the SAM approach, this extra step is not necessary as the information is already in the format that can be readably analysed.
5. The emotion wheel may had not covered all emotions. For example, emotions which were strictly on either the horizontal or vertical axis of the wheel were not covered.
6. The emotional wheel may have been confusing to participants as it was unclear as to what exactly the intensity of the emotions was representing in the wheel. As a reminder, the subjects in those studies were asked to “rate the strength of the emotion from weak (1) to strong (7) by clicking the corresponding circle in the emotion wheel”.

Considering these points, and aiming to simplify the effort required to rate the messages and the temperature scales, two SAM scales were used over the emotion wheel approach for rating valence and arousal.

5-point SAM scales were used instead of 9-point scales used in the original Facebook study, as Krosnick and Fabrigar (1997) suggested that optimal scale size should fall between 5 to 7 points in length. They argued that having fewer scale points may improve clarity of the individual point meanings in the scale, which leads to more consistency within the subject's ratings during a survey. The precise meaning of these points will be discussed in more detail in Section 7.2.2.

7.2.2 Procedure

For the pilot study, 12 new participants, none of whom participated in the previous studies in Chapters 5 and 6, were recruited. Each participant received £10 for his or her time, and the same exclusion rules used from the studies in Chapter 5 and 6 were applied as before (they could not participate if they had medical problems that could have impeded with temperature perception such as over-sensitive skin, or where exposure to temperature could have caused discomfort or harm). The participants were given the participant information sheet shown in Appendix H.5 in advance of the study, and signed the consent form shown in Appendix H.6 before they were allowed to take part in the study. These forms were also used for the main experiment later in this chapter (Section 7.3).

To ensure consistency across participants in this study, stimulator positions were marked on the arms beforehand. Elbow distance to the wrist was measured and the midpoint was marked for placement of the middle stimulator to compensate for differing forearm lengths. Furthermore, participants were given a brief calibration session where they were presented the 'Warmest' and 'Coolest' stimuli to ensure that they could detect these temperatures and to allow themselves to be familiarized with the TAD. After the calibration setup, participants then proceeded to complete the two parts of the pilot study, beginning with the Facebook text messages, and then the temperatures.

In the first part of the pilot, subjects rated the 25 Facebook text messages, shown in Appendix F.1 (which also shows the original valence and arousal ratings from Preotiuc-Pietro *et al.*'s (2016) study). The participants were instructed to read each message (Appendix G.14), which appeared at the top of the screen on the computer display in front of them, within the context that each text message was sent by a close friend on Facebook. Participants then proceeded to rate the valence and arousal of each message by using the 5-point SAM scales provided under the text, as shown in Figure 7.2. The top scale denotes valence, and the bottom row denotes arousal. After assigning a rating to each, they clicked the 'Next' button at the bottom, which proceeded to the next message.

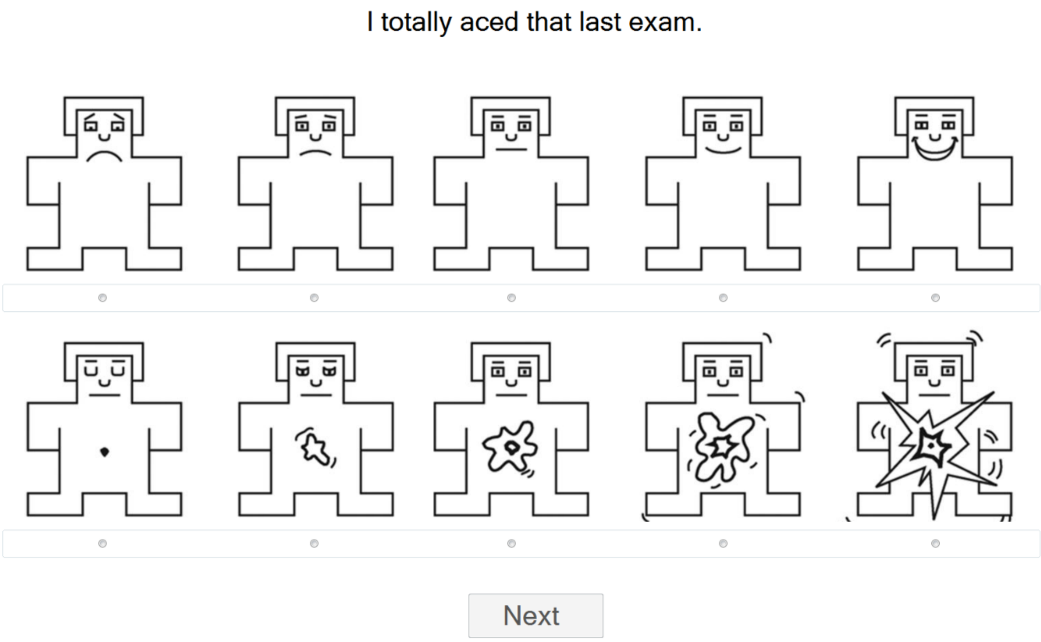


Figure 7.2: SAM interface for the pilot study. The message “I totally aced that last exam” is displayed at the top of the screen, with the two SAM scales below it. The top SAM scale is used to illustrate valence and the bottom SAM scale is used to illustrate arousal. Underneath each illustration are radio button selections for each manikin representing the points in the scales. For the thermal portion of the study, no message was displayed and only the scales and the ‘Next’ button were presented

.

After completion of the message portion of the pilot study, the subjects then rated the thermal stimuli. Before this portion of the test, the TAD device was again attached to their non-dominant arm and remained on until this portion of the test was over. Unlike the messages, the temperatures were not given a context in the instructions, and participants were instructed to just rate how the temperatures made them feel while perceiving them (Appendix G.15). Like the first experiment in Chapter 6, there was a ten second re-adaptation period between each stimulus presentation to return the skin to a baseline temperature in between trials.

All message and thermal stimuli for both parts were repeated three times in a random, counter-balanced order unknown to either the participant or the lab monitor until after the test. There was no time limit to making selections. The temperatures and messages were presented to the subject until the subject made their selections on the SAM scale and pressed the OK button to signify that they were ready for the next trial. To summarize the procedure of the two parts:

- In Part 1, participants rated 25 messages, each repeated three times in random order.
- In Part 2, participants rated the seven thermal states presented using the Amplification Method (Section 5.2.2.2), each repeated three times in random order.
- Participants were given written instructions for both parts of the pilot study and a five-minute break in between.
- Participants reported the valence and arousal selections on two, 5-point SAM scales.

7.2.3 Results: Rating Message Valence and Arousal

Table 7.1 shows the valence and arousal mean ratings for the 25 messages presented in the pilot. As a 5-point scale was used in the pilot, neutral scores had a rating of three. Five messages were selected that each represented one of the five valence/arousal categories based on how strongly they were rated across all 12 participants. Message #9 was selected as the high valence/high arousal text, Message #10 as the high valence/low arousal text, Message #17 as the low valence/low arousal text, Message #16 as the low valence/high arousal text, and Message #25 as the neutral message. The raw data collected from the pilot can be found in Appendices F.2 – F.4.

Figure 7.3 illustrates the valence and arousal rated means of these five selected messages in a scatterplot. The horizontal axis denotes the valence scale and the vertical axis denotes the arousal scale. The two quadrants above the horizontal axis denote messages that were highly arousing to the subjects, and the bottom two quadrants denote messages that were not very arousing. Messages to the right of the vertical axis were rated as pleasant, and messages to the left of the vertical axis are rated as unpleasant. The selected messages fall within their respective quadrants, with each one representing one of the four valence/arousal categories that were studied in the pilot, as well as the neutral message, which is positioned close to the intersection point of the four quadrants (the neutral area).

ID	Message	V	A
1	We'll be off and running to a lil' place called SILVERWOOD today! Can't wait! :)	3.6	2.9
2	Happy happy happy new year to everybody!! I have optimistic hopes for 2016.	3.9	3.2
3	OH EM GEE I LOVE MY SISTER SO MUCH! I WISH I WERE AS COOL AS HER!!!!!!!!!!!!! LIKE I CANT EVEN BELIEVE THAT I AM SO LUCKY TO HAVE HER AS MY SUPER DUPER AWESOME BIG SISTER!!!!!!! :DDDDDDD	3.8	3.3
4	What a weekend? EAT, EAT and EAT some more, BBQ TIME!!!!	4.1	3.1
5	i bought my wedding dress monday and i cant wait to have it on again!!!! its sooo beautiful	3.8	3.1
6	happy, got new friends, and lifes getting smoother.	4.0	2.9
7	Thanks everyone for your birthday wishes another year is good thing blessed to have so many wonderful people in my life I love you all. P.S Tamika a birthday baby is a great gift thanks and much love to you all even you colts fans lol	3.7	3.0
8	Life Gets Better from Here :)	4.0	2.6
9	Blessed with a baby boy today...	4.1	3.5
10	life is beautiful	3.7	2.3
11	i wasn't the son my father wanted	2.2	3.0
12	you just killing me inside	2.2	3.2
13	got a gun pulled on him last night	1.8	3.9
14	My heart is broken for my sister. Her husband died today. She is a total mess, but I will help her get through this. I am strong enough. Maybe if I tell myself that enough, it will come true.	1.4	3.3
15	well, we're in the hospital. my poor baby has had two spinal taps. we still dont know whats wrong....	1.5	3.4
16	At least 15 dead as israeli forces attack Gaza aid ahips!!!!!!! i hhhhhhate israil	1.4	3.8
17	SICK AGAIN !!!! HATE IT !!!!!	2.3	2.4
18	WTF WHY ARE YOU CHEATING IN A GAME OF THIS IMPORTANCE THAT WAS A CLEAN HIT ANYBODY COULD SEE THAT.YOU REFS COULDNT CALL A PLAY IF YOUR LIFE DEPENDED ON IT.WHEN A RECEIVER CATCHES A PLAY AND GET HIT THAT IS FOOTBALL.	2.5	3.3
19	Is feeling especially racist against Americans today now that they've fXXked up skins!!THE IGNORANCE!!!!!!!!:'(	2.1	3.6
20	HEADACHE!!!	2.1	2.8
21	i'm not dirty as yo think I am!	2.6	2.9
22	School is about to start!	3.7	3.3
23	is facing one of the most difficult decisions ever! The job offers are in: DC or Paris!	3.6	3.5
24	i run over a fork on ur car, coz im a ninja!! Lol	3.4	3.0
25	And one careless match can start a forest fire but it takes a whole damn box to get a campfire going!	3.1	2.8

Table 7.1: Messages studied in the pilot, with the mean ratings of valence (V) and arousal (A) for each text message which were calculated from the subjects' responses.

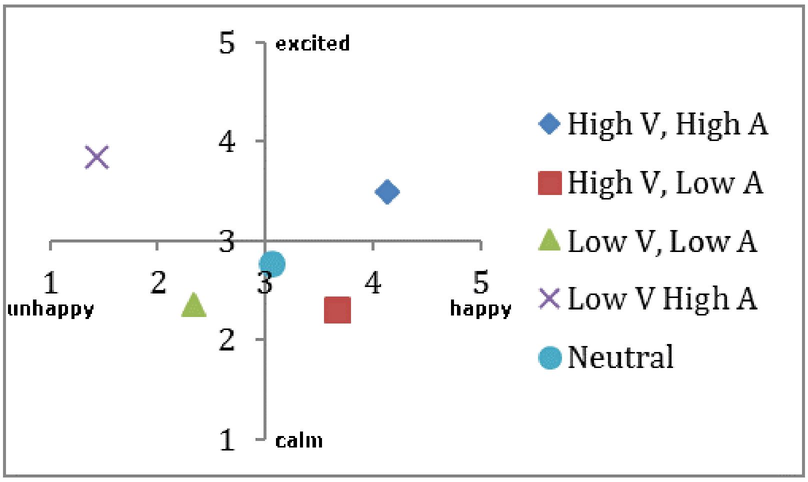


Figure 7.3: Message mean valence and arousal ratings for each of the five selected messages from the pilot study.

The outcome of this part of the pilot study showed that subjects could reliably rate the emotional content of the Facebook text message posts with the SAM scale. Furthermore, five text messages were selected for further study which will be detailed in Section 7.3. The text messages were categorised by valence and arousal to represent a particular combination of these two dimensions of emotion so that the effect of temperature on the valence and arousal of the text messages could be studied.

7.2.4 Results: Rating Thermal Valence and Arousal

The raw data for the thermal state ratings can be found in Appendices F.2 – F.4. Table 7.2 shows the valence means and standard deviations for all the seven thermal states as rated by all 12 subjects. The table results suggest that the subjects rated the thermal stimuli quite neutrally overall. However, closer inspection reveals strong disagreements amongst the participants pertaining to which temperature states were pleasant or unpleasant. Participants P8 - P12 interpreted cool states as pleasant (means were 'Coolest' = 3.7, 'Cooler' = 3.7, and 'Cool' = 3.3) and the warm states as unpleasant (means were 'Warm' = 2.9, 'Warmer' = 2.7, and 'Warmest' = 1.8). P7 rated cool states as unpleasant ('Coolest' = 2, 'Cooler' = 2, and 'Cool' = 2) and the warm states as pleasant ('Warm' = 3.3, 'Warmer' = 3.3, and 'Warmest' = 4). P2 and P5 rated all thermal states as unpleasant (means were 'Coolest' = 2.2, 'Cooler' = 2.2, 'Cool' = 2.5, 'Warm' = 2.8, 'Warmer' = 2.7, and 'Warmest' = 2.3). The other four participants (P1, P3, P4, and P6) rated only particular states of warmth or cool as pleasant, for instance, the ‘Cool’ state as pleasant, but not ‘Cooler’ or ‘Coolest’.

	Coolest	Cooler	Cool	Neutral	Warm	Warmer	Warmest
Mean	2.9	2.8	3.0	3.1	2.9	2.9	2.6
Std Dev	0.9	0.9	0.5	0.4	0.4	0.6	1.1

Table 7.2: Valence mean and standard deviation (std dev) ratings for the seven thermal states used in the pilot.

Figure 7.4 shows box plots of the valence SAM ratings for all seven thermal states. This figure and the standard deviations shown in Table 7.2 suggests that there was more variance in how subjects rated the more extreme thermal states than the mild and neutral states. This can be observed in how the whiskers of the extreme states extend further from their means than the thermal states located in the centre of Figure 7.4.

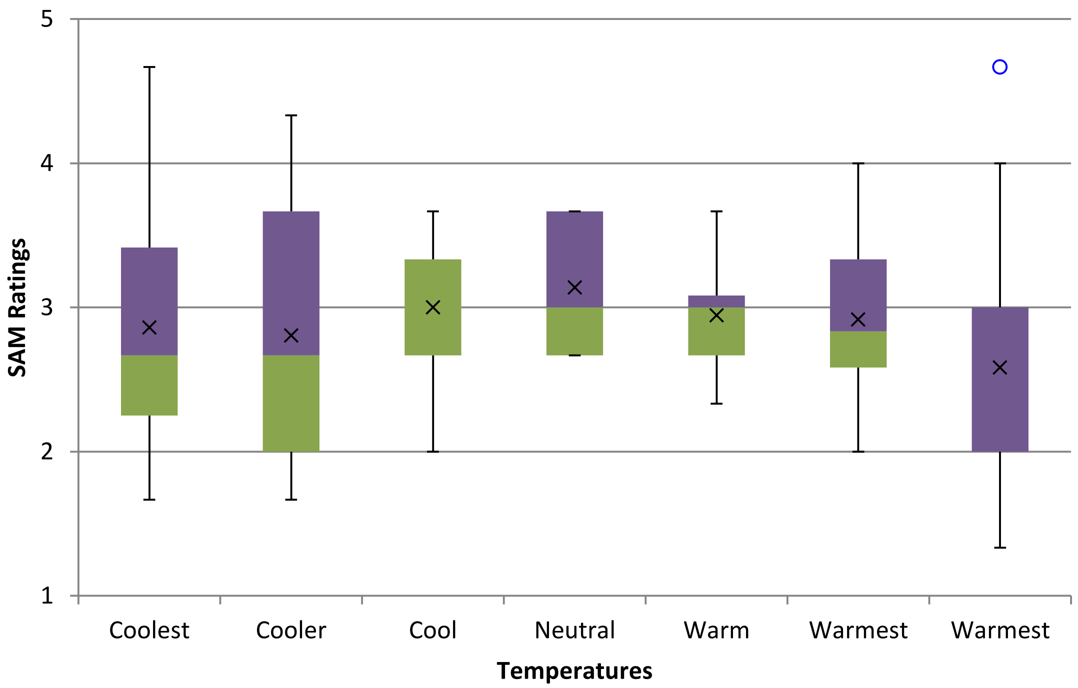


Figure 7.4: Box plots of the SAM valence scale ratings for all seven thermal states.

On the other hand, there was stronger agreement amongst participants on how temperature mapped to subjective feelings of arousal. In general, more intense stimuli were perceived as more arousing. A Friedman Test run on all seven thermal state treatments resulted in significance ($p = 0.04$, $H = 13.02$, $df = 6$), indicating that at least one of treatments had different arousal ratings than the rest. Table 7.3 shows the arousal SAM rating means and standard deviations of all seven thermal states, and

Figure 7.5 illustrates the SAM arousal ratings as box plots. These show, again, that subjects appeared to rate the extreme temperature states as more arousing than the more mild and neutral states. The results in Table 7.3 indicate that the 12 participants did not find the 'Cool', 'Neutral', and 'Warm' states to be very arousing, as their means laid below 3 (the neutral point on the SAM scale), but they did find the other states to be arousing, as their means were rated above 3 on average. From Table 7.3 and Figure 7.5, participants also appeared to find the warmer states to be slightly more arousing than the cooler states, however, this was not statistically significant. This last point may have depended on how intense they perceived the stimuli as some participants remarked that warm stimuli felt more intense than the cool ones. In general though, these findings are in agreement with the prior literature with regards to arousal (Suhonen *et al.*, 2012; Halvey *et al.*, 2012a; Salminen *et al.*, 2013; Wilson *et al.*, 2016).

	Coolest	Cooler	Cool	Neutral	Warm	Warmer	Warmest
Mean	3.1	3.1	2.8	2.6	2.7	3.2	3.4
Std Dev	1.0	0.6	0.8	0.7	0.6	0.9	0.9

Table 7.3: Arousal mean and standard deviation (std dev) ratings for the seven thermal states used in the pilot.

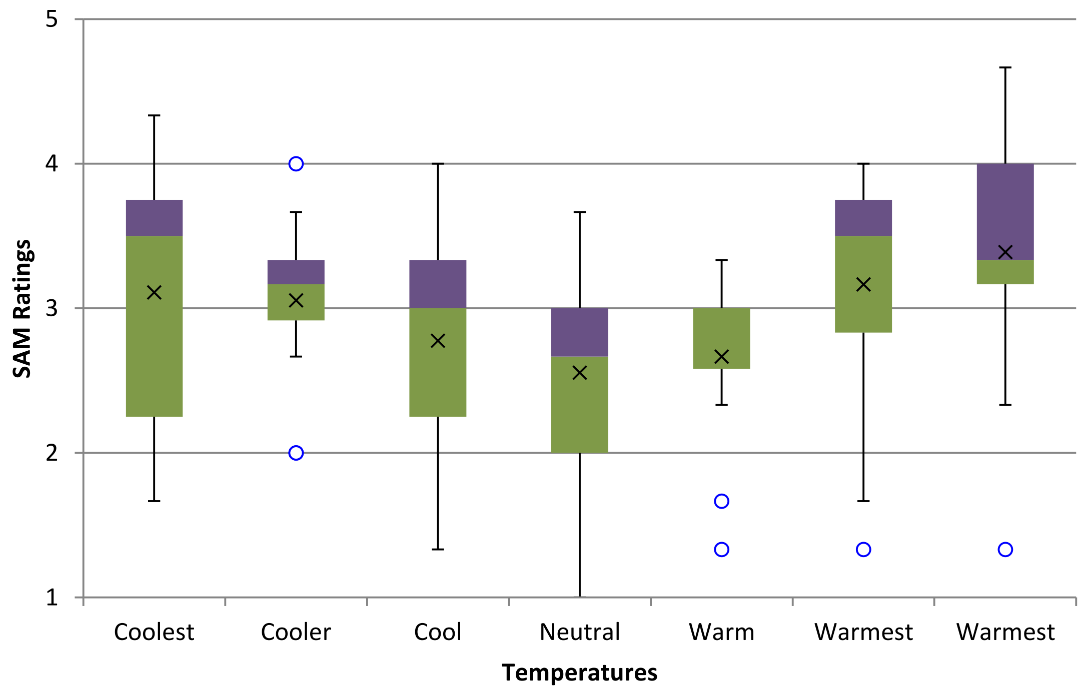


Figure 7.5: Box plots of the SAM arousal scale ratings for all seven thermal states.

Surprisingly, participants took almost the same amount of time to rate both the messages and the thermal states. The mean time to rate the messages was 6.82 seconds (σ = 1.5 seconds). The mean time to rate thermal states was 6.84 seconds (σ = 0.8 seconds). This suggests that, even with the latency of thermal perception, participants were able to recognise the emotion the thermal stimulus conveyed in the same amount of time it took to read and emotionally rate the messages. In other words, rating both types of stimuli appeared to require a similar effort to both perceive the stimulus and to process the affective output, in this case, deciding how pleasant and aroused the stimulus made the subjects feel.

The biggest question raised by these results however, was why there was no observed agreement on the valence? Research in prior literature appeared to have a few differing views on the relationship between temperature and valence. First, Lee and Lim (2010; 2012) reported that warm temperatures lead to increased feelings of pleasantness and that cool temperatures decreased their subjects' subjective feelings of pleasantness. A challenge of comparing this pilot study's results with Lee and Lim's findings though, is that they only assessed their subjects using qualitative data, as opposed to having participants rate the temperatures they were given on a scale.

Suhonen *et al.* (2012), whom investigated the use of temperature to augment speech in conversations using a wrist worn device, also claimed to have found a similar effect as Lee and Lim's work (2010; 2012). Suhonen *et al.*'s (2012) subjects remarked they preferred to use warm temperatures to supplement positive words in a conversation and preferred using cool temperatures to accompany more unpleasant discussions. However, it appeared from the quantitative data that their subjects used warmer feedback more frequently in sadder and more neutral conversations, and also that the subjects used colder feedback more frequently in happier discussions. The authors also noted there were instances where the recipient partner misinterpreted their senders' haptic messages, which may had caused some confusion in the discussions.

Continuing this point, Halvey *et al.,* (2012a) provided a more detailed assessment of rating temperature by emotion, as their subjects used Likert scale ratings for valence and arousal in their study to assess the content of the thermal stimuli. Halvey *et al.* reported that warm stimuli were, again, generally given higher valence ratings than the cool stimuli used in their study, though they noted there were “some exceptions” to this (pg. 95). However, no explanation was given as to why neutral temperatures were observed to result in higher valence ratings than warm stimuli. Wilson *et al.*, (2016) also took a similar position, though they noted that the thermal stimuli needed to be kept at low to moderate magnitudes for their suggestion to hold, as 8°C warming changes actually decreased the valence in their subjects' responses, compared to the 2°C, 4°C, and 6°C changes.

Contrary to Lee and Lim's (2010; 2012) and Halvey *et al.*'s (2012a) findings, and similar to the pilot results of this section, Salminen *et al.,* (2011) noted that temperature changes did not affect pleasantness (valence) ratings, and that it only affected the emotional dimensions of arousal and dominance. However, in a latter study (Salminen *et al.,* 2013), they found that temperature could affect valence, and that very warm temperatures (6°C changes) were rated as unpleasant compared to less warming (2°C changes). Again, this affirmed the idea that larger, warming magnitudes tended to decrease valence as was also reported later by Wilson *et al.*, (2016). However this was only evident when Salminen *et al.* (2013) used their dynamic presentation method (placing the skin on the stimulator as it warmed or cooled from neutral instead of placing the skin on the stimulator after it had finished warming or cooling). Salminen *et al.* concluded that valence, or pleasantness, was not just affected by the direction or magnitude of the temperature changes, but also the manner in which it was presented to the user. “This may indicate that instead of temperature as such, the change in temperature is the factor making the experience of thermal stimulation as pleasant or unpleasant” (pg. 28).

Akazue *et al.* (2016), noted this, and while they observed that individual parameters of temperature did not affect the valence of images they augmented, temperature changes, as a whole, did appear to affect the valence difference, or the degree of error between what the users reported on the SAM scale and the original IAPS rating of the images. Akazue *et al*. reported that the parameters of rate of change, intensity, and temperature direction did not have a statistically, significant effect on the users' ratings of valence of the images when users were asked to rate their perception on SAM scales, as was similarly done in this pilot study. However, when calculating the valence differences for the categories of emotion used, Akazue *et al*. did find some significant findings. First, their thermal stimuli increased the valence of images with low valence, and reduced the valence of high valence images. Their quantitative data suggested that the valence of images became ‘flipped’, irrespective of which thermal parameters were actually used. However, qualitative feedback from their subjects suggested that cooling changes, in particular, could be used to increase valence in unpleasant images, and that their subjects confirmed, again, that extreme warming changes (6°C) reduced valence.

Thermal stimuli alone may be too subjective to elicit specific valence responses consistently across a sample. While most subjects in the pilot study consistently mapped warmth or cool to either pleasant or unpleasant valences, there was considerable disagreement amongst them with regards to how this mapping worked. However, both the pilot study and literature appeared to support the view that temperature could consistently elicit arousal. Furthermore, when paired with other media, such as speech and visual images, evidence from prior research appeared to also support the view that temperature could be used to augment both their valence and arousal, either by reducing or enhancing them. This appeared to depend on whether their original valence and arousal content was positive or negative, though it was unclear how the parameters of temperature played a role in this.

Temperature has been used to augment speech (Suhonen *et al.*, 2012), images (Halvey et al., 2012a; Akazue et al., 2016), and music (Halvey et al., 2012a), though the latter was found to not be significant. Therefore, a question remained as to whether or not temperature could augment social media text messages to the same effect as speech and images?

7.3 Main Experiment

This research conducted a final study, which combined the seven thermal states alongside the five messages selected from the pilot and examined the interaction between both stimuli on the user. As discussed, research had investigated the relationship between temperature and emotions using other forms of media. However, it has not yet looked at whether thermal cues could augment the perceived emotions communicated from text messages.

7.3.1 Procedure

The procedure for the main study was similar to the pilot, in that participants were asked to report their valence and arousal responses of the stimuli using two SAM scales, one for valence and one for arousal (Appendix G.16). However, a difference was that the SAM scales were increased to nine points from the five point scales used in the pilot. This was done as almost every participant in the pilot rated the temperature scales using only the 2-, 3-, or 4-point selections, and because some participants remarked they would had preferred a wider range of choices. It was believed that increasing the scales to 9-points would capture a finer degree of emotion that would be appreciated by the participants.

One of the consequences of increasing, or changing the SAM scales, was that the messages and thermal states would have to be tested again on their own – the results of the 5-point and 9-point SAM scales could not be mixed. This was because the analysis required comparing SAM scales of equal size to validate the data, particularly, comparing the combination stimuli with the ratings of just the messages and just the temperatures. By doing this, it would be possible to see how the inclusion of temperature could change the messages' valence and arousal ratings. Because of this action of changing the SAM scale size, the five message stimuli chosen from the pilot and the seven thermal states were re-tested again in the manner they were presented in the pilot, but using 9-point SAM scales instead.

The important aspect of the main study was to collect data of the combinational stimuli – the stimuli that consisted of both temperatures and text messages paired together. To create these, the seven thermal states were combined into pairs with one of the five message types and a blank message (this allowed for testing the temperature-only conditions discussed above). This amounted to 42 unique, combinational pairings of a message and a temperature state. These 42 pairings were presented to the participant twice during the test, resulting in a total of 84 trials. As before in the pilot, there was a ten second re-adaption period between each of these trials. The order of all trials was randomized and divided into three blocks, with five-minute breaks between the blocks to prevent the subjects from fatigue. The user interface for a trial, showing the message at the top and the SAM scales below it, are shown in Figure 7.6.

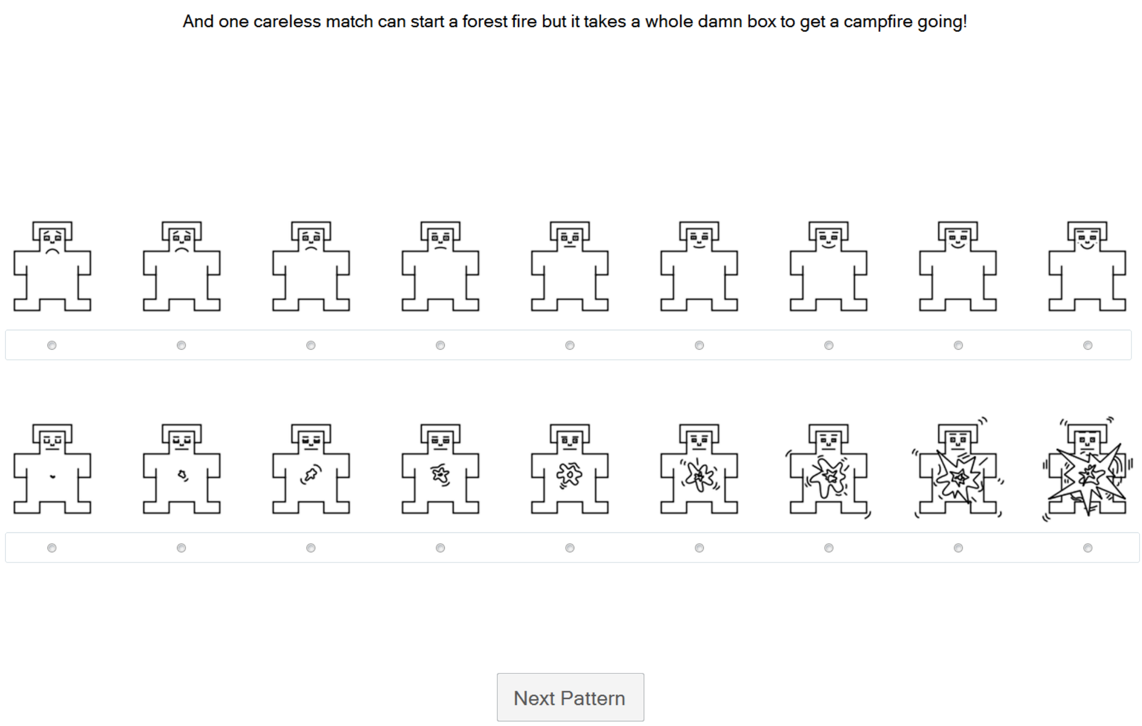


Figure 7.6: User interface for the main study. At the top is the message, with the two SAM scales beneath it for valence and arousal. The participant made a selection with the radio buttons beneath each manikin for both scales and then pressed the 'Next Pattern' button to continue to the next trial.

The only remaining issue was how to present the message-only stimuli again to the subjects. As discussed, this was the condition where the messages were displayed without a thermal state. As it would have been difficult to detach the thermal device each time a message-only stimulus was presented during the main block of the other 84 trials, it was decided to test the message-only trials separately. To prevent ordering effects, participants were split into two groups for this. The first group rated the messages and then proceeded to rate the other 84 thermal trials. The second group rated the 84 thermal trials and then proceeded to rate the messages. Like the main block, the five messages were tested twice in random order, for a total of 10 trials during this block of the main study.

To summarize the procedure of the main study:

- The study consisted of 94 trials total that were comprised of 47 unique stimuli that were each used twice.

- 10 trials consisted of message-only stimuli. 70 trials consisted of pairs of a message and a temperature state, and the remaining 14 trials were temperature-only stimuli.
- 6 participants received the 10 message-only trials before the other 84 trials and the other 6 participants received the 10 message-only trials after the 84 trials.
- The other 84 trials (which consisted of the 14 temperature-only stimuli and the 70 pairings of temperatures and messages), were split into 3 blocks with 5 minute breaks between them.

7.3.2 Results

The raw data can be found in Appendices F.5 – F.7. The distribution of the participants' ratings of valence and arousal was tested first. Researchers have previously raised concerns on the validity of using ANOVA on Likert scale data, but when data is found to be normally distributed, ANOVA is appropriate (Cairns and Cox, 2008, pg. 126) and can be used to test for interaction effects.

To test for normality of the data, Shapiro-Wilk tests were used on the global data set, regardless of stimuli type (message-only or temperature-only/message-temperature pairs). After separating the data set by message and thermal stimuli, further Shapiro-Wilk tests were run on these subsets to ensure they were also normally distributed. All results produced $W > 0.975$, and exceeded the critical values at $p < 0.01$. This confirmed the normality of the data, and permitted the use of ANOVA.

The ratings for valence had a global mean of 4.8 and a standard deviation of 1.9; while arousal had a mean of 4.7 and standard deviation of 1.6. To again test for the validity of ANOVA on the data, standard deviations were obtained for the subsets of the thermal and message stimuli, with valence ranging between 1.1 and 1.7, and arousal from 1.8 to 2.1. The level of variance in standard deviations was within the tolerances expected of a two-factor ANOVA assumption. Therefore, ANOVA testing proceeded, first a 'pre-test' to ensure there was no influence from the setup of wearing the device on the user's arm, and then main tests afterward to test for interaction effects with the temperatures and messages.

To check for experimental effects from wearing the apparatus, two tests were used. First, the temperature-only stimuli results were tested against the trials that paired thermal states with a neutral message. Second, the message-only responses were tested against the trials with the same messages paired with a neutral thermal state. For each of these two tests, two ANOVA tests were run: one test on the valence data and the other test on the arousal data. Any positive result would indicate an undesirable and substantial, experimental effect. Using ANOVA, F-values varied between 0.07 ($p > 0.85$) and 1.5 ($p > 0.20$). For the main effects, scores were at or above $F = 8.5$ ($p < 0.005$). For all tests, the F-values need to be larger than 8.5 to achieve $p < 0.05$, so a range of 0.7 - 1.5 for the F-values are far from significant. In other words, the differences in means between the first test (temperature-only stimuli vs. temperature + neutral message stimuli) and the second test (message stimuli vs message + neutral temperature stimuli) were not significant, which is the expected result. This means that simply wearing the device did not cause the users to rate the stimuli differently, and thus discounted the likelihood of a significant side effect from wearing the device.

Finally, the main tests using two-factor ANOVA tests were run to test for interaction effects with the temperatures and messages. The global descriptive data suggested that arousal responses were diffuse and inconsistent, whereas valence responses were more concentrated and consistent. As such, valence will be addressed first before proceeding to test arousal.

Valence was tested using the message and thermal stimuli as the two variables. The ANOVA result was $F(2,385) = 118.45$ ($p < 0.001$) for the messages dimension, but the thermal dimension yielded $F = 0.43$, and the interaction produced $F = 0.29$, both very far from significant. While messages substantially influenced the perceived valence, the thermal states had no discernible effect.

For arousal, the ANOVA result was $F(2,385) = 3.62$ ($p < 0.05$) for the message effect and 3.41 ($p < 0.05$) for the thermal effect, with the interaction producing $F = 0.20$ ($p > 0.80$). There was again, no evidence of an interaction effect. Both the messages and the thermal stimuli had a similar and reliable effect, but neither was as marked as the impact of the messages with valence.

Thus, for valence and arousal, the message content had a reliable main effect, and was much more powerful in valence than in arousal. In contrast, thermal stimulation had no reliable effect on valence, but had a similar level of efficacy to the messages' arousal levels.

Figure 7.7 shows the plots of the mean valence and arousal scale responses (y-axis) as a function of temperature change (x-axis) for each of the six categories of message and thermal scale pairings. Plot (a), for instance, shows the pairing with a blank message for testing temperature only. The bottom of the y-axis denotes ratings of 1 for the valence and arousal scales (unpleasant and calm, respectively, marked with a '-' for negative), and the top of the y-axis denotes ratings of 9 on the scales (pleasant and excited, marked with a '+' for positive). The tick marks along the y-axis denote the other points on either scale, from 1 to 9, with neutral valence/arousal in the middle where the y-axis and x-axis intersect. The far-right dash mark of the x-axis denotes the 'Coolest' temperature state, marked with a 'C', and the far-left dash mark denotes the 'Warmest' state, marked with a 'W'. The tick marks along the x-axis denote the other thermal states, with the 'Neutral' thermal state at the intersect point with the y-axis in the middle.

The mean arousal ratings are marked by the red lines in each plot. As temperature increased, or became warmer, arousal ratings for the stimuli generally increased as well on the scale. This indicated that subjects became more aroused when they felt a warm sensation, regardless of the content of the message, if one was shown. Except for plot (c), arousal ratings also tended to be rated negative, or calmer, for cooler temperatures. The mean ratings only crossed the x-axis when warmer stimuli were applied. For all categories though, temperature had a reliable main effect on arousal, including plot (f).

Valence is marked with the blue lines in each plot. As discussed earlier in this section, temperature did not have a reliable effect on valence, and this is illustrated in the plots in Figure 7.7. As plots (c), (d), (e), and (f) illustrate, the valence of the message contents clearly dominated, with the blue line always remaining above or below the x-axis. These lines also remained relatively straight horizontally, regardless of which thermal stimulus was applied. For plot (a), where only temperature was presented with no message, and plot (b), where temperatures were paired with the neutral message, the valence means remained close to neutral. Plot (a) also illustrates comparable results from the pilot test, showing no thermal valence effect.

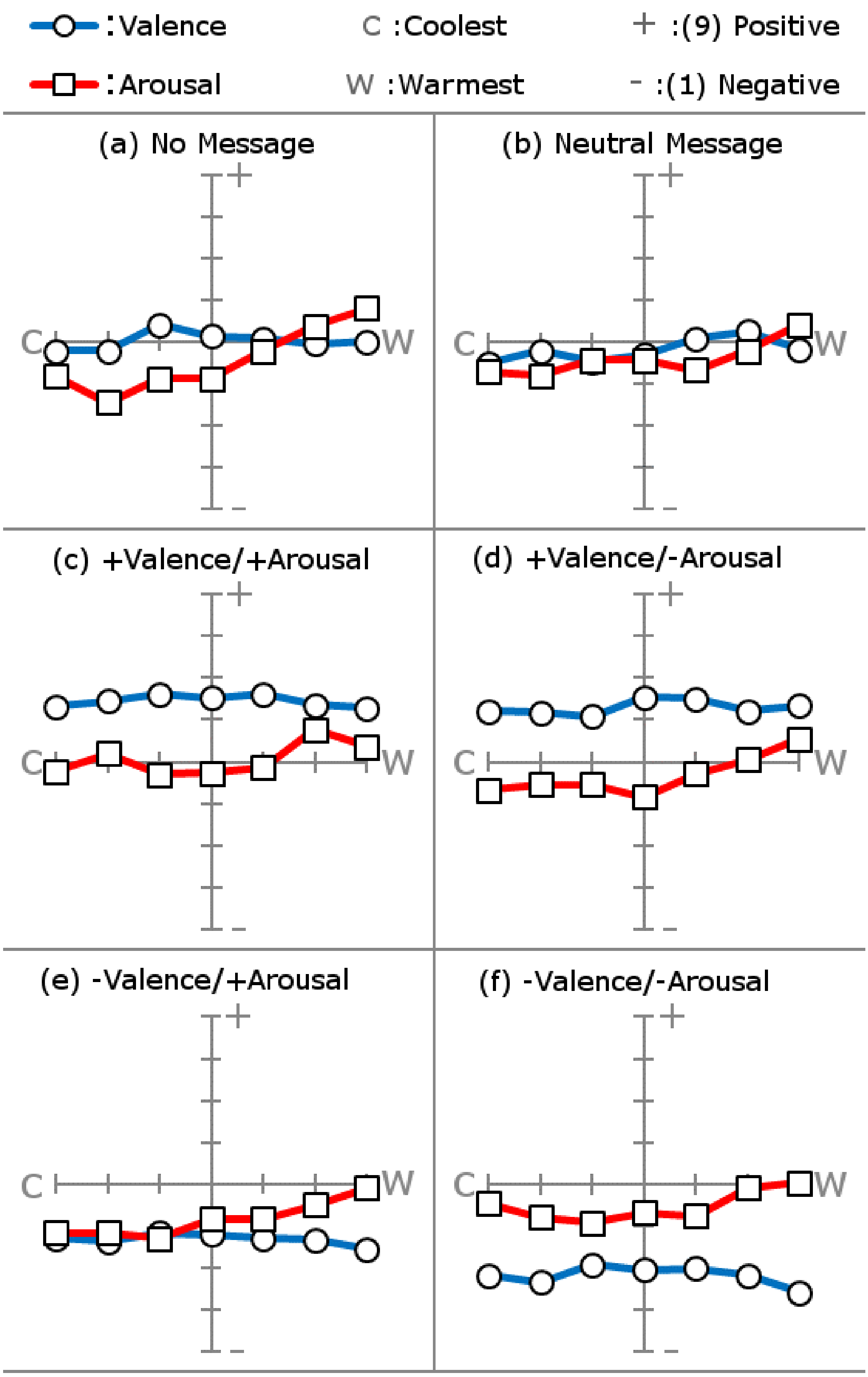


Figure 7.7: The six message and temperature pairings' mean plots for valence and arousal. Red lines show the mean arousal ratings and blue lines show the mean valence ratings.

7.3.3 Discussion

It appears that temperature was able to exert a reliable main effect on the emotional dimension of arousal. This was evident when temperatures where paired with text messages, as warm temperatures caused subjects to feel more excited when viewing the message contents. Subsequently, the cool temperatures caused subjects to feel more relaxed. Figure 7.7 illustrates this effect quite well: for all messages, regardless of whether the messages' arousal contents were calm or excited, the cool temperatures caused the messages to feel relaxing, and as the temperature increased, so did subject's ratings of arousal. Furthermore, temperature was able to arouse subjects when presented by itself without message content, reconfirming what was observed in the pilot study in Section 7.2 (though cool temperatures in the main study were rated much calmer than in the pilot).

While the thermal effect on arousal appeared evident, the non-effect on valence was puzzling. Once again, like the pilot study, a question remained as to why there was no observed thermal effect on valence? Continuing this discussion from Section 7.2.4, Lee and Lim (2010) offer some clues. They reported environmental factors could influence thermal expression, as humans tend to feel safe from factors that change body temperature. The study in this section did not control this, and though thermal feedback recommendations still hold in varying ambient temperatures (Halvey *et al.*, 2012b), it may influence thermal expression of valence. Therefore, future work should test the affective perception of thermal cues in different ambient environments, for instance, testing a similar setup in the winter vs the summer, by varying the humidity, or by asking subjects to wear heavier and lighter clothing.

Lee and Lim (2010, pg. 4235) also reported that "heat seems to have hardly any meaning by alone without its context". As participants were instructed to "rate how the temperature made you feel", this context may had been ambiguous, as the participants were not asked to interpret it in a context like with the messages: "The message post should be treated as if one of your friends on Facebook had posted it". However, even the message instructions could be interpreted differently: for instance, how might had subjects viewed the message and temperature pairs if they were sent from a friend they were currently upset with or their close relative? Therefore, a better context should had been setup and emphasised (e.g. "rate how the message and temperature made you feel as if they were sent by a friend you are close to"). Modifying context here as an independent variable could be interesting to examine for future work, which should address the effect of context on the affective perception of thermal cues, including a control condition where temperature is presented in an ambiguous context.

Previous work had looked at augmenting different media, such as speech (Suhonen *et al.*, 2012), images (Halvey *et al.*, 2012a; Akazue et al., 2016), and music (Halvey *et al.*, 2012a) with temperature cues. The study presented in this chapter was the first study that looked at augmenting social media text messages with temperature. Temperature could potentially be used to augment feelings of arousal in recipient users when viewing texts on social media. However, more work needs to be done to rule out that temperature does not excite valence. As explained above, different contexts could be vital to explore and lack of a directed context in this experiment could had been seen as a limitation of exploring valence in a way that is closer to daily life usage, as the users in this study may had felt the temperatures were too abstract to convey feelings of pleasantness to be of use in the context used in the study.

It may also be interesting for future work to examine combinations of text with and without other media, like images, along with temperature, for more practical studies. Text messages, particularly Twitter posts, are more likely to be used without images: researchers found that 42% of tweets contained an image and 58% did not (Lee, 2015). It may be interesting to see if subjects emotionally rate text and temperatures similarly to text paired with images, as there can be some advantages to using temperature in lieu of images (such as saving data and time needed to download images). On the other hand, images can be used to communicate emotion alongside texts. "People often used text for expressing their emotions using images with text… or images with added texts…" (Yoon and Chung, 2016, para. 26). Therefore, it may be interesting for future work to experiment with using other media, like images, in conjunction with texts and thermal feedback, to see if temperature can augment the perceived emotion of text messages paired with an image.

Furthermore, tweets with images often get more 'engagement' (retweets, favourites, and mentions) than tweets without images (Lee, 2015). Without images, Lee argues, tweets need to be longer to be more engaging with readers. Engagement, therefore, may be another good indicator of how effective thermal feedback can be in augmenting text messages in social networks, not only with conversation between friends, but also to communicate brands. For example, beverage companies could tweet about a particular beverage product. When the user views the tweet, the user could also receive warm or cool feedback, depending on the tweet's intended message. Depending on how many times the tweets get re-tweeted with and without thermal feedback may be of interest to researchers in social media.

"*Can a wearable array of thermal stimulators augment the emotional content of social media messages?"* This section concludes that temperature itself can consistently generate arousal responses. In the temperature-augmented message stimuli, the strong perceived valence of the text messages' contents dominated the valence communicated to the users. However, for all messages, but particularly when the message was neutral, temperature significantly influenced the perceived arousal communicated.

7.4 Conclusion

This chapter investigated the research question "Can a wearable array of thermal stimulators augment the emotional content of social media messages?" It answered this by first providing a more thorough review of previous work in HCI that used controlled studies to examine if temperature could be used to communicate emotion. These were significant works which had attempted to map parameters of temperature to certain emotions, or emotional dimensions, such as valence and arousal. Furthermore, research such as the works of Suhonen *et al.* (2012) and Halvey *et al.* (2012a) had looked to using temperature stimulation as a means of enhancing and reducing the effect of such dimensions when co-experiencing temperature stimuli with other modalities, such as speech or media, like images and sounds. It remained if temperature could be used to augment other kinds of media, such as text messages.

A pilot study was carried out to see if users could demonstrate agreement on rating text messages from the internet, as well as thermal states, using SAM scales. The results of the pilot study demonstrated that subjects could agree on the valence and arousal of the messages, in line with previous work. However, subjects disagreed on the emotional meaning of the thermal states, particularly valence, though there was stronger agreement on how the thermal states aroused them.

The subsequent main study confirmed three findings. First, warm temperatures were perceived as more arousing than cool temperatures. Second, for valence, the message content was highly effective, and temperature was ineffective, regardless of the thermal state used. Third, temperature exerted a discernible and reliable effect on arousal when paired with neutral messages. This effect was also observed when temperature states were paired with low and high arousal messages, providing an additive effect on the subjects' perceived arousal of the texts. Furthermore, no reliable interaction effect was found between temperature and message for arousal. These results demonstrate that a wearable array of thermal stimulators can augment the arousal content of social media messages, but not their valence.

Chapter 8

Discussion and Conclusion

Humans combine their senses to enhance the world around them. "These senses enhance each other in various ways, adding synergies or further information dimensions" (Blattner and Dannenberg, 1992, pg. xvii). Computers have evolved to reflect these sensory demands, as it has been argued that the addition of all sensory modalities will be necessary for computers to fully understand and communicate with human beings (Blattner and Dannenberg, 1992). Multimedia systems should therefore strive to facilitate communication with all human senses.

This thesis' main contribution was how additional information, such as emotion and navigational assistance, might be communicated using technology-based implementations of sensory displays that output smell and touch (both vibrotactile and temperature) feedback using simple, off-the-shelf technologies. Particularly, it explored using a portable atomiser sprayer (Scentee) to deliver emotional information via smell to mobile phone users (Chapter 2), a ring-shaped device (Ring*U) worn on the finger to display emotional information using vibration and colours (Chapter 3), and an array of thermoelectric coolers (Thermal Array Display, or TAD) worn on the arm to create temperature sensations (Chapter 4). Additionally, this thesis explored two methods of signalling temperatures using the TAD (Chapter 5 and Chapter 6), and finally, conducted a controlled study using the TAD to augment the perceived emotion of text messages using temperature (Chapter 7).

There were challenges with using some of these implementations to display information. Chemical perception of smell using the Scentee suffered from poor detection, the long time required to emotionally rate the stimuli, and the strong relationship that occurred between the smells and the messages' contents, which may had been influenced by cross-adaption effects created as scents lingered in the environment (Chapter 2). Multimodal vibrotactile and colour lighting stimuli were presented using a wearable ring device, Ring*U, which was used to augment the perceived emotion of text messages. However, when text messages were read while wearing the Ring*U, it became clear that the Ring*U neutralised, rather than augmented, the valence of the text messages' contents (Chapter 3). Another implementation, the Thermal Array Display (TAD), was developed (Chapter 4), and was subsequently used to present patterns of warm, cool, and neutral temperatures to a user's forearm. However, the makeup of these thermal-spatial patterns was difficult for users to discriminate (Chapter 5).

Despite these challenges, there were positive results with using the TAD to display information in various circumstances. First, the TAD enabled users to appreciate different thermal states of warm and cool more easily with multiple stimulators than with only one stimulator (Chapter 5). This result demonstrated the feasibility of using spatial summation as a parameter in thermal feedback design. Continuous thermal feedback was also explored as a viable method of utilising temperature cues to guide user navigation in a 2D maze task (Chapter 6). Finally, Chapter 7 examined whether or not thermal cues could augment the emotion of text messages. In general, temperature could consistently convey arousal by itself, and could affect the arousal content of text messages, while the valence content of the text messages' contents dominated over the perceived valence of the temperature cues, regardless of which temperature state was presented to subjects.

The research in this thesis had therefore addressed the following research questions that were posed in the Introduction in Chapter 1:

RQ1: Can a mobile smell display augment the perceived emotional content of SMS text messages?

RQ2: Can a wearable ring device augment the perceived emotional content of SMS text messages with tactile and colour feedback?

RQ3: Can a wearable array of thermal stimulators be constructed to provide information using temperature?

RQ4: What are the benefits of using an array of thermal stimulators over a single stimulator design?

RQ5: Can continuous feedback provide reliable information from a thermal display?

RQ6: Can a wearable array of thermal stimulators augment the emotional content of social media messages?

Main RQ: Can additional information, such as emotions and navigation assistance, be communicated through different implementations of sensory displays that use smell and touch?

These research questions provided the basic framework to design empirical-based studies and to fabricate technology to create sensory implementations to provide smell, vibrotactile touch, and thermo-touch stimuli to human subjects in a safe and ethical manner. The results of these studies were subsequently measured using an appropriate emotion model and analysed.

This final chapter will summarise all reported work in this thesis (Section 8.1) and discuss the findings that addressed all seven of the research questions (Section 8.2). Afterwards, the limitations of how the research was conducted will be discussed along with potential directions for future work with thermal feedback (Section 8.3). Finally, a summary of the general conclusions and contributions will be provided at the end of this chapter (Section 8.4).

8.1 Thesis Summary

Chapter 2 examined utilising the Scentee, a portable atomising sprayer, to augment the emotional content of text messages with smell. This chapter examined issues pertaining to the accuracy and sensitivity of smell by discussing the challenge of interaction effects due to lingering odours, and the delay of perception (latency) caused by the duration of initial exposure to a smell and its concertation. The behavioural and emotional responses from smell were examined, which supported the notion of using smell to communicate emotional information. Work in HCI had examined this closer by constructing prototypes to actuate the sense of smell through dispersion of chemical scents to the nose, mainly through the action of spraying mixed scents towards the user’s face. Previous work was discussed, which used smells to communicate emotional qualities, such as intimacy and closeness, between subjects. However, no previous work had attempted to augment the perceived emotional content of text messages using smell, as most research in HCI had focused on developing novel methods of dispersing smell and the form factors of such technology.

Chapter 2 then conducted several studies: two pilot studies and then a main study. The two pilot studies were used to determine that subjects could reliably and consistently rate the emotional content of smells based on pleasantness (valence), as well as rating the perceived emotional content of text messages. The experiment then examined if the emotionally rated smells could augment the perceived emotional content of the text messages using the Scentee technology implementation. The results of the study revealed three difficulties: (1) poor ability to detect smells when presented with an scent and when subjects were presented with plain water, (2) the long length of time taken to emotional rate each stimulus, and (3) that smell type (pleasant, unpleasant, and neutral) could not significantly augment the perceived emotion of text messages. Furthermore, delivery of smells within a controlled environment was difficult and it was highly likely that the smells lingered after their delivery to each user, which may had caused cross-adaptation effects when smells mixed in the air, leading to inconsistent emotional ratings as subjects perceived the mixed smells instead. Thus, the Scentee failed to augment the emotional content of the text messages.

Chapter 3 examined using multimodal vibrotactile and colour lighting cues sent from a ring-shaped device (Ring*U) to augment the perceived emotional content of text messages. Unlike smell, tactile feedback is quickly perceived and does not linger. Furthermore, its versatility can be demonstrated across the variety of literature in haptics discussed in this chapter, as well as commercial applications, such as game controllers and mobile phones. This thesis turned its attention to a speciality of haptics research, affective haptics, to examine how computer mediated touch could be used to augment media emotionally. Wearable, electronic devices capable of delivering touch feedback were reviewed, which influenced the design of the implementation presented in this chapter, Ring*U, to study whether tactile icons (TCONS) and colour lighting stimuli could communicate emotion to the wearer.

This chapter conducted three pilot tests and a main study. Pilot testing demonstrated the Ring*U's ability to deliver TCONs and colour lighting effects to users. These pilot studies had users identify stimuli which could be emotionally rated as strongly pleasant, unpleasant, and neutral. The main study then examined combinations of these two modalities and additionally presented them with text messages to observe if the perceived emotional content of the text messages could be augmented. The initial results revealed that the Ring*U could communicate emotion, and that the messages' valences appeared to be affected by the Ring*U device. However, when these results were compared to the pilots, which rated the message stimuli on their own without the Ring*U being worn, it became clear that the Ring*U exhibited a strong neutralisation effect over the valence of the text message content. This diminished the applicability of using the Ring*U's multimodal functionality for augmenting the perceived emotional content of text messages.

In Chapter 4, this thesis explored the use of temperature as a communication modality and constructed an implementation, the Thermal Array Display (TAD). There are challenges with using temperature in HCI research, however. First, temperature is carried on nerve endings that have slow response times for the human subject to both perceive and react to the thermal stimulus applied to the skin. Second, the body's poor ability to localize temperature on the skin results in non-linear interactions which occur due to the un-uniform distribution of cool and warm receptors under the skin's surface. Third, the limitations of thermoelectric coolers (TECs) are high power consumption, high latency with detectable temperature changes occurring over seconds, and low accuracy. The TAD was constructed with the intent of examining these physiological and technical constraints closer. The resulting implementation was an array-based, thermal display that could output temperature patterns of warm, cool, and neutral temperatures safely to users.

Chapter 5 investigated signalling discrete thermal feedback, first by examining the feasibility of providing thermo-spatial patterns for users to discriminate, and then to investigate how the TAD could be used to signal thermal states using spatial summation as a parameter. A pilot study was conducted to observe if participants could discriminate alternating warm and cool thermal-spatial patterns presented on the forearm from the TAD. The study, however, demonstrated the difficulty of discriminating thermo-spatial patterns, attributed to the non-linear interactions caused by stimulating areas of skin tissue in close proximity. The main study then experimented with several approaches to observe how effectively participants could differentiate temperature values on a scale. The first approach, the Single Method, used only one stimulator to present a temperature state. The second approach, the Amplification Method, used all three stimulators which were set to the same temperature value to signal the temperature state. The third approach, the Quantification Method, indicated a temperature state by setting the quantity of activated stimulators set to either the warmest or coolest temperature value on the scale. The results confirmed some advantages of a multi-stimulator approach to thermal stimulation, with the Amplification Method outperforming the other two methods in terms of error rate and the degree of error.

Chapter 6 investigated using the TAD to signal continuous thermal feedback, which did not require resetting the temperature to neutral each time a new signal was sent. A study then investigated if the continuous feedback could provide directional cues for guidance in a 2D maze task. The results demonstrated that the participants who received the thermal feedback performed significantly better than the participants who did not receive the thermal feedback for a given maze, in terms of the amount of moves made and the time taken to completion (in seconds). Thus, despite the latency of the temperature changes, the subjects who did not receive the thermal feedback made more moves and took longer to complete each maze compared to subjects who did have thermal feedback provided to guide them. These results showed that continuous feedback could provide reliable information from a thermal display.

Chapter 7 investigated whether or not temperature presented using the TAD could be used to augment the perceived emotional content of text messages. HCI literature was reviewed which examined how temperature could communicate emotion as well as how temperature could augment the perceived emotion of other media, such as music and images. Pilot studies in this chapter demonstrated that subjects could assign emotional ratings to messages using the SAM scale. Furthermore, the subjects could also assign ratings of arousal to temperature states consistently. However, the mapping of which temperatures felt either pleasant or unpleasant appeared to be user dependent: some subjects perceived warmer temperatures as feeling pleasant (high valence) and cooler temperatures as feeling unpleasant, while other subjects attributed warmer temperatures as unpleasant and cooler temperatures as pleasant. There were also other subjects who attributed specific temperature states of cool or warm to either feeling emotionally pleasant or unpleasant.

The main experiment in Chapter 7 then combined the messages and thermal stimuli tested in the pilot into pairs to examine whether temperature could augment the perceived emotional content of text messages. Results of the main study demonstrated that (1) warm temperatures were perceived as more arousing than cool temperatures, (2) the message content was highly effective at conveying valence but temperature was ineffective, and (3) temperature exerted a discernible and reliable effect on arousal when paired with neutral messages. This last point was also observed when temperature states were paired with low and high arousal messages, providing an additive effect on the subjects' perceived arousal of the texts. Furthermore, no reliable interaction effect was found between the temperature states and messages for arousal. Thus, the thermal states could portray emotional arousal to participants as effectively as the text messages.

8.2 Research Questions

8.2.1 Research Question 1

Can a mobile smell display augment the perceived emotional content of SMS text messages?

The results of the experiment in Chapter 3 revealed that, while smells could consistently convey particular emotions by themselves, emitting those smells with the Scentee to augment text messages was difficult and no significant differences could be found between the smell types. The results of the main study showed evidence that the dispersed scents were not thoroughly removed from the environment, despite the measures undertaken to do so, and that there remained the strong possibility that these lingering smells may have interacted with subsequent presented smell stimuli. In addition, the results also pointed to a relationship between pairing the smells and messages together, as the smells emitted from the Scentee neutralised the valence of the messages. However, there was no statistically, significant evidence over which smells had a greater effect on neutralising the message valence than others.

Furthermore, there was no evidence that the valence of the messages were augmented at all: pleasant smells did not cause text messages to be perceived as more pleasant, nor were unpleasant smells shown to make unpleasant messages feel less pleasant. Surprisingly, the addition of smells, regardless of their type, appeared to actually make unpleasant messages feel slightly pleasant with respect to neutral rather than slightly unpleasant, as the smells neutralised the perceived emotional content of the messages.

The experiment also demonstrated that smell can be highly subjective and required significant attention from the user in order for the user to both perceive and emotional evaluate the emotional meaning of the stimuli. This was evidenced by the time logs, which revealed the long length of time it took subjects to rate each stimulus, as well as whether (or not) subjects were able to correctly detect that either a pleasant or unpleasant smell had been presented to them or if they were presented with just water, which had no scent. This latter point, the detection frequencies, revealed that participants detected smells at nearly chance levels (almost 50% of the time). Both of these observations limited the application of using the Scentee for communication in the real world. While the smells by themselves could significantly communicate emotion to subjects, as evidenced in the pilot results, it remained doubtful if using the Scentee in the context described in this chapter could augment the perceived emotional content of the text messages with the smells.

Because of these issues, the utility of using the Scentee to augment the perceived emotion of text messages was considerably diminished. Smell would need to be better controlled with the Scentee, to prevent lingering and to prevent interacting with other smells. There was also the issue of response time to both detect and emotional perceive the combined smell and text message stimulus. This time would need to be significantly reduced to have practical applications with the Scentee. Therefore, the empirical studies carried out in this chapter indicated that using the Scentee in these circumstances to communicate emotion is quite challenging and could not augment the perceived emotional content of text messages. Future work should investigate an implementation to enable better delivery of smell and its removal from the environment to minimise any cross-adaption effects resulting from smells lingering and mixing together. For example, an olfactometer device would be more useful for such controlled studies, as it can deliver far more precision to dispersing scents than what the Scentee could provide.

8.2.2 Research Question 2

Can a wearable ring device augment the perceived emotional content of SMS text messages with tactile and colour feedback?

Tactile icons (TCONs) and colored lighting effects were explored as sensory modalities to augment the perceived emotional content of text messages using a ring-shaped device (Ring*U). Previous work in affective haptics experimented with using TCONs to elicit emotional reactions from subjects. However, little work had examined using a wearable ring device to communicate emotion, nor had previous work examined how such TCONs could augment the perceived emotion of text messages. This thesis conducted a study to examine the effect of pairing TCONs with messages and compared them with and without a color effect condition, a primary sensor modality, using the Ring*U.

This experiment initially found that the Ring*U could be used to communicate emotion using the multimodal sensory cues (the TCON and colour stimuli). In addition, the Ring*U appeared, at least in the initial results, to augment the emotion of the text messages: the larger quantity of pleasant modalities made the pleasant messages more pleasant than the other conditions, and likewise, the more unpleasant both modalities became, the less pleasant the valence was rated of the text messages. However, when comparing these results of the main study to those of the pilots, where the text messages were rated without wearing the Ring*U, a clear neutralisation effect was observed, in which the emotion of the text messages was driven to a more neutral state compared to when no modalities were presented with the messages at all.

This neutralization effect was first apparent when examining whether TCONs or colors played a stronger role in augmenting the emotion of the text messages. In general, both appeared to have the same effect on valence: the pleasant TCON produced the same, measured effect on augmenting the perceived valence of the messages compared to the pleasant colour, and similarly, the unpleasant TCON produced the same, emotional effect of augmenting the perceived valence of the messages compared to the effect from the unpleasant colour. Statistically, there were no significant differences between either modalities effect on the text messages' valences or when their emotional effect was compared to the neutral condition (the absence of both colour and vibration). When comparing the most pleasant and most unpleasant conditions (where both the TCON and colour channels were set to either pleasant or unpleasant), users still gave higher ratings to the pleasant messages and gave lower ratings to the unpleasant messages when they did not wear the Ring*U at all: when the message was rated for its emotional content on its own. This was surprising, as the only difference in the main study was that the user was simply wearing the Ring*U when perceiving the emotional content of the text messages.

To address the research question, the Ring*U did not augment, but rather neutralized, the perceived emotional ratings of the messages. If the Ring*U had augmented the messages, pleasant messages would had been rated even happier (if augmented with pleasant stimuli) and unpleasant messages would had been rated less happy (if augmented with less pleasant stimuli). This ultimately reduces the contribution of the Ring*U to present multimodal cues for augmenting the perceived emotional content of text messages. This thesis does not argue, however, that vibrotactile feedback cannot be interpreted emotionally, as the pilot results clearly showed that they could. Rather, it argues against the usage of a ring to provide such feedback to augment the emotional content of text messages, as wearing the Ring*U either reduced the pleasantness, or decreased the unpleasantness, of the text messages' valences, making them feel more neutral compared to just perceiving the text messages' contents alone.

8.2.3 Research Question 3

Can a wearable array of thermal stimulators be constructed to provide information using temperature?

A novel, array-based, thermal feedback system was proposed and described in Chapter 4 called the Thermal Array Display (TAD). The TAD incorporates thermoelectric cooler (TEC) units that are driven using simple, off the shelf, electronic components. In addition, a PID controller is used to control each stimulator's temperature set point in the system's control software, and different methods of tuning the PID controller for thermal feedback was examined during the construction process. The resulting implementation was a thermal display that incorporated many safety features, such as large heatsinks and DC fans to dissipate heat, safety thermal thresholds, and a copper plate medium to deliver the thermal cues comfortably to the skin. In addition, the TAD's ability to display alternating patterns of warm, cool, and neutral temperature stimuli is a unique feature compared to most previous work, and it allowed for further study of thermo-spatial patterns, which will be discussed in the next research question. Thus, a wearable array of thermal stimulators can be constructed to provide information (such as thermo-spatial patterns) using temperature.

8.2.4 Research Question 4

What are the benefits of using an array of thermal stimulators over a single stimulator design?

This research question was addressed in two studies, both of which used the TAD developed in Chapter 4. The first (pilot) study examined if users could discriminate thermo-spatial patterns of alternating temperatures felt on the arm (which cannot be achieved if using just one stimulator). The second (main) study then examined three different methods of signalling seven, discrete temperature states on a scale from 'Coolest' to 'Warmest'.

The results of the pilot study clearly demonstrated that users could not easily discriminate thermo-spatial patterns, as none of the participants could accurately discriminate any of the patterns presented to them using the TAD. Furthermore, confidence ratings indicated that participants were not confident about their responses. It was concluded that participants had a great deal of difficulty in perceiving the patterns when asked to match what they thought they were experiencing with visual representations of the patterns on a screen. This result makes it impractical to assign data, or qualities, to temperature values at specific stimulator positions within a thermal-spatial pattern for further research.

The main study then experimented with three approaches to observe how effectively participants could differentiate different temperature states on a scale with the TAD implementation. The Single Method used only a single stimulator to present a temperature state. The Amplification Method used all three stimulators set to the same temperature value to signal the temperature state. The Quantification Method indicated a temperature state by setting the quantity of activated stimulators to either the warmest or coolest temperature value on the scale. The results of the study demonstrated that the TAD device enabled more reliable discrimination of different temperature states using the Amplification Method and Quantification Method than the Single Method, using a smaller temperature scale (29°C to 35°C) than what had been previously tested with in studies that indicated temperature on scales from cool to warm. The error rate and degree of error of the Amplification Method were significantly lower than the Single Method and resulted in less error rates than the Quantification Method, though no significant differences were found in the degree of error between the two multi-stimulator methods. Within a degree of error, participants could detect different temperature values of warm and cool, and they could accurately detect the neutral state. Thus for discrete signalling, the benefit of using a multi-stimulator design is that it can utilise spatial summation as a parameter to convey thermal states better than a single stimulator design.

8.2.5 Research Question 5

Can continuous feedback provide reliable information from a thermal display?

The study in Chapter 6 examined how well continuous thermal feedback could provide navigational information to users. The study demonstrated the effectiveness of continuous thermal feedback for guiding navigation behaviour without having to pause between signals to re-adapt the skin as was done in the studies in Chapter 5. This was the first experimental evaluation of using continuous feedback for guiding navigation in a 2D maze. The results showed that thermal feedback enhanced user performance, in terms of the number of moves made and the time users took to complete the mazes, compared to when there was no feedback provided. This thesis advocates the usage of continuous thermal feedback in situations where feedback can be ambient, remaining in the periphery of a users' attention span and only shifting to their attention when users need to notice the change in temperature. Thus, continuous feedback can provide reliable information, such as guiding user navigation, from a thermal display.

8.2.6 Research Question 6

Can a wearable array of thermal stimulators augment the emotional content of social media messages?

The experiments in Chapter 7 demonstrated that temperature could influence the perceived arousal of a text message but not the perceived valence. Message content was highly effective at conveying both arousal and valence, but temperature alone was ineffective at conveying valence: the valence of the text messages was found to dominate the emotion communicated to the user when combined with the temperature cues. However, the temperatures had a reliable, main effect on arousal when paired with the messages, and especially with the neutral message. In general, warm temperatures conveyed increased arousal and cool temperatures conveyed decreased arousal. This had a significant effect of the subject's perceived emotion of the text messages: warm temperatures caused messages to be perceived as more arousing to subjects, and cool temperatures led to the messages being perceived as less arousing. It can be concluded from these results that temperature generated a consistent arousal response in subjects for all types of messages.

8.2.7 Main Research Question

Can additional information, such as emotions and navigation assistance, be communicated through different implementations of sensory displays that use smell and touch?

There is little evidence in the research presented in this thesis that supports using the Scentee and Ring*U implementations to present information that can, for example, augment the emotion of text messages. The sense of smell could communicate valence, as was demonstrated by the results of the pilot which showed that subjects could assign consistent emotional ratings to the smells selected. On the other hand, using the Scentee to present smell was found to be poor for augmenting the perceived emotional content of text messages. Smell emitted from the Scentee was difficulty to control, and possibly mixed with lingering smells in the environment to create cross-adaptation effects. These effects on the perceived valence of the text messages caused subjects to rate their affective reactions at chance levels when they were asked to rate how the combined stimuli made them feel emotionally. Additionally, detection was poor, and subjects took considerable time to emotionally rate the smell stimuli. Similarly, multimodal cues, such as TCONs and colored lighting effects, could each communicate valence on their own with the Ring*U. However, usage of the Ring*U to augment the emotion of text messages was difficult: the Ring*U conversely neutralized the perceived emotions of the text messages instead.

On the other hand, the temperature implementation used in this research, the Thermal Array Display (TAD), was demonstrated to be an effective means of displaying various kinds of information to users. While users struggled with identifying thermo-spatial patterns using the TAD, they were able to appreciate different states of warmth and cool better than using a single stimulator. Additionally, while users were able to understand discrete thermal feedback, that is, feedback that requires resetting temperature to neutral each time a new cue is sent, they were also able to understand continuous thermal feedback as well, which does not require resetting temperature to neutral. Furthermore, continuous feedback was shown to be able to communicate information to users, in the case used in this thesis, navigation assistance in a 2D maze. Finally, the TAD demonstrated using discrete thermal feedback to augment the emotion of text messages: warm feedback caused subjects to perceive the messages as more arousing, and cool temperatures caused them to relax, though the valence of the text messages still dominated over the thermal feedback provided.

8.3 Limitations and Future Work

8.3.1 Environmental Considerations

This thesis acknowledged some limitations in how carefully controlled the studies presented in this research were and how these limitations may had influenced their results. Controlling the testing environment was difficult and requiring its control reduces the application of using multisensory feedback in real life use cases. Nevertheless, better environmental control in this thesis' experiments might had eliminated some external factors to allow for a better understanding of the effect of such stimuli on emotion. For example, the uncontrolled temperature of the environment might had influenced the perception of the smells, as temperature may vary the release of volatile compounds in scents (Green, 1993). The ambient temperature in the testing room might had also modified the sensitivity of vibrotactile feedback tested in Chapter 4 (Green *et al.*, 1979).

Environmental factors might had also influenced why there was no observed thermal effect on valence in Chapter 7. Ambient temperature might had changed the way users emotionally perceived the warm and cool temperatures, since environmental factors can influence thermal expression (Lee and Lim, 2010). None of the thermal studies in Chapters 5 - 7 controlled the ambient temperature in the rooms the studies took place, and all studies were conducted at different times of the year. Future research should investigate the effect of ambient environmental temperatures and control them in further studies that examine the effect of temperature cues on the emotional content of media.

Particularly, in the smell studies, better control of the dispersed scent and its disposal might had also eliminated the cross-adaptation effects from occurring, and it could had greatly improved the detection rates of perceiving a smell when presented (and especially not detecting a scent when the smell presented was water). Smell might had also affected the environment as the scents lingered. This would had resulted in the contamination of the environment, should the smells had gradually mixed until the effects of cross-adaptation would had occurred. The use of a box fan was crucial to blow scents outside through a window, but wind from the outside might had blown some of the smells back into the room.

8.3.2 Data Collection

One of the biggest changes in the thermal chapters compared to the early studies in this thesis was how subjects reported their responses to the thermal stimuli using Likert and SAM scales. This was markedly different from the emotion wheel implementation discussed back in Section 2.4.1.1. As was discussed in Section 7.2.1, the emotion wheel approach has several complications. First, it may had been too complicated to use: subjects were given a total of 57 possible selections on the wheel, all of which were arranged in an abstract manner that may had been too incomprehensible. The emotion wheel is less illustrative than the SAM method, which presents pictures of manikins to illustrate concepts like valence and arousal. Furthermore, the idea that emotion has 'intensity', may had been too abstract of a concept to directly present to subjects, as it may had been unclear as to what exactly the intensity of the emotions was representing in the wheel. Finally, the emotion wheel may had not covered all emotions that the user may had felt, particularly those that strictly lie on either the horizontal or vertical axis of the wheel.

Additionally, the emotion wheel presents a challenge in how to quantify the data collected so that it can be analysed. As the emotions are categorical, this research presented an approach to quantify the emotions based on their position in the wheel. This was used to determine the selected emotion's respective valence and arousal, and then its intensity, which was used to determine the strength of its valence and arousal. This presented a tedious and unnecessary step to convert the emotion wheel results into 'valence ratings' and 'arousal ratings', as this thesis described them to differentiate these ratings from the original ratings on the emotion wheel. This conversion may had also resulted in some loss of data, as two emotions in the same quadrant share the same valence and arousal, though one could have a higher degree of valence or arousal than the other, which was ignored in the conversion.

These reasons might had effected why the Scentee and Ring*U implementations were not as emotionally effective as the thermal implementation assessed later in this thesis. While the choice of the emotion wheel is not the only limitation in the earlier studies (it certainly does not explain the detections in the smell study), its choice may had played a role in why subjects did not give consistent ratings with the Scentee device or why the Ring*U appeared to neutralise the emotions of the text messages. Therefore, this thesis advocates the use of the SAM scale due to its simplicity in gathering and analysing valence and arousal ratings of similar stimuli for future work.

8.3.3 Study Design

The study designs in Chapters 2 and 3 were arguably not as robust as the later chapters with temperature, as lessons were learned from the earlier studies to make more informed decisions of how to design better studies in Chapters 5 – 7. These limitations include the translation of English text messages into Japanese, the criteria used to select neutral messages in Chapter 2, no repeating stimuli, lack of contexts, and labelling devices. Many of these limitations were discussed previously in Chapter 2 (Section 2.6.4) and will be reiterated here for summary.

The choice to translate English SMS messages into Japanese may had been a limitation. Though the texts were accurately translated, they may had carried different connotations in Japanese and interpreted differently by male and female participants. As non-native English speakers rated the British English texts chosen from the corpus after they were translated, a question could be raised of how valid the responses actually were. This was a major reason for the decision to not reuse these messages for the study in Chapter 7, as the emotional ratings of these messages may had not reflected how English speakers would had rated them.

Another limitation may had been the criteria used for selecting neutral messages in Section 2.4.2.3, as the same criteria had not been applied for selecting other neutral stimuli, like the smells. Instead of being neutrally rated, these messages may had rather been 'ambiguous' to the subjects, since the criteria only considered minimising the difference of the subjects' pleasant and unpleasant emotional ratings. Thus, the neutral messages may had not been truly emotionally neutral, though the analysis in Section 2.4.2.3 showed that they were similarly rated.

A limitation with the smell study in Chapter 2 could had been the Scentee devices themselves and how they were labelled. Despite efforts to clean them after use, there may had still been traces of residue left inside the Scentees, which could had contaminated the scent stimuli. Participants also claimed to had been distracted by the Scentee technology, since it was seen as a 'cool' piece of technology which enabled an ordinary mobile phone to disperse scents. Consequently, this caused them to focus more on the novelty of the technology rather than the scents, and they admittedly rated the stimuli more pleasantly because of this. In addition, the subjects could also see the labels on the Scentee devices ('A+, 'B+', etc.), which were used by the experimenter to know which Scentee to attach to the phone next. Though subjects were not told what the labels were, they may had still been able to remember what a smell was if they had seen the label previously, which may had caused unintentional priming to occur.

Another limitation of the studies in Chapters 2 and 3 was that stimuli were not repeated. Repeating the stimuli two or three times, as was done in the later studies with temperature feedback, might had allowed insight as to whether subjects were rating stimuli consistently, or if they were selecting ratings by chance, which is what the main study in Chapter 2 indicated. However, a reason why stimuli in some of the studies in Chapter 2 were not repeated was because of the amount of trials that needed to be tested, particularly, the trials in the message pilot study and in the main study. Repeating them would had made the studies last too long, risking fatigue in the participants. Nevertheless, this was an important consideration learned for designing the latter temperature studies in this thesis.

Finally, there was also a limitation with regards to the context (or lack of) in which to interpret the stimuli in Chapters 2, 3, and 7. Subjects found it hard to rate stimuli without a context, especially when they did not know who the sender was. They remarked that they needed to know how close the sender was to them as it affected how they would react. This was a limitation that was considered more carefully in the experiments of Chapter 7: the instructions in that chapter specified that "The message post should be treated as if one of your friends on Facebook had posted it." Still, context continued to be a challenge in Chapter's 7 main study, as the "friend" in question could had been interpreted in various ways, such as a friend that they were close to or a friend that they might have had a recent fight with. Context is an important consideration that should not be overlooked in future work, especially with thermal feedback.

8.3.4 Thermal Feedback Technology

The thermal-electric coolers (TECs) used in the construction of the TAD device were not originally designed for human haptic applications, and their usage with the TAD required users to extend their arms out for long periods of time during the studies, due to their rigid and stiff form factors. This might had resulted in some discomfort, which might had influenced the participants' ratings of the temperatures and messages. As such, different form factors should be considered in future work. For example, a thermal enabled Ring*U, with a casing made from heat conducted metal, could be considered over the design of the TAD for better aesthetics and comfort, since a ring design does not require the user to manually strap bulky stimulators to their arm like that in the TAD design. Thermal-enabled shoes could also embed the TEC technology within the insoles, the material of which could be replaced by a soft, graphite-based material for transferring the heat. However, the problems with these two examples are that they stimulate areas of the body that have poor perception of detecting temperature changes (Stevens and Choo, 1998): the fingers for a ring design and the feet for the shoes. The arms and palms of hands, along with the head, on the other hand, are more suitable for temperature reception. Thus, future work should investigate areas of the body that are excellent at perceiving temperature changes that are also associated with garments that can be easily worn or attached to the body.

There are also challenges with creating portable and wearable devices with TECs that result from their size and power constraints. Most standard TECs that are accessible on the market can be rated as high as 60 Watts, and thus are capable of pumping heat faster than the TECs used in this thesis. However, they are also larger (4 cm^2) than the ones used in this thesis (1.5 cm^2). Such a size is too large and the form factor too rigid for aesthetically pleasing and comfortable form factors. Additionally, the power constraints demand larger and more efficient power supplies, like batteries, for mobile and wearable usage, which would inevitably drive up the cost and total size of the wearable device. Power constraints also require even larger means of dissipating the wasted heat, as TECs are largely inefficient in this respect, which will further increase the size of the wearable.

Therefore, experimenting with different size TECs could be an interesting venue to explore in future work. This was an area of interest initially in this research. However, due to time and budget constraints, this thesis took a conservative approach and used smaller TECs instead. Nevertheless, it is possible that the size of the TEC may influence results as larger TECs would stimulate more skin area, which could increase the intensity of a stimulus (Stevens and Marks, 1971). Larger TECs would also have the benefits of faster rates of change with the trade-off of more heat dissipation, especially if the device is meant to be worn like the TAD. Future work should experiment with different size TECs to establish an upper and lower bound on what is permissible with the TEC design for human interaction purposes.

One area of thermo-dynamics research which could potentially mitigate the issues of TEC size, power, and heat dissipation, is the use of thin-film thermoelectric coolers. These operate on the same basis as the TECs used in this research and previous HCI literature. However, they are fabricated using a different manufacturing process that utilises techniques from the micro-electronics industry, like surface mounted components (SMD). Consequently, this results in a drastically reduced footprint, while maintaining similar power ratings to transfer heat using less space. They are also vastly more power efficient in comparison to standard TECs, which could drastically improve battery usage and require less invasive ways of dissipating wasted heat, such as the use of fans and heat sinks in the TAD design. This may open new possibilities in wearable computing that could be explored in future work.

Another improvement with better hardware would be the ability to adapt presented temperature values with the surrounding environmental ambient temperatures. As examined in Chapters 4 - 7, almost all research conducted in HCI had used static temperatures for re-adaption and parameters of the thermal stimuli. For example, the neutral temperature used in this thesis was 32°C, which was discussed as a suitable point within the adaptable range of resting skin temperatures, with 29°C and 35°C temperatures as minimum and maximum temperature values, both of which fell within the scale ranges specified by the literature reviewed. However, the neutral temperature is actually not a single, discrete point, but instead a continuous range of temperatures in which the skin does not feel a temperature change. This range can fluctuate in a given sample size, which is caused by individual differences between people who may adapt better to other neutral temperatures, such as 30°C or 33°C. In addition, there also might had been differences in the sensitivity of subjects between temperatures changes, as the temperature scale used was centred on a single neutral point, instead of adapting the scale to suite different neutral points, which could had been calibrated beforehand by measuring the sensitivity of the user. As was observed in the main study in Chapter 5 (Section 5.2), some subjects were better at detecting smaller temperature differences than others, who required feeling the warmest or coolest temperature values in the scale in order to perceive any change.

To mitigate these issues, future work should investigate integrating the ambient, or surrounding temperature, as well as the user's resting skin temperature beforehand as input to the system for setting the neutral temperature. Adapting the ambient temperature could also be used to set different parameters of the temperature stimuli, such as the rate of change, the magnitudes or differences between each thermal state used on the scale, or in the case of continuous feedback, the maximum and minimum thermal values. This data could be obtained using additional sensors built into the stimulator unit to detect the resting skin temperature, built into the control circuit to detect the room temperature, or could be drawn from online information sources to detect the ambient temperature resulting from the weather outdoors.

8.3.5 Spatial Navigation

Spatial navigation was chosen to test the utility of continuous thermal feedback in Chapter 6. It was found that continuous thermal feedback improved user performance in a navigation task compared to when the user was only presented with limited visual information on a screen. While the focus of the study was mainly to demonstrate the effectiveness of continuous thermal feedback, the further application of temperature in real life navigation scenarios could be an area worth exploring further.

Figure 8.1: Game examples with minimaps in the top right corner of their screens. Left - Enemy Territory: Quake Wars. Right - Lost Planet: Extreme Condition.

Future experiments could investigate applications such as 3D gaming, where a character traverses over a complex and unfamiliar area. Usually in such a game, a 2D minimap is overlayed on top of the game world display in a corner of the screen, such as in the top right corner of the screens in Figure 8.1. The minimap contains a simplified view of the overall game world terrain (or a large portion around the player), along with enemy locations, pickup items, etc. However, it is distracting for the player since they need to glance at it to figure out their orientation in the 3D world space, as well as avoiding enemies and collecting items at the same time.

One idea is to extend the minimap data to a temperature display. Players could then use the temperature feedback provided to orient or guide them toward a goal or particular items within a game world. This could also lead to further studies in mixed reality, where a user wears a portable temperature device and would be tasked with finding a destination in a city setting. Thermal feedback could provide such ambient cues for pedestrian exploration of city centres, by allowing the traveller to make serendipitous discoveries along the way (Traunmueller and Fatah gen Schieck, 2013) using a thermal-enabled pedestrian navigational system.

The idea could also be adapted to automobile satnav systems where thermal feedback could be incorporated into steering wheels. TECs are already used in automobiles to cool and heat seating and steering wheels and to prevent drowsiness (Chang, 2015). This hardware could potentially be appropriated to provide navigational cues to drivers as well.

8.3.6 Using Temperature Cues to Reinforce Arousal

The results of Chapter 7 demonstrated that temperature could affect the perceived emotional arousal content of text messages. Temperature feedback may therefore be useful for those with cognitive impairments, such as Autism, which may impede the sensing of the emotional content of messages sent from social media (Lartseva *et al.*, 2014). Sufferers of autism could wear a thermo-enabled device, or be situated in a computer environment, such as a desk chair that provides thermal feedback, similarly to what is done in vibrating chairs used for massage, to allow the person to sense that a message they received is, for example, intended to excite them.

Another possible application is education, where language learning could be reinforced by augmenting foreign sentences with temperature, which could be mapped to intended emotional meanings of words. Again, it would be worth exploring the form factors for such scenarios so that they would be more applicable to the situation of the user. In the case of language education, one possible form factor may be thermal-enabled headphones. Audio tracks could be synchronized with thermal cues, the head being an ideal body location as it is also very sensitive of temperature changes.

8.4 Conclusions

This thesis investigated how additional information, such as emotion and navigational assistance, might be communicated through technology-based implementations of sensory displays that output smell and touch (both vibrotactile and temperature) feedback. This was achieved by examining a variety of areas in olfaction and cutaneous touch literature, in order to build and assess technology implementations that could be constructed using off-the-shelf components or were readily available on the market as affordable products. For smell, a commercial product, Scentee, was used to deliver scents to users. For vibrotactile touch, as well as additional colour lighting effects, the Ring*U was developed, which used a familiar form factor that could be easily worn like a real ring. For thermo-touch, the Thermal Array Display was developed initially to investigate how well participants could discriminate thermo-spatial patterns.

The chemical sense of smell was investigated initially to examine the possibilities of communicating emotion. No previous research had investigated how smell could be used to augment the perceived emotional content of text messages. The pilot study carried out in this thesis (Section 2.4.1) demonstrated that subjects could agree on the perceived valence, or pleasantness, of scents. However, the delivery of scents within a controlled environment using the Scentee was a challenge (Section 2.6), and cross-adaptation effects resulting from lingering smells might had made it difficult for subjects to emotional rate the intended smell presented to them along with the message. This, along with the unusually long time it took subjects to emotional rate the stimuli, and along with poor detection of smells when they were presented to the subjects, diminished the applicability of using the Scentee in text-based communication.

Subsequent research in this thesis examined using multimodal cues sent from a ring shaped device to augment the emotional content of text messages. The ring-shaped device, called Ring*U, was developed over the course of three iterations (Section 3.4), to signal these multimodal cues to subjects. Several pilot studies (Section 3.5) were then carried out which asked subjects to emotionally rate the multimodal cues separately. These multimodal cues consisted of two types of sensory modalities: Tactile icons (TCONs), from affective haptics, and colour lighting effects. The pilot test results showed that subjects could emotionally rate the TCONs by themselves when the TCONs were presented using the Ring*U system, and that subjects could emotionally rate the colour stimuli as well. Furthermore, the initial main study results (Section 3.6) demonstrated that the Ring*U appeared be able to augment the valence of the text messages. However, after comparing the results of the main study with those of the pilot, where the messages were rated without wearing the Ring*U, it was discovered that the Ring*U neutralised the emotional effect of the messages when the subjects wore the Ring*U while reading the content of the messages. This reduced the applicability of using the Ring*U as an appropriate communication tool for augmenting the perceived emotion of text messages from social media.

This thesis finally examined using temperature as a communication modality. Temperature however, is slowly perceived and suffers from non-linear interactions when temperature sensations are applied too close to each other on the skin. The Thermal Array Display (TAD) system was constructed to examine these issues further (Chapter 4), and to determine if participants could discriminate alternating warm and cool thermal patterns on the forearm. A study demonstrated the difficulty of this task however, due to the discussed non-linear interactions caused by stimulating areas of the skin in close proximity (Section 5.1).

However, there is a use for temperature to convey ambient information and arousal, which can be signalled either as discrete states (Section 5.2) or continuously (Chapter 6). In discrete signalling, several approaches were trialled to observe how well participants could differentiate several temperature states of warmth and cool. The results confirmed the advantage of using a multi-stimulator approach in terms of error rate and the degree of error when compared to the single stimulator use case. Furthermore, this thesis described the first controlled study of using continuous thermal feedback to provide directional cues for guidance in a 2D maze task. Participants who received the thermal feedback performed significantly better in terms of moves made and the time taken to complete each maze compared to subjects who were not provided feedback to guide them. This thesis also provided the first study in which temperature was shown to augment the arousal of social media text messages (Chapter 7), especially when the content of the text messages was neutrally rated. The study furthermore demonstrated that warm temperatures were sensed as more exciting than cool temperatures, and that warm temperatures could subsequently cause the perceived arousal of text messages to feel more arousing and likewise, that cool temperatures could cause the subjects' perception of text messages to feel less arousing. The results of the study therefore, found that temperature signalled by the TAD can be used to augment the perceived arousal of test messages from social media.

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Appendix A

Chapter 3 Data

A.1 Pre-Test Results

Smell ID	Smell Name	P1-Male	P2-Female	P3-Female	P4-Male
1	Dust	Disgust 2	Disgust 4	Fear 2	Acceptance 3
2	Pink Grapefruit	Acceptance 4	Joy 2	Anticipation 1	Disgust 2
3	Baby Powder	Disgust 1	Joy 4	Fear 2	Sadness 3
4	Swimming Pool	Anticipation 2	Joy 6	Joy 2	Joy 5
5	Oud	Disgust 2	Joy 1	Sadness 4	Sadness 4
6	Mildew	Disgust 5	Sadness 2	Sadness 3	Neutral 0
7	Fresh Hay	Anticipation 2	Joy 6	Disgust 3	Fear 3
8	Rain	Sadness 2	Sadness 1	Angry 1	Sadness 4
9	Dirt	Disgust 5	Disgust 3	Anticipation 2	Acceptance 3
10	Pure Soap	Joy 5	Joy 5	Angry 4	Disgust 4
11	Earthworm	Disgust 6	Disgust 6	Anticipation 2	Joy 1
12	Honey	Disgust 2	Joy 6	Joy 4	Angry 3

A.2 Pilot Participant Information

Participant	P1	P2	P3	P4	P5	P6	P7
Gender	Female	Male	Female	Male	Male	Female	Male
Age	24	22	23	24	23	23	23
Nationality	Japanese	Indonesian	Brazilian	Japanese	Japanese	Japanese	Japanese

Participant	P8	P9	P10	P11	P12	P13	P14
Gender	Male	Female	Male	Male	Female	Female	Male
Age	22	24	25	23	29	27	23
Nationality	Japanese	Japanese	Japanese	Japanese	Taiwanese	Japanese	Japanese

Participant	P15	P16	P17	P18	P19	P20
Gender	Male	Female	Female	Male	Male	Male
Age	23	23	19	23	22	25
Nationality	Japanese	Malaysian	Brazilian	Japanese	Japanese	Japanese

A.3 Smell Pilot Results

Smell ID	P1	P2	P3	P4	P5	P6	P7
1	Disgust 2	Disgust 2	Disgust 4	Disgust 2	Disgust 1	Fear 4	Acceptance 3
2	Anticipation 7	Acceptance 4	Anticipation 5	Acceptance 3	Anticipation 2	Acceptance 5	Disgust 2
3	Disgust 6	Disgust 1	Acceptance 2	Joy 4	Joy 2	Acceptance 1	Sadness 3
4	Acceptance 7	Anticipation 2	Surprise 3	Disgust 2	Sadness 3	Joy 5	Joy 5
5	Fear 5	Disgust 2	Sadness 2	Acceptance 2	Acceptance 2	Sadness 5	Sadness 4
6	Disgust 7	Disgust 5	Disgust 3	Disgust 5	Angry 2	Angry 3	Neutral 0
7	Anticipation 7	Anticipation 2	Disgust 7	Sadness 3	Acceptance 4	Joy 4	Fear 3
8	Surprise 2	Sadness 2	Disgust 7	Disgust 5	Sadness 5	Surprise 4	Sadness 4
9	Fear 3	Disgust 5	Disgust 7	Sadness 4	Anticipation 2	Neutral 0	Acceptance 3
10	Acceptance 7	Joy 5	Joy 6	Acceptance 4	Sadness 2	Anticipation 4	Disgust 4
11	Disgust 7	Disgust 6	Angry 2	Angry 3	Disgust 2	Disgust 5	Joy 1
12	Disgust 7	Disgust 2	Acceptance 5	Fear 2	Anticipation 3	Fear 4	Angry 3

Smell ID	P8	P9	P10	P11	P12	P13	P14
1	Angry 1	Joy 5	Sadness 2	Anticipation 2	Disgust 4	Fear 2	Sadness 5
2	Acceptance 2	Anticipation 5	Joy 4	Acceptance 4	Joy 2	Anticipation 1	Anticipation 5
3	Joy 4	Disgust 2	Anticipation 3	Acceptance 4	Joy 4	Fear 2	Disgust 5
4	Neutral 0	Acceptance 4	Sadness 3	Disgust 1	Joy 6	Joy 2	Angry 5
5	Angry 3	Sadness 4	Neutral 0	Sadness 2	Joy 1	Sadness 4	Joy 6
6	Angry 2	Disgust 6	Surprise 3	Fear 3	Sadness 2	Sadness 3	Angry 6
7	Fear 4	Sadness 3	Neutral 0	Surprise 1	Joy 6	Disgust 3	Sadness 3
8	Surprise 4	Disgust 2	Fear 3	Disgust 2	Sadness 1	Angry 1	Fear 3
9	Neutral 0	Acceptance 4	Neutral 0	Anticipation 3	Disgust 3	Anticipation 2	Neutral 0
10	Joy 6	Anticipation 4	Joy 4	Sadness 1	Joy 5	Angry 4	Sadness 1
11	Neutral 0	Sadness 4	Neutral 0	Disgust 1	Disgust 6	Anticipation 2	Sadness 5
12	Surprise 3	Disgust 3	Fear 4	Joy 3	Joy 6	Joy 4	Joy 6

Smell ID	P15	P16	P17	P18	P19	P20
1	Fear 3	Acceptance 2	Acceptance 5	Acceptance 3	Fear 4	Fear 4
2	Acceptance 4	Joy 4	Surprise 4	Joy 5	Acceptance 6	Acceptance 5
3	Anticipation 3	Fear 2	Acceptance 5	Acceptance 5	Joy 5	Acceptance 1
4	Joy 4	Neutral 0	Sadness 4	Anticipation 4	Acceptance 5	Sadness 3
5	Acceptance 3	Disgust 3	Disgust 5	Anticipation 4	Sadness 5	Acceptance 2
6	Surprise 2	Disgust 3	Angry 5	Anticipation 2	Fear 3	Sadness 3
7	Surprise 4	Joy 1	Joy 4	Acceptance 3	Sadness 4	Disgust 3
8	Acceptance 5	Surprise 2	Angry 5	Sadness 3	Joy 5	Angry 5
9	Disgust 3	Disgust 2	Angry 4	Neutral 0	Angry 4	Angry 4
10	Anticipation 2	Surprise 2	Acceptance 5	Surprise 4	Sadness 4	Sadness 1
11	Disgust 1	Disgust 2	Disgust 5	Neutral 0	Disgust 4	Disgust 1
12	Angry 3	Fear 2	Joy 4	Anticipation 4	Anticipation 5	Joy 3

A.4 SMS Messages (English)

Text ID	Text Message Contents
1	:-) :-)
2	:)
3	I'm going to try for 2 months ha ha only joking
4	I'll leave around four, ok?
5	Been running but only managed 5 minutes and then needed oxygen! Might have to resort to the roller option!
6	Are you available for soiree on June 3rd?
7	Beerage?
8	Hm good morning, headache anyone? :-)
9	Oops sorry. Just to check that you don't mind picking me up tomo at half eight from station. Would that be ok?
10	Oops. 4 got that bit.
11	Ah, well that confuses things, doesn't it?
12	Aah bless! How's your arm?
13	Err... Cud do. I'm going to at 8pm. I haven't got a way to contact him until then.
14	Erm. I thought the contract ran out the4th of october.
15	Did you show him and wot did he say or could u not c him 4 dust?
16	They can try! They can get lost, in fact. Tee hee
17	I think your mentor is , but not 100 percent sure.
18	I just cooked a rather nice salmon a la you
19	She's borderline but yeah whatever.
20	did u get that message
21	Thnx dude. u guys out 2nite?
22	Thank you. And by the way, I just lost.
23	Good stuff, will do.
24	What time. I'm out until prob 3 or so
25	I like to think there's always the possibility of being in a pub later.
26	R u in this continent?
27	Nope thats fine. I might have a nap tho!
28	No, but you told me you were going, before you got drunk!
29	No. Yes please. Been swimming?
30	Hmm well, night night
31	Hmm ok, i'll stay for like an hour cos my eye is really sore!
32	Annoying isn't it.
33	;-(oh well, c u later
34	Yes i thought so. Thanks.
35	Yeah do! Don't stand to close tho- you'll catch something!
36	Yeah whatever lol
37	Yes i will be there. Glad you made it.
38	Yeah work is fine, started last week, all the same stuff as before, dull but easy and guys are fun!
39	Yes. Last practice
40	Yes fine
41	Yeah no probs - last night is obviously catching up with you... Speak soon
42	yay! finally lol. i missed our cinema trip last week :-(
43	Boo. How's things? I'm back at home and a little bored already :-(
44	;-) ok. I feel like john lennon.
45	What i mean was i left too early to check, cos i'm working a 9-6.
46	Have you been practising your curtsey?
47	:-(sad puppy noise
48	Okay but i thought you were the expert

49	Can not use foreign stamps in this country.
50	Can not use foreign stamps in this country. Good lecture .
51	sorry, no, have got few things to do. may be in pub later.
52	Sorry . I will be able to get to you. See you in the morning.
53	Sorry * was at the grocers.
54	Hi my email address has changed now it is
55	Hello! Good week? Fancy a drink or something later?
56	Hello- thanx for taking that call. I got a job! Starts on monday!
57	Miss ya, need ya, want ya, love ya.
58	Well I might not come then...
59	Well done and ! luv ya all
60	Velly good, yes please!
61	* Will be september by then!
62	I didn't get the second half of that message
63	Ok cool. See ya then.
64	Not sure I have the stomach for it ...
65	:-(that's not v romantic!
66	Lovely smell on this bus and it ain't tobacco...
67	I wonder if you'll get this text?
68	, how's things? Just a quick question.
69	At home by the way
70	Tee hee. Off to lecture, cheery bye bye.
71	[...] anyway, many good evenings to u! s
72	Man this bus is so so so slow. I think you're gonna get there before me
73	whatever, im pretty pissed off.
74	Oi when you gonna ring
75	Did u find out what time the bus is at coz i need to sort some stuff out.
76	Ho ho - big belly laugh! See ya tomo
77	... Are you in the pub?
78	Now thats going to ruin your thesis!
79	Well I'm going to be an aunty!
80	Wow v v impressed. Have funs shopping!
81	See you there!
82	Have you not finished work yet or something?
83	:-) yeah! Lol. Luckily i didn't have a starring role like you!
84	Hi hope u get this txt~journey hasnt been gd,now about 50 mins late I think.
85	Hiya, probably coming home * weekend after next
86	Hiya, had a good day? Have you spoken to since the weekend?
87	Hello! How r u? Im bored. Inever thought id get bored with the tv but I am. Tell me something exciting has happened there? Anything! =/
88	Okey dokey, i'll be over in a bit just sorting some stuff out.
89	Should I have picked up a receipt or something earlier
90	Hey! Congrats 2u2. id luv 2 but ive had 2 go home!
91	Okay, good, no problem, and thanx!
92	Thought we could go out for dinner. I'll treat you! Seem ok?
93	Are you driving or training?
94	Was the farm open?
95	* Thought I didn't see you.
96	* Am on my way
97	Only just got this message, not ignoring you. Yes, i was. Shopping that is
98	This weekend is fine (an excuse not to do too much decorating)

99	Forgot you were working today! Wanna chat, but things are ok so drop me a text when you're free / bored etc and i'll ring. Hope all is well, nose essay and all xx
100	I have lost 10 kilos as of today!
101	Everybody had fun this evening. Miss you.
102	Not tonight mate. Catching up on some sleep. This is my new number by the way.
103	That's a shame! Maybe cld meet for few hrs tomo?
104	I had a good time too. Its nice to do something a bit different with my weekends for a change. See ya soon
105	Lol! Oops sorry! Have fun.
106	No worries, hope photo shoot went well. have a spiffing fun at workage.
107	You know, wot people wear. T shirts, jumpers, hat, belt, is all we know. We r at Cribbs
108	Men like shorter ladies. Gaze up into his eyes.
109	I think I'm waiting for the same bus! Inform me when you get there, if you ever get there.
110	Indeed and by the way it was either or - not both !
111	I'm really sorry i won't b able 2 do this friday.hope u can find an alternative.hope yr term's going ok:-)
112	You all ready for * big day tomorrow?
113	have * good weekend.

A.5 SMS Messages (Japanese Translations)

Text ID	Text Message Contents
1	(・∀・)(・∀・)
2	(^^)
3	２ヶ月試してみるわ。なんてね笑
4	4時くらいに出発するね、平気？
5	5分走っただけで息切れしたよ。ローラースケートに頼るしかないかも！
6	6月３日は空いてる？夜集まってパーティするよ。
7	Beerageって何？
8	あ、おはよう。頭痛いのなおった？
9	あ、ごめん。明日８時半に駅に迎えにきてもらっても大丈夫か確認したくて。大丈夫？
10	あぁ、そのことちょっと忘れてた。。
11	あー、まぁ、それは混乱しちゃうよね。
12	ああ、祈っとく！腕の調子はどう？
13	あぁ。。。出来たかも。８時に行くけど、それまではあの人と連絡とる手段はないよ。
14	あああ。契約は１０月４日に終わるんだと思ってた。
15	あいつにみせた？なんていってた？てかすぐどっかいっちゃった？
16	あいつら、挑戦するらしいよ！実際やったら負けちゃうかもね。てへ
17	あなたのメンターだと思うけど、１００％自身がある訳ではないわ。
18	あなた流のかなりおいしいサーモン料理を今つくってみたよ
19	あのこ、ボーダーラインだったけど、なんとか大丈夫だったみたい。
20	あのメッセージ届いてた？
21	ありがと！今夜、きみたち出掛けるんだっけ？
22	ありがとう。ところで、負けちゃったわ。
23	いいものだね、役に立つよ！
24	いつ？多分３時くらいまでは出かけるよ。
25	いっつも後で飲みにいくかもって考えるの好きなんだ。
26	いま、こっちにいるの？
27	いや、それで大丈夫だよ。仮眠とりたかったけどね！
28	いや、でも酔っぱらう前に、行くっていったじゃん！
29	いや。うん、お願い。泳いでたの？
30	うーん、まぁ夜ね、夜。
31	うーん、わかった。目が本当に痛いから一時間くらいこのままいるわ。
32	うっとうしくない?
33	うん、じゃあまた後で（^_-)
34	うん、そうだと思う。ありがと。
35	うん、だいたいそれくらいの時間に会おう。
36	うん、何でも良いよ！笑
37	うん、後で行くね。うまくいってよかったね。
38	うん、先週から始めた仕事は楽しいよ、相変わらずだけどね、退屈だけど気楽かな。みんな楽しい人たちだよ。
39	うん、前回の練習。
40	うん、大丈夫
41	うん、問題ないよ。
42	うん！結局ね笑、先週、一緒にいった映画楽しかったね、また行きたいな(><)
43	えー。。最近どう？私は家に戻って、もうちょっと退屈してる（＾＾；）
44	おっけ（^_^)ジョンレノンみたいな気分。
45	おっけー！金曜はメジャー持っていくね！
46	お辞儀の練習してたの？
47	ガーン(・_・；)
48	こういうの詳しいと思ったんだけどな。おっけー。
49	この国じゃ、海外の切手は使えません。

50	この国では海外の切手が使えないのか。なるほど
51	ごめん、ちょっとやらなきゃ行けないことあって無理だわ。もしかしたら後でパブに行くかも。
52	ごめん、もうすぐ連絡できるようになると思う。また、朝にね。
53	ごめん、食料品店にいたよ。
54	こんにちは、アドレス変更しました。
55	こんにちは！今週良いかんじ？今後で、飲むかなんかしない？
56	こんにちはー。電話でてくれてありがと。仕事見つけたよ！月曜から始めるんだ！
57	さびしい、会いたい、恋しい、愛してる
58	じゃあ、もしかしたらいけないかも。。
59	すごいよ！みんな大好き！
60	すばらしいねー、うん、お願い！
61	そのときは、もう９月だね！
62	そのメッセージの後半は届いてなかった。
63	それはいいね！じゃあまた後で
64	それを食べる余裕があるか分からないよ・・・
65	そんなにロマンチックじゃないよね(>_<)
66	たばこじゃないけど、このバスすごく愛おしいにおいする。
67	ちゃんとこのメール届いている？
68	ちょっと質問、最近どう？
69	てか、今家だよ
70	てへ、授業に行くね。またね。
71	とにかく、良い夕方を！
72	なあ、乗ってるバスがめちゃくちゃ遅いんだよ。お前もそこ行くことになっていると思うけど。
73	なんにしても、かなり煩わしいよ。
74	ねー、いつ電話するの
75	バスの時間わかった？時間の調整しなきゃいけないからさ。
76	はは、すごいおもしろいね！また明日！
77	パブにいるの？
78	まあ、それだと、卒論はめちゃくちゃになるね
79	まあ、そろそろ私もおばちゃんだ！
80	まじか、それは感心だわ。お買い物楽しんで！
81	また後でー!
82	まだ仕事終わってないの？それとも別の何か？
83	もちろん！^^笑,きみみたいに重要な役じゃなくて運が良かったわ！
84	やあ、このメール届いてるといいな。旅はあまりよくなかったよ。で、５０分遅れると思う。
85	やあ、再来週の週末にたぶん家帰るね。
86	やぁ、良い一日だった？週末から話したっけ？
87	やぁ。元気？私は退屈してる。テレビに退屈なんてしないと思ったけど、あきた。なんかおもしろいことなかった？なんでもいいから！
88	りょーかい。ちょっと整理したらすぐ終わるから。
89	レシートみたいなのもっとはやくもらっとくべきだった？
90	わーおめでとう！行きたいけど、家に帰らなきゃ。
91	わかった、良いね、問題ないよ、ありがとー。
92	一緒にディナー行けるかと思って。おごるよ！それで大丈夫？
93	運転中か練習中かな？
94	会社空いてた？
95	見かけなかったとおもった
96	向かってるところー。
97	今メールきたよ。無視したんじゃないよ。ごめん、したわ。
98	今週末は大丈夫だよ。（いろいろ飾らないための言い訳）
99	今日きみが仕事があったの忘れてた！話したいよー、でも大丈夫。暇なとき、退屈なときにメールして。そしたら電話するから。元気だといいな。

100	今日で、１０キロやせたよ。
101	今晩、みんな楽しんでたね。またあいたいよ。
102	今夜じゃないよ。ちょっと寝ないと。ところでこれ、新しい番号ね。
103	残念！明日、２、３時間あえるかな？
104	私も楽しかった。たまにはちょっと違うことをするのも良いね。また今度ー！
105	笑！あ、ごめんね！楽しんでー。
106	心配しないで、写真撮影うまくいったといいな。仕事、めいいっぱい楽しんで！
107	人々が着てるやつだよ。Tシャツ、ジャンパー、帽子、みんな知ってるもの。クリブにいるよ。
108	男は背の低い女が好きなんだよ。彼の目を見つめてみたら。
109	同じバスを待っていると思う！もしついたら教えて
110	本当だよね、ところでどっちでもいいよ。どっちもやらなくてもいいよ！
111	本当に申し訳ないんだけど、金曜は無理だわ。別の人が見つかると良いね。うまく行くと良いね
112	明日の大事な日に向けた準備,全部できた？
113	良い週末をー

A.6 SMS Messages Pre-Test Results

SMS ID	P1-Female	P2-Male	P3-Male
1	Joy 5	Joy 2	Joy 1
2	Joy 4	Joy 4	Joy 2
3	Surprise 3	Joy 1	Disgust 1
4	Acceptance 4	Anticipation 1	Anticipation 2
5	Surprise 3	Neutral 0	Surprise 2
6	Joy 6	Joy 5	Joy 3
7	Angry 2	Neutral 0	Fear 1
8	Joy 2	Acceptance 1	Joy 2
9	Anticipation 3	Anticipation 2	Anticipation 1
10	Angry 2	Fear 1	Angry 4
11	Anticipation 2	Acceptance 5	Disgust 2
12	Joy 2	Acceptance 3	Joy 1
13	Anticipation 2	Sadness 2	Sadness 2
14	Anticipation 1	Sadness 4	Joy 2
15	Angry 1	Angry 4	Disgust 1
16	Fear 2	Neutral 0	Acceptance 3
17	Angry 1	Acceptance 1	Disgust 3
18	Surprise 2	Joy 2	Joy 4
19	Anticipation 1	Surprise 3	Acceptance 3
20	Anticipation 2	Neutral 0	Neutral 0
21	Surprise 2	Neutral 0	Disgust 3
22	Sadness 2	Sadness 3	Sadness 2
23	Joy 6	Joy 3	Joy 4
25	Anticipation 3	Acceptance 1	Anticipation 2
26	Joy 2	Joy 1	Disgust 3
26	Surprise 2	Anticipation 1	Fear 3
27	Acceptance 3	Acceptance 4	Acceptance 4
28	Anticipation 3	Angry 5	Fear 2
29	Surprise 3	Surprise 1	Disgust 4
30	Acceptance 3	Disgust 2	Anticipation 3
31	Acceptance 3	Neutral 0	Anticipation 3
32	Surprise 2	Anticipation 2	Disgust 6
33	Joy 4	Joy 3	Sadness 2
34	Joy 4	Neutral 0	Sadness 3
35	Anticipation 3	Joy 1	Anticipation 4
36	Joy 5	Neutral 0	Disgust 3
37	Joy 3	Neutral 0	Joy 2
38	Joy 4	Neutral 0	Acceptance 4
39	Acceptance 2	Neutral 0	Sadness 1
40	Acceptance 4	Acceptance 1	Sadness 1
41	Acceptance 4	Acceptance 4	Sadness 1
42	Joy 6	Joy 2	Joy 5
43	Sadness 2	Neutral 0	Anticipation 2
44	Joy 2	Joy 6	Acceptance 4
45	Joy 2	Joy 4	Anticipation 3
46	Anticipation 2	Anticipation 3	Disgust 4
47	Sadness 3	Sadness 1	Disgust 2
48	Acceptance 3	Acceptance 1	Sadness 1
49	Surprise 2	Neutral 0	Acceptance 3
50	Acceptance 4	Acceptance 3	Disgust 3
51	Anticipation 3	Acceptance 1	Anticipation 4
52	Anticipation 4	Acceptance 4	Anticipation 3

53	Fear 1	Neutral 0	Acceptance 2
54	Acceptance 2	Neutral 0	Neutral 0
55	Anticipation 2	Joy 1	Joy 5
56	Joy 5	Joy 6	Joy 4
57	Sadness 4	Sadness 4	Joy 3
58	Anticipation 3	Acceptance 1	Sadness 4
59	Joy 7	Joy 4	Joy 4
60	Joy 7	Joy 2	Acceptance 4
61	Anticipation 4	Neutral 0	Anticipation 2
62	Surprise 3	Surprise 1	Disgust 2
63	Joy 2	Joy 1	Disgust 1
64	Sadness 3	Disgust 3	Acceptance 3
65	Angry 4	Sadness 1	Sadness 5
66	Angry 1	Joy 1	Anticipation 3
67	Anticipation 2	Anticipation 2	Disgust 3
68	Disgust 3	Anticipation 2	Joy 3
69	Joy 1	Disgust 1	Acceptance 1
70	Joy 1	Neutral 0	Disgust 2
71	Joy 2	Joy 1	Joy 4
72	Fear 3	Disgust 2	Disgust 4
73	Disgust 4	Disgust 5	Disgust 1
74	Surprise 5	Angry 3	Joy 5
75	Angry 3	Disgust 1	Joy 1
76	Joy 3	Neutral 0	Disgust 1
77	Joy 1	Anticipation 2	Joy 2
78	Anticipation 1	Anticipation 1	Acceptance 2
79	Sadness 5	Sadness 1	Acceptance 2
80	Surprise 3	Joy 1	Joy 2
81	Joy 2	Joy 1	Sadness 1
82	Surprise 2	Angry 3	Disgust 3
83	Joy 2	Joy 1	Disgust 2
84	Anticipation 4	Disgust 1	Acceptance 2
85	Anticipation 4	Neutral 0	Joy 3
86	Joy 4	Neutral 0	Joy 3
87	Disgust 2	Disgust 1	Disgust 3
88	Anticipation 3	Neutral 0	Anticipation 3
89	Anticipation 2	Fear 3	Acceptance 2
90	Joy 2	Neutral 0	Acceptance 2
91	Joy 4	Acceptance 2	Acceptance 2
92	Anticipation 3	Acceptance 1	Joy 3
93	Surprise 2	Acceptance 1	Acceptance 2
94	Surprise 2	Anticipation 4	Anticipation 2
95	Surprise 2	Surprise 2	Acceptance 1
96	Acceptance 2	Neutral 0	Disgust 3
97	Sadness 3	Angry 3	Disgust 6
98	Acceptance 3	Neutral 0	Disgust 2
99	Acceptance 3	Sadness 3	Joy 4
100	Joy 4	Joy 3	Acceptance 4
101	Joy 2	Joy 5	Joy 5
102	Anticipation 3	Joy 1	Joy 3
103	Sadness 3	Fear 1	Anticipation 5
104	Joy 3	Joy 3	Joy 6
105	Acceptance 3	Neutral 0	Joy 2

106	Joy 3	Joy 3	Joy 4
107	Acceptance 2	Neutral 0	Anticipation 2
108	Joy 2	Acceptance 1	Surprise 4
109	Joy 2	Acceptance 1	Anticipation 5
110	Joy 2	Acceptance 5	Acceptance 3
111	Fear 3	Acceptance 5	Acceptance 4
112	Anticipation 3	Acceptance 5	Joy 3
113	Joy 4	Joy 1	Joy 5

A.7 SMS Messages Pilot Results

Text ID	P1	P2	P3	P4	P5	P6	P7
1	Joy 7	Joy 1	Neutral 0	Joy 4	Joy 2	Joy 5	Joy 3
2	Joy 7	Joy 2	Joy 2	Acceptance 3	Joy 4	Acceptance 6	Acceptance 2
3	Anticipation 6	Disgust 1	Acceptance 1	Acceptance 2	Joy 1	Disgust 1	Acceptance 1
4	Acceptance 6	Anticipation 2	Acceptance 6	Acceptance 3	Anticipation 1	Acceptance 4	Anticipation 3
5	Surprise 5	Surprise 2	Joy 3	Surprise 3	Neutral 0	Joy 5	Disgust 1
6	Joy 7	Joy 3	Joy 3	Anticipation 4	Joy 5	Anticipation 5	Anticipation 4
7	Acceptance 1	Fear 1	Acceptance 3	Neutral 0	Neutral 0	Neutral 0	Neutral 0
8	Anticipation 4	Joy 2	Surprise 3	Acceptance 5	Acceptance 1	Acceptance 4	Sadness 1
9	Acceptance 6	Anticipation 1	Acceptance 2	Disgust 2	Anticipation 2	Disgust 1	Fear 1
10	Disgust 1	Angry 4	Angry 2	Disgust 2	Fear 1	Angry 3	Fear 1
11	Sadness 1	Disgust 2	Acceptance 2	Acceptance 2	Acceptance 5	Acceptance 2	Acceptance 3
12	Disgust 4	Joy 1	Anticipation 1	Acceptance 2	Acceptance 3	Acceptance 3	Sadness 2
13	Disgust 4	Sadness 2	Angry 1	Angry 1	Sadness 2	Angry 4	Neutral 0
14	Acceptance 3	Joy 2	Surprise 3	Sadness 3	Sadness 4	Disgust 4	Angry 2
15	Disgust 4	Disgust 1	Disgust 3	Disgust 3	Angry 4	Angry 4	Disgust 2
16	Disgust 2	Acceptance 3	Joy 2	Disgust 2	Neutral 0	Disgust 3	Surprise 2
17	Sadness 3	Disgust 3	Neutral 0	Acceptance 1	Acceptance 1	Sadness 3	Fear 2
18	Anticipation 7	Joy 4	Surprise 5	Joy 2	Joy 2	Anticipation 5	Anticipation 2
19	Joy 5	Acceptance 3	Anticipation 3	Joy 2	Surprise 3	Acceptance 5	Joy 2
20	Surprise 2	Neutral 0	Neutral 0	Acceptance 1	Neutral 0	Neutral 0	Neutral 0
21	Joy 5	Disgust 3	Acceptance 2	Joy 1	Neutral 0	Joy 5	Joy 2
22	Sadness 5	Sadness 2	Sadness 3	Sadness 3	Sadness 3	Sadness 5	Sadness 1
23	Acceptance 3	Joy 4	Anticipation 2	Joy 5	Joy 3	Joy 4	Surprise 3
24	Acceptance 5	Anticipation 2	Acceptance 3	Sadness 2	Acceptance 1	Neutral 0	Neutral 0
25	Joy 6	Disgust 3	Neutral 0	Acceptance 1	Joy 1	Joy 4	Joy 4
26	Anticipation 5	Fear 3	Acceptance 3	Acceptance 2	Anticipation 1	Neutral 0	Neutral 0
27	Acceptance 5	Acceptance 4	Neutral 0	Acceptance 1	Acceptance 4	Acceptance 3	Disgust 1
28	Angry 2	Fear 2	Angry 1	Angry 3	Angry 5	Angry 4	Angry 3
29	Acceptance 4	Disgust 4	Acceptance 2	Disgust 1	Surprise 1	Neutral 0	Neutral 0
30	Disgust 1	Anticipation 3	Surprise 2	Acceptance 1	Disgust 2	Disgust 1	Disgust 1
31	Acceptance 1	Anticipation 3	Acceptance 3	Sadness 2	Neutral 0	Angry 1	Disgust 1
32	Angry 6	Disgust 6	Disgust 2	Acceptance 1	Anticipation 2	Disgust 1	Angry 5
33	Anticipation 7	Sadness 2	Joy 4	Acceptance 5	Joy 3	Joy 5	Joy 5
34	Acceptance 6	Sadness 3	Joy 6	Acceptance 2	Neutral 0	Acceptance 5	Joy 1
35	Anticipation 5	Anticipation 4	Surprise 5	Acceptance 1	Joy 1	Anticipation 4	Neutral 0
36	Joy 7	Disgust 3	Acceptance 6	Joy 2	Neutral 0	Joy 4	Joy 3
37	Anticipation 6	Joy 2	Acceptance 3	Acceptance 2	Neutral 0	Joy 5	Surprise 3
38	Joy 7	Acceptance 4	Anticipation 4	Joy 1	Neutral 0	Acceptance 4	Acceptance 2
39	Disgust 1	Sadness 1	Acceptance 3	Neutral 0	Neutral 0	Neutral 0	Acceptance 1
40	Acceptance 7	Sadness 1	Neutral 0	Acceptance 1	Acceptance 1	Acceptance 2	Acceptance 3
41	Acceptance 7	Sadness 1	Acceptance 4	Acceptance 1	Acceptance 4	Acceptance 1	Acceptance 2
42	Joy 7	Joy 5	Acceptance 5	Joy 3	Joy 2	Joy 4	Joy 4
43	Disgust 1	Anticipation 2	Anticipation 6	Neutral 0	Neutral 0	Sadness 2	Disgust 2
44	Acceptance 1	Acceptance 4	Sadness 2	Joy 3	Joy 6	Joy 2	Surprise 2
45	Joy 5	Anticipation 3	Joy 2	Anticipation 3	Joy 4	Joy 3	Acceptance 3
46	Disgust 1	Disgust 4	Surprise 3	Neutral 0	Anticipation 3	Neutral 0	Neutral 0
47	Sadness 7	Disgust 2	Sadness 3	Sadness 3	Sadness 1	Sadness 4	Sadness 3
48	Sadness 3	Sadness 1	Disgust 5	Disgust 1	Acceptance 1	Disgust 1	Sadness 1
49	Sadness 1	Acceptance 3	Angry 2	Acceptance 1	Neutral 0	Neutral 0	Neutral 0
50	Sadness 1	Disgust 3	Sadness 3	Acceptance 3	Acceptance 3	Neutral 0	Acceptance 1
51	Anticipation 1	Anticipation 4	Anticipation 2	Sadness 2	Acceptance 1	Neutral 0	Fear 1
52	Sadness 1	Anticipation 3	Acceptance 2	Acceptance 2	Acceptance 4	Sadness 1	Sadness 2

53	Acceptance 1	Acceptance 2	Acceptance 2	Acceptance 1	Neutral 0	Acceptance 1	Sadness 1
54	Acceptance 7	Neutral 0	Acceptance 7	Neutral 0	Neutral 0	Neutral 0	Neutral 0
55	Acceptance 4	Joy 5	Joy 3	Anticipation 3	Joy 1	Joy 2	Joy 2
56	Anticipation 3	Joy 4	Surprise 3	Joy 3	Joy 6	Joy 3	Surprise 2
57	Sadness 4	Joy 3	Surprise 7	Disgust 2	Sadness 4	Anticipation 5	Sadness 3
58	Sadness 2	Sadness 4	Sadness 4	Sadness 2	Acceptance 1	Sadness 3	Sadness 1
59	Joy 7	Joy 4	Surprise 5	Acceptance 4	Joy 4	Joy 6	Surprise 4
60	Acceptance 5	Acceptance 4	Joy 6	Joy 2	Joy 2	Anticipation 5	Surprise 4
61	Acceptance 2	Anticipation 2	Acceptance 3	Anticipation 2	Neutral 0	Anticipation 6	Neutral 0
62	Sadness 2	Disgust 2	Sadness 4	Neutral 0	Surprise 1	Sadness 4	Neutral 0
63	Anticipation 5	Disgust 1	Anticipation 5	Neutral 0	Joy 1	Anticipation 1	Surprise 3
64	Sadness 2	Acceptance 3	Sadness 3	Sadness 3	Disgust 3	Sadness 3	Disgust 2
65	Sadness 1	Sadness 5	Sadness 2	Sadness 2	Sadness 1	Sadness 3	Angry 1
66	Anticipation 1	Anticipation 3	Surprise 2	Acceptance 1	Joy 1	Acceptance 1	Joy 1
67	Acceptance 1	Disgust 3	Acceptance 3	Acceptance 1	Anticipation 2	Neutral 0	Angry 1
68	Acceptance 1	Joy 3	Surprise 3	Acceptance 2	Anticipation 2	Anticipation 2	Anticipation 1
69	Acceptance 3	Acceptance 1	Disgust 2	Sadness 2	Disgust 1	Acceptance 1	Neutral 0
70	Acceptance 3	Disgust 2	Sadness 1	Joy 2	Neutral 0	Joy 2	Joy 1
71	Acceptance 4	Joy 4	Surprise 5	Acceptance 2	Joy 1	Joy 3	Sadness 1
72	Angry 3	Disgust 4	Angry 2	Angry 3	Disgust 2	Surprise 3	Disgust 4
73	Angry 7	Disgust 1	Sadness 4	Disgust 2	Disgust 5	Surprise 4	Angry 2
74	Disgust 1	Joy 5	Angry 3	Acceptance 1	Angry 3	Neutral 0	Disgust 2
75	Disgust 1	Joy 1	Acceptance 4	Neutral 0	Disgust 1	Disgust 1	Neutral 0
76	Anticipation 4	Disgust 1	Joy 3	Joy 2	Neutral 0	Anticipation 2	Joy 3
77	Acceptance 1	Joy 2	Surprise 2	Acceptance 1	Anticipation 2	Neutral 0	Neutral 0
78	Disgust 1	Acceptance 2	Sadness 2	Disgust 3	Anticipation 1	Disgust 1	Angry 1
79	Disgust 2	Acceptance 2	Joy 2	Acceptance 2	Sadness 1	Joy 3	Fear 1
80	Joy 7	Joy 2	Anticipation 5	Joy 3	Joy 1	Joy 4	Surprise 2
81	Anticipation 6	Sadness 1	Joy 3	Acceptance 1	Joy 1	Joy 4	Joy 1
82	Angry 1	Disgust 3	Disgust 6	Sadness 2	Angry 3	Neutral 0	Angry 1
83	Acceptance 4	Disgust 2	Disgust 3	Disgust 2	Joy 1	Disgust 4	Joy 1
84	Sadness 1	Acceptance 2	Disgust 3	Angry 1	Disgust 1	Angry 4	Sadness 1
85	Acceptance 4	Joy 3	Joy 5	Acceptance 2	Neutral 0	Anticipation 5	Neutral 0
86	Acceptance 3	Joy 3	Surprise 2	Joy 3	Neutral 0	Joy 3	Anticipation 1
87	Disgust 1	Disgust 3	Disgust 2	Joy 3	Disgust 1	Disgust 3	Disgust 3
88	Acceptance 2	Anticipation 3	Acceptance 4	Acceptance 1	Neutral 0	Acceptance 2	Neutral 0
89	Acceptance 2	Acceptance 2	Neutral 0	Fear 1	Fear 3	Neutral 0	Joy 1
90	Sadness 1	Acceptance 2	Sadness 2	Joy 3	Neutral 0	Sadness 1	Surprise 3
91	Acceptance 5	Acceptance 2	Anticipation 5	Acceptance 5	Acceptance 2	Acceptance 2	Joy 1
92	Acceptance 7	Joy 3	Acceptance 6	Joy 5	Acceptance 1	Anticipation 3	Anticipation 3
93	Acceptance 3	Acceptance 2	Neutral 0	Acceptance 3	Acceptance 1	Neutral 0	Neutral 0
94	Acceptance 3	Anticipation 2	Neutral 0	Neutral 0	Anticipation 4	Anticipation 2	Neutral 0
95	Acceptance 3	Acceptance 1	Disgust 1	Fear 2	Surprise 2	Neutral 0	Surprise 1
96	Acceptance 3	Disgust 3	Joy 2	Neutral 0	Neutral 0	Neutral 0	Joy 1
97	Disgust 1	Disgust 6	Angry 4	Angry 5	Angry 3	Angry 5	Fear 2
98	Acceptance 1	Disgust 2	Acceptance 2	Disgust 2	Neutral 0	Neutral 0	Neutral 0
99	Acceptance 1	Joy 4	Surprise 6	Acceptance 4	Sadness 3	Acceptance 6	Anticipation 4
100	Acceptance 7	Acceptance 4	Joy 4	Surprise 4	Joy 3	Fear 6	Fear 2
101	Anticipation 7	Joy 5	Surprise 6	Anticipation 4	Joy 5	Anticipation 6	Anticipation 2
102	Disgust 1	Joy 3	Surprise 2	Acceptance 2	Joy 1	Joy 4	Disgust 1
103	Anticipation 1	Anticipation 5	Surprise 4	Anticipation 2	Fear 1	Anticipation 4	Anticipation 2
104	Anticipation 2	Joy 6	Joy 5	Joy 4	Joy 3	Joy 5	Joy 5
105	Acceptance 2	Joy 2	Sadness 2	Acceptance 3	Neutral 0	Neutral 0	Acceptance 3

106	Acceptance 3	Joy 4	Surprise 5	Joy 4	Joy 3	Acceptance 4	Anticipation 2
107	Acceptance 2	Anticipation 2	Acceptance 2	Acceptance 1	Neutral 0	Neutral 0	Neutral 0
108	Acceptance 7	Surprise 4	Acceptance 2	Neutral 0	Acceptance 1	Neutral 0	Disgust 1
109	Acceptance 4	Anticipation 5	Acceptance 5	Acceptance 6	Acceptance 1	Acceptance 4	Anticipation 2
110	Acceptance 4	Acceptance 3	Acceptance 4	Acceptance 3	Acceptance 5	Joy 2	Neutral 0
111	Anticipation 1	Acceptance 4	Sadness 2	Joy 3	Acceptance 5	Acceptance 4	Sadness 4
112	Anticipation 1	Joy 3	Disgust 2	Fear 2	Acceptance 5	Anticipation 3	Neutral 0
113	Joy 7	Joy 5	Joy 3	Acceptance 2	Joy 1	Joy 3	Joy 1

Text ID	P8	P9	P10	P11	P12	P13	P14
1	Joy 5	Joy 5	Joy 3	Joy 3	Joy 5	Disgust 4	Joy 6
2	Joy 6	Acceptance 4	Joy 3	Anticipation 1	Joy 4	Joy 3	Joy 6
3	Acceptance 2	Disgust 3	Joy 3	Anticipation 3	Surprise 3	Anticipation 1	Anticipation 3
4	Neutral 0	Acceptance 4	Neutral 0	Joy 1	Acceptance 4	Acceptance 3	Acceptance 4
5	Disgust 2	Joy 3	Disgust 2	Surprise 2	Surprise 3	Joy 1	Joy 5
6	Neutral 0	Acceptance 4	Anticipation 2	Anticipation 6	Joy 6	Joy 3	Acceptance 6
7	Fear 2	Acceptance 3	Neutral 0	Acceptance 1	Angry 2	Fear 1	Fear 1
8	Sadness 1	Disgust 2	Acceptance 2	Anticipation 3	Joy 2	Acceptance 2	Acceptance 1
9	Neutral 0	Disgust 2	Neutral 0	Disgust 1	Anticipation 3	Acceptance 3	Acceptance 6
10	Fear 2	Disgust 4	Sadness 1	Angry 2	Angry 2	Fear 1	Sadness 3
11	Acceptance 1	Disgust 5	Acceptance 3	Disgust 3	Anticipation 2	Disgust 1	Acceptance 3
12	Neutral 0	Disgust 5	Fear 3	Disgust 1	Joy 2	Acceptance 1	Anticipation 4
13	Sadness 2	Disgust 3	Angry 2	Disgust 2	Anticipation 2	Fear 3	Anticipation 4
14	Sadness 5	Acceptance 2	Disgust 2	Disgust 3	Anticipation 1	Disgust 2	Anticipation 6
15	Neutral 0	Acceptance 2	Angry 4	Disgust 1	Angry 1	Disgust 2	Angry 7
16	Acceptance 2	Disgust 4	Joy 2	Anticipation 2	Fear 2	Anticipation 1	Anticipation 4
17	Neutral 0	Acceptance 3	Neutral 0	Acceptance 1	Angry 1	Disgust 1	Surprise 5
18	Neutral 0	Anticipation 4	Anticipation 3	Anticipation 5	Surprise 2	Joy 1	Acceptance 6
19	Joy 3	Acceptance 2	Fear 2	Acceptance 4	Anticipation 1	Acceptance 1	Neutral 0
20	Fear 3	Acceptance 5	Neutral 0	Sadness 1	Anticipation 2	Fear 1	Acceptance 5
21	Neutral 0	Joy 3	Joy 3	Joy 1	Surprise 2	Anticipation 2	Acceptance 7
22	Sadness 3	Acceptance 3	Neutral 0	Sadness 3	Sadness 2	Anticipation 1	Sadness 7
23	Joy 3	Acceptance 3	Surprise 2	Anticipation 7	Joy 6	Joy 1	Joy 2
24	Neutral 0	Acceptance 3	Neutral 0	Acceptance 1	Anticipation 3	Fear 1	Acceptance 3
25	Joy 4	Anticipation 3	Joy 3	Fear 1	Joy 2	Anticipation 1	Neutral 0
26	Neutral 0	Acceptance 5	Neutral 0	Anticipation 5	Surprise 2	Anticipation 1	Acceptance 5
27	Angry 1	Disgust 2	Angry 1	Sadness 1	Acceptance 3	Anticipation 1	Angry 6
28	Angry 5	Angry 4	Angry 3	Sadness 3	Anticipation 3	Fear 1	Angry 7
29	Neutral 0	Disgust 3	Neutral 0	Acceptance 3	Surprise 3	Anticipation 2	Neutral 0
30	Neutral 0	Disgust 5	Disgust 1	Anticipation 2	Acceptance 3	Fear 1	Neutral 0
31	Sadness 3	Disgust 4	Neutral 0	Fear 2	Acceptance 3	Anticipation 1	Fear 5
32	Angry 3	Disgust 6	Angry 3	Acceptance 1	Surprise 2	Anticipation 1	Angry 5
33	Neutral 0	Joy 3	Neutral 0	Anticipation 2	Joy 4	Joy 1	Joy 4
34	Neutral 0	Acceptance 1	Joy 1	Acceptance 6	Joy 4	Anticipation 1	Joy 2
35	Neutral 0	Acceptance 4	Neutral 0	Anticipation 6	Anticipation 3	Acceptance 1	Neutral 0
36	Neutral 0	Disgust 3	Neutral 0	Sadness 1	Joy 5	Acceptance 1	Joy 6
37	Joy 5	Acceptance 5	Joy 2	Acceptance 1	Joy 3	Joy 2	Neutral 0
38	Joy 4	Acceptance 1	Neutral 0	Acceptance 2	Joy 4	Joy 1	Joy 3
39	Neutral 0	Acceptance 2	Neutral 0	Sadness 1	Acceptance 2	Acceptance 1	Joy 2
40	Neutral 0	Sadness 4	Neutral 0	Acceptance 7	Acceptance 4	Anticipation 2	Neutral 0
41	Neutral 0	Sadness 4	Neutral 0	Acceptance 7	Acceptance 4	Anticipation 2	Neutral 0
42	Joy 7	Acceptance 1	Joy 4	Anticipation 7	Joy 6	Joy 1	Acceptance 6
43	Neutral 0	Acceptance 2	Sadness 2	Joy 1	Sadness 2	Anticipation 2	Fear 1

44	Joy 2	Joy 5	Joy 3	Joy 3	Joy 2	Acceptance 1	Fear 4
45	Neutral 0	Anticipation 4	Acceptance 1	Anticipation 6	Joy 2	Joy 1	Joy 3
46	Neutral 0	Acceptance 5	Neutral 0	Acceptance 2	Anticipation 2	Anticipation 1	Fear 2
47	Sadness 4	Joy 4	Sadness 1	Sadness 2	Sadness 3	Fear 2	Joy 2
48	Neutral 0	Disgust 4	Disgust 3	Sadness 6	Acceptance 3	Sadness 1	Joy 3
49	Sadness 3	Sadness 5	Neutral 0	Angry 2	Surprise 2	Disgust 1	Neutral 0
50	Neutral 0	Acceptance 5	Surprise 2	Sadness 1	Acceptance 4	Acceptance 2	Acceptance 3
51	Neutral 0	Acceptance 5	Sadness 1	Anticipation 1	Anticipation 3	Fear 1	Sadness 2
52	Neutral 0	Acceptance 4	Neutral 0	Anticipation 1	Anticipation 4	Fear 1	Sadness 3
53	Neutral 0	Acceptance 4	Neutral 0	Acceptance 2	Fear 1	Acceptance 1	Sadness 2
54	Neutral 0	Acceptance 4	Neutral 0	Acceptance 2	Acceptance 2	Acceptance 1	Neutral 0
55	Joy 2	Disgust 4	Joy 2	Anticipation 6	Anticipation 2	Acceptance 1	Joy 2
56	Neutral 0	Disgust 3	Joy 4	Surprise 4	Joy 5	Joy 2	Joy 4
57	Sadness 3	Sadness 2	Sadness 4	Anticipation 7	Sadness 4	Joy 1	Sadness 2
58	Sadness 2	Sadness 2	Sadness 1	Sadness 3	Anticipation 3	Fear 1	Sadness 2
59	Joy 5	Joy 4	Joy 1	Joy 6	Joy 7	Joy 4	Sadness 3
60	Joy 2	Disgust 1	Acceptance 3	Joy 6	Joy 7	Joy 2	Sadness 2
61	Neutral 0	Anticipation 4	Neutral 0	Acceptance 3	Anticipation 4	Anticipation 1	Sadness 4
62	Neutral 0	Sadness 3	Neutral 0	Fear 2	Surprise 3	Fear 1	Sadness 6
63	Neutral 0	Acceptance 4	Neutral 0	Anticipation 3	Joy 2	Joy 1	Joy 3
64	Fear 2	Sadness 3	Anticipation 2	Sadness 2	Sadness 3	Fear 1	Sadness 3
65	Sadness 1	Sadness 3	Sadness 3	Joy 3	Angry 4	Sadness 2	Angry 5
66	Joy 2	Anticipation 4	Anticipation 3	Joy 4	Angry 1	Surprise 1	Sadness 3
67	Neutral 0	Acceptance 4	Angry 3	Disgust 1	Anticipation 2	Fear 1	Acceptance 5
68	Neutral 0	Acceptance 2	Neutral 0	Disgust 1	Disgust 3	Anticipation 1	Neutral 0
69	Neutral 0	Disgust 2	Neutral 0	Disgust 4	Joy 1	Acceptance 1	Neutral 0
70	Neutral 0	Acceptance 3	Fear 1	Anticipation 1	Joy 1	Acceptance 1	Neutral 0
71	Neutral 0	Disgust 2	Acceptance 1	Joy 1	Joy 2	Joy 1	Joy 3
72	Angry 2	Disgust 3	Disgust 2	Fear 1	Fear 3	Fear 1	Angry 6
73	Neutral 0	Disgust 4	Angry 5	Disgust 3	Disgust 4	Anticipation 2	Angry 7
74	Angry 2	Disgust 4	Joy 2	Anticipation 1	Surprise 5	Fear 1	Sadness 3
75	Angry 6	Acceptance 1	Neutral 0	Acceptance 3	Angry 3	Acceptance 1	Angry 2
76	Joy 3	Sadness 3	Joy 3	Sadness 1	Joy 3	Joy 1	Joy 4
77	Neutral 0	Acceptance 5	Neutral 0	Anticipation 1	Joy 1	Anticipation 2	Neutral 0
78	Neutral 0	Fear 5	Sadness 3	Fear 1	Anticipation 1	Fear 3	Fear 7
79	Neutral 0	Anticipation 4	Disgust 2	Acceptance 3	Sadness 5	Joy 1	Fear 6
80	Neutral 0	Disgust 5	Joy 2	Joy 2	Surprise 3	Joy 1	Joy 3
81	Neutral 0	Acceptance 6	Neutral 0	Anticipation 4	Joy 2	Joy 1	Joy 3
82	Angry 4	Angry 3	Angry 2	Disgust 2	Surprise 2	Fear 2	Fear 4
83	Joy 3	Disgust 7	Joy 1	Sadness 1	Joy 2	Anticipation 2	Joy 3
84	Sadness 3	Disgust 7	Disgust 2	Sadness 1	Anticipation 4	Fear 1	Sadness 3
85	Neutral 0	Acceptance 2	Neutral 0	Acceptance 3	Anticipation 4	Acceptance 1	Neutral 0
86	Neutral 0	Disgust 3	Joy 1	Joy 2	Joy 4	Anticipation 1	Joy 2
87	Neutral 0	Disgust 4	Acceptance 2	Anticipation 3	Disgust 2	Acceptance 3	Sadness 5
88	Neutral 0	Acceptance 1	Neutral 0	Anticipation 6	Anticipation 3	Acceptance 2	Neutral 0
89	Neutral 0	Acceptance 2	Sadness 2	Acceptance 1	Anticipation 2	Anticipation 2	Fear 2
90	Neutral 0	Sadness 3	Neutral 0	Sadness 1	Joy 2	Anticipation 2	Joy 4
91	Neutral 0	Disgust 5	Neutral 0	Acceptance 1	Joy 4	Acceptance 2	Neutral 0
92	Neutral 0	Disgust 3	Acceptance 2	Anticipation 1	Anticipation 3	Joy 2	Joy 3
93	Neutral 0	Acceptance 2	Neutral 0	Sadness 1	Surprise 2	Anticipation 2	Fear 2
94	Neutral 0	Acceptance 4	Neutral 0	Acceptance 1	Surprise 2	Anticipation 1	Neutral 0
95	Neutral 0	Acceptance 4	Neutral 0	Fear 1	Surprise 2	Anticipation 2	Neutral 0
96	Neutral 0	Acceptance 2	Neutral 0	Angry 1	Acceptance 2	Acceptance 2	Neutral 0

97	Fear 2	Disgust 4	Anticipation 3	Angry 2	Sadness 3	Disgust 2	Sadness 3
98	Fear 5	Sadness 3	Neutral 0	Disgust 1	Acceptance 3	Anticipation 4	Neutral 0
99	Neutral 0	Disgust 3	Acceptance 4	Anticipation 4	Acceptance 3	Anticipation 1	Joy 5
100	Neutral 0	Surprise 4	Neutral 0	Fear 3	Joy 4	Anticipation 2	Joy 4
101	Neutral 0	Anticipation 4	Disgust 1	Anticipation 7	Joy 2	Joy 2	Joy 5
102	Neutral 0	Acceptance 1	Neutral 0	Acceptance 1	Anticipation 3	Joy 1	Neutral 0
103	Neutral 0	Acceptance 4	Sadness 1	Anticipation 1	Sadness 3	Anticipation 2	Neutral 0
104	Joy 5	Joy 4	Sadness 2	Anticipation 3	Joy 3	Joy 3	Acceptance 2
105	Joy 5	Disgust 2	Neutral 0	Sadness 1	Acceptance 3	Anticipation 2	Sadness 5
106	Neutral 0	Sadness 2	Fear 2	Acceptance 1	Joy 3	Joy 1	Joy 3
107	Neutral 0	Acceptance 1	Neutral 0	Acceptance 1	Acceptance 2	Acceptance 1	Neutral 0
108	Neutral 0	Disgust 3	Anticipation 2	Disgust 1	Joy 2	Acceptance 4	Angry 3
109	Neutral 0	Acceptance 4	Surprise 2	Acceptance 3	Joy 2	Joy 1	Neutral 0
110	Angry 3	Disgust 2	Disgust 1	Sadness 1	Joy 2	Acceptance 2	Angry 2
111	Sadness 3	Disgust 3	Neutral 0	Sadness 4	Fear 3	Sadness 1	Sadness 5
112	Neutral 0	Acceptance 4	Neutral 0	Acceptance 5	Anticipation 3	Fear 3	Acceptance 3
113	Neutral 0	Acceptance 3	Neutral 0	Joy 1	Joy 4	Joy 1	Joy 2

Text ID	P15	P16	P17	P18	P19	P20
1	Joy 3	Joy 3	Joy 4	Joy 4	Joy 5	Joy 4
2	Acceptance 3	Joy 3	Acceptance 5	Joy 4	Acceptance 5	Joy 5
3	Acceptance 4	Sadness 2	Sadness 4	Anticipation 4	Joy 4	Acceptance 5
4	Anticipation 2	Sadness 2	Anticipation 4	Joy 3	Acceptance 4	Acceptance 6
5	Surprise 1	Acceptance 2	Joy 4	Joy 5	Joy 5	Surprise 5
6	Neutral 0	Joy 2	Sadness 4	Anticipation 5	Anticipation 4	Acceptance 5
7	Neutral 0	Surprise 4	Fear 4	Surprise 3	Anticipation 4	Surprise 4
8	Acceptance 3	Anticipation 2	Fear 5	Acceptance 4	Anticipation 4	Acceptance 6
9	Fear 1	Joy 2	Anticipation 5	Anticipation 4	Anticipation 5	Acceptance 6
10	Surprise 1	Sadness 3	Angry 5	Sadness 2	Disgust 4	Angry 1
11	Acceptance 1	Sadness 3	Disgust 5	Acceptance 2	Fear 3	Angry 1
12	Acceptance 2	Neutral 0	Joy 5	Acceptance 3	Anticipation 4	Acceptance 6
13	Fear 2	Fear 3	Angry 6	Sadness 4	Fear 3	Sadness 5
14	Disgust 3	Surprise 3	Fear 5	Surprise 2	Neutral 0	Angry 3
15	Disgust 1	Anticipation 3	Fear 7	Fear 3	Anticipation 5	Angry 4
16	Joy 1	Joy 2	Joy 5	Joy 4	Surprise 4	Surprise 3
17	Fear 1	Sadness 1	Sadness 4	Acceptance 4	Fear 3	Acceptance 6
18	Joy 2	Joy 2	Acceptance 4	Anticipation 5	Anticipation 6	Joy 7
19	Joy 3	Joy 3	Acceptance 5	Acceptance 3	Acceptance 4	Joy 6
20	Fear 1	Fear 3	Sadness 4	Joy 3	Fear 3	Acceptance 5
21	Neutral 0	Acceptance 3	Joy 4	Joy 4	Anticipation 3	Acceptance 5
22	Disgust 2	Sadness 3	Sadness 3	Sadness 4	Sadness 3	Surprise 7
23	Anticipation 4	Joy 3	Surprise 5	Anticipation 5	Joy 5	Joy 7
24	Neutral 0	Neutral 0	Angry 3	Sadness 2	Anticipation 4	Acceptance 5
25	Anticipation 3	Acceptance 2	Joy 6	Anticipation 6	Anticipation 5	Fear 1
26	Anticipation 1	Surprise 3	Surprise 4	Anticipation 4	Neutral 0	Joy 7
27	Anticipation 4	Acceptance 2	Angry 3	Joy 4	Neutral 0	Surprise 5
28	Angry 1	Angry 3	Angry 5	Angry 4	Angry 4	Sadness 5
29	Anticipation 1	Surprise 3	Sadness 4	Joy 3	Angry 3	Joy 5
30	Disgust 1	Acceptance 2	Disgust 2	Anticipation 2	Angry 3	Angry 1
31	Disgust 3	Neutral 0	Sadness 3	Sadness 4	Angry 2	Surprise 7
32	Disgust 5	Surprise 2	Fear 5	Fear 2	Angry 4	Sadness 3
33	Acceptance 5	Joy 4	Joy 5	Anticipation 4	Anticipation 4	Joy 7
34	Acceptance 5	Acceptance 2	Acceptance 4	Acceptance 4	Angry 1	Fear 3

35	Acceptance 6	Joy 2	Joy 2	Anticipation 4	Neutral 0	Acceptance 5
36	Acceptance 6	Joy 4	Anticipation 2	Joy 4	Joy 2	Acceptance 5
37	Joy 5	Joy 4	Acceptance 2	Anticipation 4	Joy 4	Joy 5
38	Joy 4	Joy 4	Joy 2	Joy 4	Joy 3	Joy 6
39	Acceptance 1	Neutral 0	Sadness 4	Anticipation 3	Neutral 0	Acceptance 5
40	Acceptance 4	Acceptance 4	Sadness 3	Joy 3	Neutral 0	Surprise 7
41	Acceptance 4	Acceptance 4	Disgust 3	Joy 3	Neutral 0	Surprise 7
42	Joy 6	Joy 5	Joy 5	Anticipation 6	Joy 5	Joy 7
43	Sadness 3	Anticipation 3	Sadness 4	Anticipation 3	Sadness 3	Surprise 6
44	Acceptance 5	Joy 3	Anticipation 4	Joy 4	Surprise 3	Joy 6
45	Acceptance 6	Joy 3	Anticipation 4	Anticipation 3	Acceptance 4	Surprise 5
46	Neutral 0	Surprise 3	Surprise 4	Surprise 3	Neutral 0	Acceptance 5
47	Disgust 3	Surprise 1	Sadness 3	Sadness 3	Sadness 2	Surprise 7
48	Sadness 1	Sadness 2	Neutral 0	Sadness 3	Disgust 2	Surprise 6
49	Disgust 5	Sadness 3	Neutral 0	Angry 3	Disgust 2	Surprise 6
50	Neutral 0	Acceptance 4	Surprise 3	Surprise 3	Acceptance 3	Acceptance 6
51	Fear 2	Sadness 4	Sadness 4	Anticipation 2	Disgust 3	Sadness 3
52	Fear 3	Sadness 3	Anticipation 3	Anticipation 3	Anticipation 2	Sadness 3
53	Fear 1	Sadness 3	Fear 4	Surprise 3	Angry 1	Acceptance 6
54	Neutral 0	Surprise 3	Neutral 0	Anticipation 3	Neutral 0	Acceptance 6
55	Anticipation 4	Joy 3	Joy 5	Anticipation 4	Anticipation 4	Disgust 2
56	Joy 6	Joy 5	Joy 5	Surprise 4	Anticipation 4	Acceptance 1
57	Sadness 6	Neutral 0	Sadness 6	Anticipation 7	Anticipation 5	Joy 7
58	Fear 3	Sadness 4	Angry 2	Sadness 3	Sadness 1	Sadness 7
59	Joy 6	Joy 5	Acceptance 4	Joy 4	Joy 4	Joy 6
60	Anticipation 4	Joy 5	Acceptance 3	Joy 5	Anticipation 3	Joy 7
61	Surprise 3	Acceptance 3	Surprise 4	Anticipation 3	Joy 3	Surprise 3
62	Fear 1	Surprise 4	Angry 4	Sadness 4	Disgust 1	Surprise 7
63	Joy 2	Joy 3	Disgust 3	Anticipation 5	Anticipation 4	Joy 5
64	Fear 3	Sadness 3	Disgust 3	Fear 2	Disgust 3	Sadness 1
65	Sadness 3	Sadness 4	Sadness 3	Anticipation 3	Disgust 3	Sadness 1
66	Surprise 1	Neutral 0	Acceptance 5	Surprise 4	Joy 3	Surprise 2
67	Fear 1	Surprise 2	Angry 3	Angry 3	Fear 3	Acceptance 6
68	Neutral 0	Joy 3	Fear 4	Anticipation 4	Fear 2	Surprise 3
69	Neutral 0	Neutral 0	Angry 5	Anticipation 5	Angry 1	Angry 1
70	Acceptance 3	Acceptance 2	Joy 3	Sadness 2	Joy 2	Joy 1
71	Anticipation 4	Joy 3	Anticipation 3	Joy 3	Joy 2	Surprise 3
72	Disgust 4	Fear 3	Disgust 4	Angry 4	Angry 3	Angry 2
73	Disgust 6	Neutral 0	Angry 5	Sadness 3	Disgust 4	Surprise 7
74	Sadness 1	Fear 2	Sadness 5	Anticipation 3	Angry 3	Sadness 3
75	Anticipation 1	Surprise 2	Angry 4	Angry 2	Angry 1	Surprise 3
76	Surprise 2	Joy 4	Neutral 0	Joy 5	Joy 3	Sadness 6
77	Anticipation 1	Neutral 0	Angry 3	Anticipation 3	Anticipation 3	Joy 7
78	Fear 2	Sadness 3	Angry 3	Fear 6	Disgust 4	Sadness 4
79	Surprise 3	Sadness 4	Acceptance 5	Surprise 5	Acceptance 3	Surprise 6
80	Anticipation 3	Joy 4	Surprise 4	Joy 4	Acceptance 4	Joy 7
81	Acceptance 2	Joy 3	Joy 4	Anticipation 4	Anticipation 3	Joy 5
82	Sadness 2	Surprise 3	Sadness 5	Anticipation 5	Angry 2	Disgust 5
83	Joy 3	Joy 4	Acceptance 3	Joy 4	Joy 1	Joy 5
84	Fear 3	Sadness 3	Angry 5	Sadness 3	Disgust 1	Sadness 5
85	Acceptance 1	Sadness 3	Joy 2	Anticipation 4	Anticipation 4	Joy 7
86	Joy 2	Neutral 0	Sadness 2	Joy 4	Neutral 0	Disgust 2
87	Anticipation 4	Surprise 3	Anticipation 5	Anticipation 5	Disgust 2	Angry 5

88	Acceptance 3	Joy 3	Anticipation 3	Joy 4	Neutral 0	Acceptance 5
89	Fear 1	Surprise 3	Fear 3	Fear 2	Fear 1	Angry 3
90	Surprise 3	Sadness 2	Sadness 3	Sadness 3	Sadness 1	Sadness 7
91	Acceptance 3	Joy 3	Joy 4	Joy 3	Acceptance 2	Sadness 7
92	Anticipation 5	Acceptance 3	Anticipation 4	Anticipation 4	Anticipation 3	Sadness 7
93	Neutral 0	Neutral 0	Fear 3	Fear 2	Neutral 0	Acceptance 5
94	Anticipation 1	Neutral 0	Fear 3	Anticipation 3	Neutral 0	Surprise 3
95	Neutral 0	Surprise 2	Sadness 3	Surprise 3	Neutral 0	Sadness 6
96	Acceptance 1	Acceptance 3	Anticipation 2	Neutral 0	Neutral 0	Sadness 6
97	Surprise 1	Joy 3	Disgust 3	Angry 3	Disgust 2	Surprise 7
98	Acceptance 3	Sadness 2	Disgust 1	Neutral 0	Neutral 0	Angry 7
99	Anticipation 4	Joy 3	Acceptance 5	Acceptance 5	Anticipation 3	Disgust 5
100	Surprise 4	Surprise 6	Surprise 3	Surprise 6	Joy 4	Surprise 7
101	Anticipation 3	Joy 4	Sadness 3	Anticipation 4	Anticipation 3	Joy 7
102	Neutral 0	Neutral 0	Anticipation 3	Anticipation 3	Neutral 0	Joy 7
103	Anticipation 3	Neutral 0	Sadness 5	Anticipation 4	Anticipation 3	Surprise 3
104	Joy 3	Joy 4	Joy 6	Joy 5	Joy 3	Joy 2
105	Anticipation 1	Neutral 0	Joy 3	Neutral 0	Joy 2	Surprise 5
106	Anticipation 1	Joy 3	Acceptance 5	Acceptance 4	Joy 2	Joy 7
107	Neutral 0	Acceptance 2	Surprise 3	Neutral 0	Neutral 0	Surprise 7
108	Anticipation 1	Surprise 3	Acceptance 3	Anticipation 3	Joy 3	Acceptance 6
109	Anticipation 3	Neutral 0	Surprise 4	Surprise 3	Neutral 0	Joy 3
110	Surprise 1	Neutral 0	Angry 6	Joy 1	Neutral 0	Joy 5
111	Anticipation 3	Sadness 4	Disgust 2	Sadness 3	Sadness 2	Sadness 7
112	Anticipation 2	Fear 2	Anticipation 3	Fear 3	Neutral 0	Surprise 7
113	Anticipation 1	Joy 3	Neutral 0	Neutral 0	Joy 2	Sadness 7

A.8 Main Study Stimuli

Stimuli ID	Text ID	Smell Type
1	2	A
2		0
3		C
4	23	B
5		0
6		D
7	42	A
8		0
9		C
10	18	B
11		0
12		D
13	45	A
14		0
15		C
16	59	B
17		0
18		D
19	104	A
20		0
21		C
22	19	B
23		0
24		D
25	37	A
26		0
27		C
28	38	B
29		0
30		D
31	10	A
32		0
33		C
34	28	B
35		0
36		D
37	72	A
38		0
39		C
40	58	B
41		0
42		D
43	64	A
44		0
45		C
46	65	B
47		0
48		D
49	84	A
50		0
51		C

Stimuli ID	Text ID	Smell Type
52	13	B
53		0
54		D
55	15	A
56		0
57		C
58	22	B
59		0
60		D
61	20	A
62		0
63		C
64	67	B
65		0
66		D
67	43	A
68		0
69		C
70	75	B
71		0
72		D
73	89	A
74		0
75		C
76	7	B
77		0
78		D
79	11	A
80		0
81		C
82	51	B
83		0
84		D
85	52	A
86		0
87		C
88	69	B
89		0
90		D

A.9 Main Study Participant Information

Participant	P1	P2	P3	P4	P5	P6	P7
Gender	Male	Female	Male	Female	Male	Male	Female
Age	23	24	24	23	23	24	23

Participant	P8	P9	P10	P11	P12	P13
Gender	Female	Female	Male	Male	Female	Male
Age	25	25	23	24	24	24

A.10 Main Study Stimuli Ordering

	Participant Stimuli ID Order												
Stimuli ID	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**P11**	**P12**	**P13**
1	56	20	41	72	51	8	29	88	47	89	21	1	38
2	85	81	80	21	87	3	22	90	84	44	82	29	29
3	20	33	3	42	19	90	46	15	70	16	87	49	28
4	63	73	88	10	36	80	24	64	6	24	25	65	42
5	44	10	43	11	7	82	12	47	42	23	34	76	36
6	76	27	74	56	23	58	37	37	18	15	3	83	37
7	87	63	55	19	24	41	88	26	72	75	36	51	56
8	55	60	57	38	50	83	74	65	73	48	76	46	81
9	27	75	27	23	27	32	71	50	87	25	80	43	73
10	48	29	36	32	58	84	6	42	52	27	17	35	12
11	66	78	58	3	83	51	28	11	21	32	9	41	14
12	84	17	69	54	81	4	68	56	5	80	64	37	61
13	33	65	9	36	66	24	77	38	23	41	86	67	88
14	7	58	85	34	79	60	72	29	89	30	7	33	85
15	59	84	24	33	52	2	75	27	22	7	15	9	64
16	39	6	67	12	55	66	53	54	60	53	26	14	1
17	78	32	18	22	90	15	31	61	31	4	55	36	25
18	4	82	19	58	26	67	50	52	12	71	32	39	65
19	38	37	53	53	60	76	10	85	88	5	79	8	23
20	23	18	6	70	16	81	54	2	76	39	2	30	59
21	88	48	37	50	33	26	18	69	28	34	35	48	89
22	22	88	12	40	65	77	39	87	25	69	10	17	69
23	30	59	30	37	76	59	19	21	15	74	75	34	83
24	50	43	35	67	88	29	73	18	64	58	74	87	84
25	67	22	40	84	6	75	69	86	53	72	42	20	44
26	82	41	42	68	86	30	80	75	32	73	61	22	47
27	9	16	39	1	1	74	59	60	51	51	20	47	50
28	41	79	63	14	14	33	2	43	37	1	78	59	34
29	5	15	50	20	57	68	43	5	56	43	18	55	3
30	34	28	48	73	31	57	36	59	50	86	71	58	10
31	72	53	65	39	70	73	26	71	66	42	38	32	41
32	24	71	45	49	10	56	64	79	16	3	51	70	54
33	79	57	51	13	59	40	49	40	30	57	69	24	76
34	69	13	31	63	85	71	21	76	14	87	40	66	7
35	25	62	38	76	8	55	25	24	7	31	1	40	13
36	35	3	72	87	78	48	44	4	39	13	30	12	48
37	89	39	16	45	35	86	66	28	77	82	67	18	22
38	43	70	10	89	20	72	7	39	24	38	46	38	86
39	70	80	15	24	13	39	89	13	1	26	22	15	70
40	10	74	47	16	69	46	35	83	45	29	12	52	49
41	29	61	78	61	3	35	42	25	2	63	23	21	27
42	61	21	14	60	44	52	70	81	10	61	4	85	74
43	16	31	49	88	47	1	11	9	13	19	8	56	8
44	6	26	84	15	53	16	47	82	75	60	84	86	79
45	36	1	86	55	39	44	33	46	46	81	37	7	75
46	17	5	64	77	34	10	1	45	44	21	27	4	87
47	80	24	70	71	62	47	65	41	54	59	65	68	82
48	26	25	32	29	40	31	63	20	74	37	62	13	46
49	49	87	61	17	4	28	81	33	63	70	90	54	67
50	71	56	54	5	29	34	56	3	62	84	44	69	5
51	74	69	44	4	30	50	9	23	38	78	83	44	9

52	11	14	62	75	72	42	60	66	83	28	72	5	33
53	58	64	4	82	48	36	41	7	81	64	41	82	17
54	68	46	56	57	54	17	13	58	82	14	13	81	31
55	51	12	77	85	82	89	85	6	34	45	88	10	53
56	19	55	68	62	37	5	90	72	61	18	43	62	20
57	60	30	25	79	9	62	16	10	79	2	85	73	78
58	73	7	90	2	61	9	51	80	20	8	33	72	90
59	8	72	8	47	41	88	86	89	65	56	66	16	39
60	15	50	71	43	64	87	34	8	40	76	50	60	66
61	52	66	89	80	73	78	8	32	80	77	54	27	35
62	57	38	2	46	21	38	48	34	17	55	63	77	51
63	37	36	11	41	77	70	61	12	11	50	57	31	58
64	64	67	28	31	38	54	67	53	58	10	48	84	62
65	65	34	7	64	56	63	57	55	19	35	24	11	15
66	32	90	1	65	12	20	15	16	59	62	14	90	18
67	47	52	79	59	63	69	76	30	49	79	28	63	30
68	18	45	23	83	67	18	84	77	8	90	58	61	19
69	86	49	60	48	71	12	20	68	43	46	49	74	68
70	3	42	76	28	25	21	58	74	4	40	45	53	26
71	28	2	5	9	74	37	78	84	90	66	89	75	6
72	54	4	33	35	84	22	45	35	35	67	31	2	24
73	83	9	13	26	75	61	27	48	26	47	56	50	16
74	14	11	75	7	80	43	23	1	85	17	6	28	55
75	31	77	20	51	17	6	38	14	68	11	29	78	72
76	13	76	17	86	15	23	5	63	9	20	47	6	57
77	53	8	26	69	28	64	79	67	29	65	19	89	80
78	62	54	83	8	46	49	55	57	33	33	16	64	40
79	40	23	21	44	89	13	62	70	86	49	53	88	32
80	75	89	46	90	2	27	3	31	69	68	73	19	43
81	77	19	66	27	32	19	52	78	48	6	77	79	60
82	42	40	59	78	18	45	87	17	27	54	52	23	21
83	81	86	29	6	68	65	32	36	71	9	70	45	63
84	2	51	34	18	5	25	83	49	3	12	68	3	2
85	90	83	52	74	11	85	14	51	55	83	81	26	77
86	1	47	73	66	42	53	40	73	57	88	39	42	45
87	12	44	87	52	43	7	30	44	78	36	11	57	4
88	21	68	22	81	45	11	82	62	36	85	60	71	11
89	45	85	81	30	49	14	17	22	41	52	5	25	52
90	46	35	82	25	22	79	4	19	67	22	59	80	71

A.11 Main Study Results

Stimuli ID	P1	P2	P3	P4	P5	P6	P7
1	Joy 4	Joy 3	Joy 1	Sad 3	Neutral 0	Neutral 0	Joy 3
2	Acceptance 5	Acceptance 1	Neutral 0	Acceptance 4	Anticipation 2	Joy 2	Anticipation 2
3	Joy 4	Joy 5	Anticipation 3	Acceptance 4	Neutral 0	Joy 2	Anticipation 4
4	Anticipation 3	Anticipation 4	Anticipation 1	Joy 7	Anticipation 5	Joy 3	Anticipation 4
5	Acceptance 6	Anticipation 2	Neutral 0	Fear 4	Joy 1	Neutral 0	Acceptance 3
6	Joy 6	Anticipation 2	Joy 1	Sad 3	Neutral 0	Joy 2	Joy 5
7	Joy 4	Joy 6	Joy 1	Acceptance 6	Neutral 0	Sad 5	Anticipation 6
8	Sad 3	Acceptance 3	Neutral 0	Acceptance 6	Neutral 0	Acceptance 4	Acceptance 5
9	Joy 6	Anticipation 1	Anticipation 1	Sad 2	Neutral 0	Neutral 0	Joy 3
10	Anticipation 4	Joy 3	Neutral 0	Sad 3	Acceptance 5	Joy 4	Acceptance 3
11	Fear 4	Sad 3	Neutral 0	Acceptance 3	Neutral 0	Neutral 0	Sad 5
12	Anger 3	Acceptance 2	Sad 1	Fear 6	Sad 1	Acceptance 7	Disgust 4
13	Anger 4	Sad 2	Acceptance 1	Sad 3	Neutral 0	Neutral 0	Disgust 4
14	Sad 1	Sad 2	Neutral 0	Sad 4	Sad 1	Acceptance 4	Sad 4
15	Fear 4	Disgust 2	Neutral 0	Sad 4	Joy 1	Acceptance 3	Sad 5
16	Neutral 0	Sad 1	Joy 1	Sad 3	Joy 6	Joy 3	Sad 4
17	Neutral 0	Sad 1	Neutral 0	Joy 6	Joy 1	Anticipation 7	Anger 4
18	Neutral 0	Disgust 1	Disgust 1	Neutral 0	Neutral 0	Neutral 0	Acceptance 3
19	Sad 2	Sad 2	Sad 2	Fear 4	Neutral 0	Sad 2	Fear 3
20	Sad 2	Disgust 1	Neutral 0	Neutral 0	Disgust 7	Anticipation 2	Sad 4
21	Sad 2	Sad 3	Neutral 0	Joy 6	Fear 1	Neutral 0	Fear 3
22	Neutral 0	Anticipation 1	Neutral 0	Sad 2	Fear 2	Neutral 0	Fear 3
23	Neutral 0	Sad 2	Neutral 0	Joy 6	Neutral 0	Sad 2	Joy 3
24	Joy 1	Anger 1	Neutral 0	Sad 3	Neutral 0	Anticipation 4	Disgust 2
25	Neutral 0	Fear 1	Acceptance 1	Fear 2	Fear 1	Neutral 0	Anger 2
26	Neutral 0	Neutral 0	Neutral 0	Acceptance 4	Neutral 0	Acceptance 7	Fear 3
27	Acceptance 3	Acceptance 3	Acceptance 2	Anger 4	Neutral 0	Joy 3	Acceptance 4
28	Fear 1	Disgust 1	Acceptance 2	Neutral 0	Neutral 0	Neutral 0	Anticipation 3
29	Anger 1	Anger 1	Acceptance 1	Surprise 4	Neutral 0	Neutral 0	Joy 2
30	Neutral 0	Surprise 1	Neutral 0	Neutral 0	Neutral 0	Anticipation 5	Acceptance 3
31	Joy 2	Joy 1	Joy 3	Neutral 0	Sad 4	Neutral 0	Joy 5
32	Acceptance 4	Acceptance 1	Anticipation 2	Acceptance 4	Anticipation 1	Anticipation 7	Joy 4
33	Joy 2	Anticipation 3	Neutral 0	Neutral 0	Acceptance 7	Joy 2	Joy 4
34	Neutral 0	Neutral 0	Neutral 0	Fear 3	Disgust 5	Joy 6	Anticipation 3
35	Acceptance 4	Acceptance 4	Anticipation 1	Surprise 4	Neutral 0	Joy 5	Anticipation 2
36	Joy 4	Anticipation 3	Joy 2	Fear 5	Acceptance 3	Acceptance 5	Joy 2
37	Joy 4	Joy 4	Joy 1	Acceptance 3	Neutral 0	Anticipation 3	Joy 3
38	Surprise 3	Acceptance 2	Acceptance 2	Joy 6	Neutral 0	Acceptance 1	Acceptance 5
39	Joy 5	Acceptance 3	Joy 1	Neutral 0	Disgust 4	Joy 5	Joy 4
40	Acceptance 3	Anticipation 2	Neutral 0	Fear 3	Neutral 0	Anticipation 7	Joy 5
41	Sad 1	Sad 1	Acceptance 3	Sad 3	Surprise 2	Joy 6	Anger 5
42	Anger 4	Anger 6	Sad 1	Sad 5	Sad 3	Joy 1	Disgust 3
43	Disgust 2	Disgust 3	Neutral 0	Neutral 0	Disgust 2	Neutral 0	Disgust 2
44	Sad 4	Disgust 1	Sad 1	Acceptance 5	Sad 7	Neutral 0	Sad 4
45	Fear 5	Sad 1	Neutral 0	Surprise 6	Sad 3	Disgust 3	Sad 3
46	Disgust 1	Anger 1	Neutral 0	Surprise 4	Disgust 2	Disgust 2	Surprise 5
47	Sad 1	Anger 1	Neutral 0	Fear 6	Sad 7	Neutral 0	Anger 4
48	Neutral 0	Sad 1	Neutral 0	Sad 4	Sad 3	Joy 3	Fear 5
49	Sad 2	Sad 2	Anger 1	Fear 6	Disgust 2	Acceptance 6	Fear 2
50	Sad 2	Sad 1	Neutral 0	Acceptance 5	Disgust 5	Sad 7	Sad 5
51	Anticipation 1	Surprise 2	Neutral 0	Joy 5	Neutral 0	Acceptance 3	Fear 6
52	Disgust 1	Fear 1	Neutral 0	Sad 2	Sad 4	Neutral 0	Disgust 6

53	Neutral 0	Acceptance 1	Neutral 0	Joy 6	Sad 7	Joy 5	Surprise 6
54	Neutral 0	Anger 3	Neutral 0	Joy 5	Sad 4	Joy 1	Acceptance 4
55	Neutral 0	Neutral 0	Neutral 0	Neutral 0	Disgust 3	Neutral 0	Fear 4
56	Neutral 0	Surprise 1	Neutral 0	Neutral 0	Fear 1	Disgust 4	Fear 6
57	Anticipation 2	Acceptance 2	Acceptance 2	Neutral 0	Acceptance 1	Neutral 0	Acceptance 4
58	Sad 1	Sad 1	Sad 1	Neutral 0	Joy 4	Neutral 0	Sad 6
59	Anger 2	Anger 2	Neutral 0	Anticipation 6	Sad 7	Acceptance 3	Sad 4
60	Neutral 0	Neutral 0	Neutral 0	Disgust 4	Neutral 0	Sad 4	Acceptance 4
61	Joy 1	Joy 1	Joy 1	Anticipation 3	Joy 1	Neutral 0	Anticipation 3
62	Joy 3	Acceptance 2	Anticipation 1	Fear 6	Joy 5	Acceptance 5	Joy 3
63	Joy 2	Anticipation 3	Anticipation 1	Fear 3	Joy 3	Joy 6	Anticipation 5
64	Joy 4	Surprise 1	Anticipation 2	Joy 4	Neutral 0	Joy 6	Anticipation 5
65	Acceptance 5	Acceptance 1	Joy 1	Surprise 4	Neutral 0	Sad 6	Acceptance 3
66	Acceptance 6	Acceptance 3	Joy 2	Joy 6	Sad 4	Disgust 2	Joy 4
67	Joy 4	Joy 4	Joy 2	Acceptance 5	Joy 2	Joy 6	Joy 4
68	Disgust 4	Sad 2	Neutral 0	Acceptance 6	Anticipation 2	Acceptance 3	Acceptance 4
69	Joy 4	Joy 2	Neutral 0	Fear 3	Disgust 5	Sad 5	Joy 3
70	Acceptance 5	Acceptance 5	Neutral 0	Neutral 0	Disgust 4	Anticipation 5	Acceptance 5
71	Sad 4	Sad 3	Neutral 0	Sad 3	Neutral 0	Joy 1	Surprise 4
72	Anger 5	Anger 3	Neutral 0	Acceptance 4	Disgust 1	Acceptance 3	Disgust 4
73	Acceptance 3	Sad 3	Acceptance 1	Acceptance 3	Neutral 0	Anticipation 2	Disgust 4
74	Sad 5	Fear 1	Sad 3	Acceptance 5	Sad 2	Acceptance 5	Fear 4
75	Fear 6	Anger 3	Acceptance 1	Disgust 4	Neutral 0	Anticipation 2	Sad 4
76	Disgust 3	Anger 3	Neutral 0	Neutral 0	Sad 4	Neutral 0	Sad 3
77	Sad 3	Sad 3	Neutral 0	Joy 6	Neutral 0	Surprise 3	Anger 4
78	Acceptance 3	Disgust 2	Neutral 0	Fear 3	Neutral 0	Fear 1	Sad 4
79	Anger 3	Sad 1	Neutral 0	Neutral 0	Neutral 0	Disgust 4	Fear 3
80	Sad 3	Sad 1	Neutral 0	Sad 3	Neutral 0	Acceptance 6	Sad 3
81	Fear 1	Fear 1	Neutral 0	Neutral 0	Neutral 0	Acceptance 3	Fear 2
82	Disgust 3	Anger 1	Neutral 0	Sad 4	Neutral 0	Neutral 0	Fear 3
83	Neutral 0	Sad 1	Neutral 0	Joy 5	Neutral 0	Acceptance 5	Anticipation 2
84	Acceptance 4	Disgust 1	Neutral 0	Fear 4	Disgust 1	Neutral 0	Fear 3
85	Fear 1	Fear 1	Sad 2	Fear 6	Neutral 0	Sad 5	Anger 3
86	Neutral 0	Neutral 0	Neutral 0	Anticipation 5	Neutral 0	Joy 4	Fear 3
87	Acceptance 4	Sad 1	Neutral 0	Neutral 0	Joy 1	Neutral 0	Acceptance 3
88	Sad 4	Sad 1	Sad 1	Acceptance 5	Sad 5	Anticipation 4	Acceptance 3
89	Sad 2	Fear 1	Neutral 0	Neutral 0	Sad 3	Acceptance 3	Sad 3
90	Anticipation 2	Neutral 0	Acceptance 1	Acceptance 3	Disgust 1	Neutral 0	Surprise 3

Stimuli ID	P8	P9	P10	P11	P12	P13
1	Joy 2	Disgust 3	Neutral 0	Joy 2	Surprise 4	Joy 2
2	Anticipation 3	Joy 7	Joy 6	Acceptance 3	Joy 4	Disgust 3
3	Joy 4	Sad 4	Joy 2	Joy 5	Joy 3	Joy 5
4	Joy 4	Disgust 6	Joy 6	Joy 4	Anticipation 6	Disgust 4
5	Anticipation 4	Anticipation 5	Acceptance 3	Joy 3	Anticipation 5	Joy 4
6	Joy 3	Joy 7	Joy 2	Surprise 4	Joy 5	Joy 3
7	Joy 2	Anticipation 6	Anticipation 6	Joy 2	Anticipation 6	Joy 3
8	Acceptance 3	Disgust 6	Acceptance 1	Acceptance 4	Fear 1	Joy 3
9	Joy 3	Joy 7	Neutral 0	Neutral 0	Joy 5	Neutral 0
10	Acceptance 4	Joy 7	Acceptance 1	Acceptance 5	Anticipation 5	Acceptance 4
11	Anger 3	Anger 5	Anger 2	Neutral 0	Surprise 3	Joy 2
12	Anger 3	Anger 4	Sad 1	Acceptance 3	Joy 2	Acceptance 6
13	Sad 3	Disgust 5	Neutral 0	Acceptance 3	Anticipation 3	Acceptance 4

14	Disgust 1	Sad 7	Sad 3	Sad 1	Fear 2	Anticipation 3
15	Acceptance 4	Disgust 6	Anticipation 2	Neutral 0	Joy 2	Sad 2
16	Disgust 4	Disgust 5	Sad 1	Neutral 0	Acceptance 2	Disgust 2
17	Anger 3	Anger 6	Disgust 4	Anticipation 3	Surprise 4	Disgust 2
18	Disgust 4	Neutral 0	Fear 1	Neutral 0	Neutral 0	Joy 2
19	Surprise 1	Disgust 4	Disgust 1	Neutral 0	Anticipation 3	Joy 2
20	Sad 2	Sad 5	Disgust 2	Acceptance 4	Joy 3	Acceptance 5
21	Surprise 4	Neutral 0	Neutral 0	Neutral 0	Anticipation 5	Surprise 1
22	Fear 1	Anticipation 4	Neutral 0	Acceptance 3	Anticipation 1	Surprise 4
23	Acceptance 3	Acceptance 5	Acceptance 2	Acceptance 3	Joy 1	Anticipation 4
24	Fear 2	Disgust 2	Anticipation 2	Neutral 0	Joy 2	Neutral 0
25	Disgust 3	Neutral 0	Anticipation 4	Surprise 3	Sad 2	Acceptance 3
26	Neutral 0	Neutral 0	Anger 1	Surprise 1	Acceptance 3	Joy 3
27	Acceptance 3	Acceptance 5	Anticipation 3	Acceptance 2	Sad 3	Joy 3
28	Sad 2	Acceptance 6	Neutral 0	Joy 2	Sad 3	Sad 4
29	Sad 3	Acceptance 7	Sad 3	Acceptance 3	Acceptance 4	Acceptance 5
30	Neutral 0	Acceptance 5	Acceptance 1	Joy 2	Acceptance 3	Joy 2
31	Joy 1	Disgust 3	Anticipation 3	Joy 5	Joy 4	Joy 6
32	Joy 3	Joy 5	Joy 6	Acceptance 4	Anticipation 4	Neutral 0
33	Joy 2	Joy 7	Joy 6	Joy 5	Anticipation 5	Disgust 2
34	Joy 3	Acceptance 7	Anticipation 5	Joy 5	Anticipation 4	Joy 3
35	Joy 4	Joy 7	Joy 4	Neutral 0	Neutral 0	Disgust 2
36	Joy 2	Anticipation 7	Joy 7	Joy 5	Acceptance 4	Joy 3
37	Acceptance 2	Anticipation 6	Joy 5	Acceptance 2	Joy 1	Joy 3
38	Acceptance 3	Surprise 7	Neutral 0	Acceptance 3	Surprise 3	Acceptance 4
39	Joy 4	Acceptance 6	Acceptance 2	Joy 5	Joy 1	Disgust 2
40	Acceptance 3	Anticipation 7	Anticipation 2	Acceptance 2	Neutral 0	Joy 2
41	Disgust 4	Sad 6	Disgust 2	Acceptance 3	Surprise 4	Acceptance 5
42	Fear 4	Neutral 0	Acceptance 3	Neutral 0	Anger 5	Acceptance 3
43	Acceptance 3	Disgust 6	Acceptance 1	Joy 3	Anger 5	Joy 3
44	Disgust 2	Sad 6	Anticipation 2	Neutral 0	Sad 1	Joy 3
45	Disgust 4	Anger 4	Disgust 3	Acceptance 3	Sad 5	Joy 4
46	Acceptance 3	Surprise 7	Disgust 2	Acceptance 2	Anger 4	Disgust 3
47	Sad 2	Anticipation 4	Disgust 2	Acceptance 3	Sad 3	Sad 3
48	Disgust 2	Acceptance 5	Neutral 0	Acceptance 2	Fear 2	Joy 3
49	Surprise 3	Acceptance 4	Fear 1	Joy 3	Sad 2	Neutral 0
50	Sad 2	Acceptance 7	Sad 2	Sad 2	Fear 3	Sad 4
51	Surprise 2	Joy 5	Acceptance 3	Neutral 0	Anticipation 3	Joy 2
52	Surprise 3	Acceptance 6	Acceptance 5	Acceptance 3	Fear 3	Fear 3
53	Acceptance 4	Acceptance 6	Anticipation 3	Acceptance 3	Anger 2	Disgust 2
54	Fear 2	Sad 3	Acceptance 2	Acceptance 3	Acceptance 5	Anticipation 3
55	Disgust 2	Fear 4	Acceptance 2	Neutral 0	Fear 3	Joy 2
56	Surprise 2	Surprise 6	Fear 2	Acceptance 3	Anticipation 4	Anticipation 3
57	Acceptance 2	Acceptance 7	Acceptance 1	Acceptance 2	Acceptance 1	Neutral 0
58	Acceptance 3	Acceptance 7	Surprise 4	Acceptance 3	Acceptance 3	Neutral 0
59	Sad 2	Acceptance 7	Sad 1	Neutral 0	Acceptance 4	Disgust 3
60	Acceptance 3	Anticipation 5	Neutral 0	Acceptance 3	Disgust 3	Neutral 0
61	Joy 2	Disgust 1	Neutral 0	Joy 4	Anticipation 2	Anger 1
62	Joy 2	Surprise 7	Joy 1	Joy 4	Fear 2	Neutral 0
63	Anticipation 2	Joy 7	Joy 2	Joy 4	Sad 2	Joy 3
64	Joy 4	Disgust 4	Anticipation 2	Neutral 0	Joy 1	Anticipation 4
65	Anticipation 2	Fear 4	Acceptance 2	Joy 4	Surprise 1	Joy 5
66	Joy 1	Joy 6	Joy 4	Joy 5	Joy 3	Joy 2

67	Anticipation 2	Joy 6	Acceptance 3	Joy 3	Joy 6	Disgust 2
68	Joy 1	Acceptance 6	Acceptance 1	Acceptance 4	Joy 1	Disgust 3
69	Joy 2	Anticipation 6	Anticipation 2	Acceptance 1	Joy 3	Joy 2
70	Acceptance 1	Joy 5	Acceptance 2	Acceptance 5	Surprise 1	Acceptance 5
71	Disgust 3	Sad 5	Disgust 2	Neutral 0	Neutral 0	Anger 4
72	Anger 4	Surprise 4	Neutral 0	Acceptance 2	Sad 1	Neutral 0
73	Acceptance 2	Disgust 4	Acceptance 1	Acceptance 1	Sad 3	Anger 3
74	Disgust 1	Sad 7	Sad 2	Sad 1	Sad 6	Sad 2
75	Anger 3	Disgust 6	Anticipation 2	Acceptance 3	Neutral 0	Anger 3
76	Disgust 2	Disgust 4	Sad 1	Joy 3	Sad 5	Disgust 2
77	Disgust 5	Sad 2	Sad 3	Acceptance 4	Neutral 0	Anger 4
78	Disgust 4	Neutral 0	Fear 1	Acceptance 3	Disgust 3	Neutral 0
79	Surprise 3	Anger 4	Neutral 0	Acceptance 4	Anger 3	Neutral 0
80	Sad 4	Sad 7	Sad 2	Sad 1	Sad 6	Sad 2
81	Surprise 3	Acceptance 5	Neutral 0	Acceptance 3	Fear 1	Anticipation 4
82	Surprise 3	Acceptance 7	Neutral 0	Joy 4	Sad 1	Neutral 0
83	Acceptance 3	Neutral 0	Neutral 0	Acceptance 4	Disgust 2	Acceptance 3
84	Fear 2	Anticipation 5	Neutral 0	Acceptance 3	Anger 4	Anticipation 4
85	Disgust 2	Surprise 6	Fear 1	Acceptance 3	Acceptance 5	Anger 3
86	Surprise 4	Neutral 0	Neutral 0	Acceptance 1	Fear 4	Neutral 0
87	Disgust 2	Fear 5	Acceptance 2	Surprise 3	Fear 2	Neutral 0
88	Surprise 4	Sad 4	Acceptance 1	Acceptance 5	Disgust 3	Anger 3
89	Sad 4	Acceptance 6	Neutral 0	Acceptance 2	Fear 1	Sad 3
90	Neutral 0	Anticipation 5	Neutral 0	Acceptance 4	Surprise 2	Sad 2

A.12 Main Study Smell Detection Results

Stimuli ID	P1	P2	P3	P4	P5	P6	P7
1	1	1	0	1	0	0	1
2	1	1	1	1	1	0	1
3	1	0	1	1	0	1	1
4	1	1	1	1	1	1	1
5	0	1	0	1	1	0	1
6	1	1	0	0	0	0	1
7	1	0	0	1	0	0	1
8	1	1	0	1	0	1	1
9	0	1	1	0	0	0	1
10	1	1	1	1	1	1	1
11	1	1	0	0	0	1	0
12	1	1	0	1	1	1	1
13	1	1	1	0	0	0	0
14	0	1	1	0	0	1	1
15	1	1	1	1	1	1	1
16	1	1	0	1	1	0	0
17	0	1	0	1	1	1	1
18	0	1	0	1	0	0	1
19	0	1	0	1	0	1	1
20	1	1	1	0	1	1	1
21	0	1	0	1	1	0	1
22	0	1	1	1	1	0	1
23	0	1	0	1	0	1	1
24	1	1	0	1	0	1	1
25	0	1	1	1	1	1	1
26	0	0	1	1	0	1	1
27	1	1	0	0	0	1	1
28	1	1	0	0	0	0	1
29	0	1	0	1	0	0	1
30	1	1	0	1	0	1	1
31	0	0	0	1	1	0	1
32	1	1	1	1	1	1	1
33	0	0	0	1	1	0	1
34	0	0	0	1	1	1	1
35	1	0	1	1	0	1	1
36	1	1	1	0	1	1	1
37	0	0	0	1	0	1	1
38	1	0	0	1	1	1	1
39	1	1	0	0	1	1	1
40	0	1	1	0	0	1	1
41	1	1	1	1	1	1	1
42	0	1	0	1	1	0	1
43	1	1	0	0	1	1	1
44	1	1	0	1	1	0	1
45	1	1	1	1	1	1	0
46	1	0	0	1	1	1	1
47	0	1	0	1	1	0	1
48	1	0	0	1	1	1	1
49	1	1	0	0	1	1	0
50	0	0	0	1	1	0	1
51	1	1	0	1	0	1	1
52	0	1	0	1	1	0	1

53	0	1	1	1	1	0	1
54	0	1	0	0	1	1	1
55	0	0	0	0	1	0	1
56	1	1	0	1	1	0	1
57	0	1	0	1	0	1	1
58	0	1	0	0	1	0	1
59	0	1	0	1	1	1	1
60	0	1	0	1	1	1	1
61	1	0	1	1	0	0	1
62	1	1	1	0	1	1	1
63	1	1	1	1	1	0	1
64	1	1	1	0	0	1	1
65	1	1	1	1	0	0	1
66	1	0	1	1	1	0	0
67	1	0	1	1	1	1	1
68	1	1	0	0	1	1	1
69	1	0	1	1	1	0	1
70	1	0	1	1	1	1	1
71	1	1	0	0	1	0	1
72	0	1	1	1	1	1	1
73	1	1	0	0	0	0	1
74	1	1	1	1	1	1	1
75	0	1	0	1	0	1	1
76	1	1	1	1	1	1	1
77	1	1	0	1	0	1	1
78	1	1	1	1	0	1	1
79	1	1	1	1	0	0	1
80	1	1	1	1	0	1	1
81	1	1	0	1	0	1	1
82	0	1	1	1	0	1	1
83	1	1	0	0	0	1	1
84	0	1	0	0	1	0	1
85	1	0	1	1	0	0	1
86	1	0	1	1	0	0	1
87	1	1	0	1	1	0	1
88	1	1	1	1	1	1	0
89	1	1	1	1	1	1	1
90	1	0	0	1	1	1	1

Stimuli ID	P8	P9	P10	P11	P12	P13
1	1	1	1	1	1	0
2	0	1	1	1	1	1
3	1	0	1	1	1	0
4	1	1	1	1	1	1
5	1	1	1	1	1	1
6	0	1	1	1	1	1
7	1	1	1	1	1	1
8	1	1	1	1	1	1
9	1	1	1	1	1	0
10	1	0	1	1	1	1
11	1	1	1	0	1	1
12	0	0	1	1	1	1
13	0	1	1	1	1	1

14	0	1	1	0	1	1
15	1	1	1	1	1	1
16	1	1	1	0	1	1
17	1	1	0	1	1	0
18	0	1	1	1	0	1
19	0	1	1	0	1	1
20	1	1	1	1	1	1
21	1	1	1	1	1	0
22	1	1	0	1	1	0
23	1	1	1	1	1	1
24	0	1	1	0	1	0
25	1	1	1	1	1	1
26	1	1	1	1	1	1
27	1	1	1	0	1	1
28	1	1	0	1	1	1
29	0	1	1	1	1	1
30	0	1	1	1	1	1
31	0	1	1	1	1	1
32	1	1	1	1	1	0
33	1	1	1	1	1	1
34	0	1	1	1	1	1
35	1	1	1	0	1	1
36	0	1	1	1	1	0
37	1	1	1	0	0	1
38	1	1	1	1	1	0
39	1	1	1	1	0	1
40	1	0	1	0	0	1
41	1	1	1	1	1	1
42	1	0	1	0	1	1
43	1	1	1	1	1	1
44	1	1	1	0	0	1
45	1	1	1	1	1	1
46	0	1	1	1	1	1
47	1	1	1	1	1	1
48	1	1	1	1	1	1
49	0	1	1	1	1	1
50	1	1	1	1	1	1
51	0	1	1	1	1	1
52	1	1	1	1	1	1
53	1	1	1	1	0	1
54	0	1	1	1	1	0
55	1	1	1	0	1	1
56	0	1	1	1	1	1
57	1	1	1	1	1	0
58	1	1	1	1	1	1
59	1	1	1	0	1	0
60	1	1	1	1	1	0
61	0	1	0	0	1	1
62	1	1	1	1	1	0
63	0	1	1	1	1	0
64	1	1	1	0	0	1
65	1	1	0	1	1	0
66	1	1	1	1	0	0

67	1	1	1	1	1	1
68	1	1	1	1	0	1
69	0	1	1	1	1	0
70	1	1	1	1	0	1
71	0	1	1	1	0	1
72	1	1	1	0	0	0
73	0	1	1	0	1	1
74	0	1	1	1	1	0
75	0	1	1	1	0	1
76	1	1	1	1	1	1
77	1	1	1	1	1	0
78	1	1	1	1	1	0
79	0	1	1	1	1	0
80	1	1	1	1	1	0
81	0	1	1	1	0	0
82	0	1	1	1	1	0
83	0	1	1	1	0	1
84	1	1	1	1	1	1
85	1	1	0	1	1	1
86	0	1	1	1	1	0
87	0	1	1	1	1	0
88	1	1	1	1	1	1
89	1	1	0	0	1	1
90	0	1	1	1	1	0

A.13 Main Study Time Logs (in seconds)

Stimuli ID	P1	P2	P3	P4	P5	P6	P7
1	21	21	14	65	17	10	30
2	18	16	27	14	13	15	24
3	24	25	28	16	12	17	32
4	13	30	20	17	25	30	24
5	30	17	12	23	13	9	11
6	15	45	19	14	6	18	25
7	20	25	26	17	37	13	22
8	19	78	21	30	22	23	14
9	30	31	19	21	14	11	19
10	14	29	22	11	12	15	23
11	14	31	23	39	10	18	22
12	16	55	25	17	15	22	23
13	22	44	17	17	13	30	23
14	16	17	19	22	12	13	14
15	14	20	19	13	12	8	17
16	14	18	20	22	16	14	14
17	30	43	19	17	18	16	18
18	30	42	27	16	12	21	21
19	31	43	31	17	11	11	23
20	41	16	15	24	33	14	13
21	30	29	13	18	21	14	14
22	30	37	13	31	12	15	36
23	30	30	18	20	20	19	16
24	18	37	16	6	5	14	32
25	30	30	23	22	15	14	22
26	30	25	13	17	11	10	21
27	23	12	25	12	10	10	18
28	19	29	20	32	7	14	25
29	30	14	18	29	10	36	30
30	14	21	22	33	16	14	17
31	30	16	23	16	16	12	45
32	19	21	15	12	12	13	29
33	20	29	14	19	13	14	25
34	30	25	14	15	14	14	16
35	17	25	33	12	13	14	20
36	26	16	41	30	24	19	21
37	30	25	27	26	13	9	31
38	35	25	24	48	14	23	16
39	11	44	23	14	16	19	19
40	74	37	60	52	11	28	18
41	15	22	30	12	11	13	15
42	30	53	23	15	15	9	18
43	29	16	32	31	18	19	20
44	12	21	15	16	16	11	22
45	9	41	15	20	10	26	20
46	18	13	13	25	14	16	32
47	16	34	24	11	15	9	17
48	33	44	16	21	10	15	18
49	30	87	14	15	11	20	24
50	30	25	16	20	19	17	20
51	18	20	14	26	93	18	12
52	30	34	19	14	34	19	35

53	30	41	50	22	13	16	33
54	16	14	14	11	9	20	16
55	30	25	14	21	23	8	46
56	14	19	56	22	35	11	15
57	20	15	17	13	18	13	19
58	24	16	17	19	18	15	18
59	30	22	27	13	13	30	16
60	24	18	15	23	27	18	17
61	9	42	14	53	17	16	17
62	18	35	23	12	10	8	16
63	22	20	23	18	11	23	16
64	13	21	19	17	13	11	20
65	16	29	30	13	13	13	21
66	13	33	15	29	21	20	20
67	20	25	31	21	14	13	17
68	14	35	20	16	17	14	21
69	9	25	35	14	26	14	24
70	13	25	15	19	19	16	17
71	29	19	19	37	11	17	25
72	29	15	13	23	25	13	24
73	52	13	17	19	12	21	16
74	19	24	28	12	9	17	20
75	29	23	14	14	9	14	24
76	15	19	15	18	30	11	12
77	16	26	34	20	6	10	26
78	35	17	14	21	30	16	20
79	13	32	13	18	11	22	21
80	19	21	49	32	10	15	15
81	18	33	19	20	15	12	22
82	29	51	17	21	11	19	15
83	26	25	16	18	22	12	21
84	51	24	18	18	11	18	20
85	22	25	25	14	13	19	15
86	17	25	20	11	13	30	18
87	27	18	19	10	46	9	16
88	25	21	19	18	22	12	59
89	15	41	30	21	14	18	21
90	25	36	15	16	14	11	30

Stimuli ID	P8	P9	P10	P11	P12	P13
1	15	31	15	22	11	16
2	19	11	22	12	18	15
3	17	25	13	16	19	18
4	17	10	13	13	25	13
5	15	28	16	13	31	15
6	19	20	18	11	18	19
7	26	23	14	12	16	6
8	24	14	14	12	25	13
9	19	14	11	16	20	11
10	19	33	15	18	19	18
11	16	17	12	9	27	18
12	18	49	14	22	25	19
13	21	21	14	28	26	15

14	17	11	12	20	15	16
15	38	24	28	15	29	18
16	19	13	31	12	30	11
17	15	18	15	17	29	25
18	20	27	17	12	20	12
19	14	27	17	17	20	18
20	23	12	12	25	21	19
21	21	24	10	80	20	12
22	16	27	19	10	21	17
23	17	52	23	14	12	20
24	22	24	23	25	17	4
25	24	20	14	17	78	20
26	20	12	16	16	14	24
27	15	15	20	18	24	8
28	19	31	27	12	15	37
29	25	10	15	15	19	37
30	31	33	11	13	28	20
31	14	50	11	10	35	9
32	31	25	11	15	17	8
33	37	13	9	10	30	25
34	15	13	13	13	10	12
35	37	25	12	12	18	30
36	27	15	11	12	23	18
37	30	29	11	14	20	25
38	18	21	15	30	11	85
39	15	23	18	38	13	21
40	16	28	14	12	14	17
41	17	8	15	26	24	30
42	23	27	30	23	22	35
43	22	27	11	19	18	11
44	18	12	60	30	20	15
45	30	5	13	11	17	5
46	19	14	20	14	23	12
47	40	93	10	12	18	19
48	15	16	24	15	16	15
49	16	15	16	11	30	20
50	24	11	11	17	21	25
51	14	18	10	10	18	13
52	17	20	7	12	23	13
53	14	19	12	16	29	14
54	24	15	15	30	27	17
55	19	11	13	9	15	9
56	23	22	29	13	17	36
57	16	11	16	17	17	20
58	18	11	15	21	19	12
59	20	11	16	11	35	25
60	21	36	12	15	27	8
61	17	21	27	25	16	15
62	18	15	14	12	14	14
63	20	16	14	11	27	16
64	20	31	18	16	55	19
65	25	17	16	14	27	19
66	24	30	20	33	25	14

67	28	13	12	13	24	18
68	19	18	10	21	19	20
69	20	20	28	18	22	18
70	16	40	13	11	13	16
71	34	14	14	15	19	13
72	19	35	12	14	25	14
73	18	32	20	13	19	20
74	19	16	17	14	14	14
75	61	15	18	17	17	14
76	26	27	19	25	16	24
77	33	26	30	13	27	22
78	20	15	13	16	25	16
79	21	24	10	16	16	13
80	22	30	18	27	20	11
81	31	18	13	10	32	22
82	19	14	12	18	18	20
83	17	20	15	15	21	16
84	14	59	11	13	24	18
85	26	15	13	15	21	16
86	22	22	25	17	1	10
87	19	22	16	21	1	12
88	66	35	12	10	1	18
89	24	30	68	16	1	20
90	30	19	12	9	1	13

Appendix B

Chapter 4 Data

B.1 TCON Pre-Test Results

TCON1 ID	P1-Male	P2-Male	P3-Female
0	Neutral 0	Neutral 0	Neutral 0
1	Acceptance 1	Sadness 2	N/A
2	Anticipation 2	Surprise 3	Fear 3
3	Disgust 2	Anticipation 4	Disgust 3
4	N/A	Surprise 5	Surprise 4
5	Disgust 3	Surprise 5	Angry 3
6	Joy 3	Fear 3	Anticipation 5
7	Anticipation 2	Acceptance 3	Anticipation 1
8	Acceptance 2	Joy 3	Sadness 2
9	Anticipation 2	Angry 4	Angry 4
10	Angry 3	Joy 5	Joy 5
11	Joy 5	Sadness 2	Sadness 5
12	Acceptance 2	Sadness 3	Fear 4
13	Disgust 4	Surprise 3	Fear 3
14	Disgust 3	Angry 3	Angry 2
15	Angry 3	N/A	Surprise 3
16	Joy 6	Acceptance 4	Anticipation 6
17	Joy 2	Fear 2	Fear 4
18	Angry 2	Angry 4	Angry 5
19	Disgust 5	Fear 4	Angry 6
20	Disgust 5	Acceptance 4	Disgust 6
21	Joy 4	Sadness 4	Fear 3
22	Joy 1	Disgust 3	Sadness 2
23	Surprise 4	Anticipation 4	Anticipation 2
24	Disgust 2	Disgust 4	Disgust 3
25	Angry 5	Joy 6	Joy 5

B.2 TCON Pilot 1 Results

TCON1 ID	P1	P2	P3	P4	P5	P6	P7
0	Anticipation 7	Neutral 0	Sadness 3	Neutral 0	Neutral 0	Neutral 0	Neutral 0
1	Anticipation 6	Acceptance 1	Acceptance 2	Acceptance 2	Angry 1	Anticipation 4	Sadness 2
2	Acceptance 2	Anticipation 2	Neutral 0	Fear 2	Sadness 1	Sadness 2	Surprise 3
3	Surprise 1	Disgust 2	Joy 5	Surprise 2	Angry 5	Surprise 3	Anticipation 4
4	Joy 1	Joy 3	Acceptance 5	Anticipation 3	Surprise 3	Anticipation 3	Surprise 5
5	Angry 1	Disgust 3	Joy 3	Joy 3	Surprise 1	Anticipation 4	Surprise 5
6	Anticipation 3	Joy 3	Sadness 5	Acceptance 4	Fear 5	Sadness 4	Fear 3
7	Acceptance 1	Anticipation 2	Disgust 1	Sadness 2	Fear 2	Joy 3	Acceptance 3
8	Acceptance 4	Acceptance 2	Acceptance 3	Sadness 4	Acceptance 2	Joy 3	Joy 3
9	Anticipation 2	Anticipation 2	Surprise 6	Surprise 5	Anticipation 2	Surprise 5	Angry 4
10	Acceptance 5	Angry 3	Joy 2	Angry 4	Joy 5	Surprise 4	Joy 5
11	Sadness 1	Joy 5	Sadness 2	Acceptance 3	Disgust 2	Fear 4	Sadness 2
12	Acceptance 1	Acceptance 2	Anticipation 4	Sadness 4	Fear 2	Joy 4	Sadness 3
13	Disgust 1	Disgust 4	Surprise 2	Fear 4	Angry 5	Angry 3	Surprise 3
14	Disgust 1	Disgust 3	Anticipation 1	Fear 4	Joy 3	Disgust 3	Angry 3
15	Surprise 1	Angry 3	Angry 4	Surprise 5	Acceptance 4	Angry 4	Angry 1
16	Sadness 1	Joy 6	Sadness 3	Sadness 3	Fear 4	Sadness 3	Acceptance 4
17	Neutral 0	Joy 2	Angry 3	Disgust 5	Sadness 2	Acceptance 3	Fear 2
18	Acceptance 4	Angry 2	Fear 2	Acceptance 4	Surprise 6	Joy 4	Angry 4
19	Anticipation 3	Disgust 5	Joy 3	Surprise 4	Angry 3	Surprise 4	Fear 4
20	Acceptance 6	Disgust 5	Angry 1	Surprise 6	Surprise 6	Disgust 5	Acceptance 4
21	Sadness 1	Joy 4	Anticipation 2	Sadness 5	Disgust 5	Sadness 5	Sadness 4
22	Acceptance 3	Joy 1	Fear 4	Surprise 5	Acceptance 1	Joy 3	Disgust 3
23	Acceptance 6	Surprise 4	Neutral 0	Disgust 3	Anticipation 2	Fear 4	Anticipation 4
24	Acceptance 5	Disgust 2	Fear 5	Surprise 5	Angry 6	Anticipation 3	Disgust 4
25	Acceptance 5	Angry 5	Fear 4	Surprise 5	Angry 7	Joy 6	Joy 6

TCON1 ID	P8	P9	P10	P11	P12	P13	P14
0	Neutral 0	Sadness 5	Neutral 0	Neutral 0	Neutral 0	Neutral 0	Neutral 0
1	Sadness 1	Sadness 5	Sadness 1	Acceptance 4	Sadness 5	Sadness 2	Sadness 2
2	Joy 2	Sadness 3	Sadness 2	Anticipation 1	Acceptance 2	Fear 3	Joy 2
3	Angry 3	Acceptance 4	Angry 3	Surprise 1	Angry 2	Disgust 3	Joy 3
4	Acceptance 3	Acceptance 5	Surprise 5	Surprise 1	Surprise 3	Surprise 4	Joy 2
5	Surprise 2	Angry 6	Angry 7	Disgust 2	Angry 6	Angry 3	Angry 3
6	Sadness 3	Surprise 5	Sadness 3	Sadness 2	Sadness 1	Anticipation 5	Sadness 7
7	Acceptance 3	Fear 5	Sadness 2	Anticipation 3	Sadness 2	Anticipation 1	Acceptance 4
8	Joy 3	Sadness 4	Disgust 5	Sadness 2	Acceptance 2	Sadness 2	Acceptance 5
9	Angry 3	Acceptance 4	Disgust 3	Anticipation 2	Angry 4	Angry 4	Joy 4
10	Angry 4	Acceptance 5	Angry 4	Surprise 6	Angry 6	Joy 5	Joy 4
11	Sadness 1	Fear 7	Sadness 2	Fear 5	Anticipation 2	Sadness 5	Sadness 4
12	Sadness 2	Disgust 5	Sadness 4	Acceptance 1	Acceptance 5	Fear 4	Joy 4
13	Fear 4	Sadness 6	Angry 6	Acceptance 1	Joy 2	Fear 3	Angry 5
14	Surprise 3	Angry 4	Disgust 6	Fear 1	Fear 3	Angry 2	Sadness 5
15	Angry 7	Surprise 5	Angry 7	Fear 7	Angry 7	Surprise 3	Surprise 7
16	Neutral 0	Sadness 7	Disgust 1	Surprise 2	Fear 3	Anticipation 6	Fear 5
17	Neutral 0	Sadness 5	Disgust 3	Angry 1	Acceptance 4	Fear 4	Fear 4
18	Surprise 4	Disgust 7	Disgust 4	Disgust 2	Acceptance 4	Angry 5	Joy 7
19	Surprise 5	Disgust 4	Surprise 5	Joy 3	Angry 7	Angry 6	Angry 4
20	Angry 5	Anticipation 4	Angry 7	Angry 1	Angry 7	Disgust 6	Angry 7
21	Fear 4	Fear 5	Sadness 1	Acceptance 6	Sadness 5	Fear 3	Sadness 6
22	Neutral 0	Sadness 5	Joy 3	Sadness 3	Sadness 3	Sadness 2	Joy 7
23	Surprise 3	Angry 7	Disgust 4	Fear 3	Acceptance 2	Anticipation 2	Angry 3

24	Angry 3	Disgust 4	Disgust 3	Fear 1	Fear 6	Disgust 3	Joy 7
25	Angry 5	Angry 7	Angry 7	Fear 5	Angry 4	Joy 5	Joy 6

TCON1 ID	P15	P16	P17	P18	P19	P20
0	Angry 1	Sadness 3	Neutral 0	Neutral 0	Sadness 3	Neutral 0
1	Neutral 0	Sadness 2	Acceptance 2	Sadness 6	Sadness 4	Acceptance 2
2	Sadness 2	Acceptance 2	Neutral 0	Fear 4	Anticipation 5	Sadness 3
3	Neutral 0	Surprise 2	Disgust 3	Disgust 4	Joy 5	Anticipation 5
4	Disgust 1	Joy 2	Surprise 5	Joy 4	Angry 4	Disgust 2
5	Angry 2	Surprise 2	Angry 4	Surprise 5	Angry 6	Surprise 7
6	Surprise 4	Joy 4	Acceptance 3	Acceptance 6	Sadness 4	Sadness 3
7	Sadness 5	Joy 4	Acceptance 3	Disgust 3	Surprise 4	Joy 3
8	Sadness 4	Surprise 2	Angry 3	Anticipation 3	Fear 5	Disgust 3
9	Fear 1	Joy 3	Surprise 3	Neutral 0	Joy 5	Disgust 7
10	Angry 6	Angry 3	Angry 5	Surprise 3	Joy 5	Joy 4
11	Fear 3	Acceptance 2	Acceptance 3	Fear 5	Sadness 4	Sadness 3
12	Sadness 3	Joy 3	Fear 4	Sadness 4	Joy 6	Angry 3
13	Disgust 2	Surprise 2	Joy 4	Anticipation 3	Joy 5	Surprise 3
14	Angry 5	Fear 4	Surprise 4	Angry 5	Angry 5	Fear 5
15	Angry 5	Fear 2	Disgust 3	Joy 3	Angry 5	Fear 7
16	Sadness 4	Sadness 2	Fear 6	Fear 6	Sadness 4	Sadness 7
17	Sadness 3	Joy 3	Neutral 0	Acceptance 4	Surprise 5	Acceptance 6
18	Fear 3	Surprise 6	Surprise 3	Sadness 3	Joy 5	Acceptance 4
19	Surprise 3	Angry 3	Angry 6	Anticipation 5	Angry 6	Joy 4
20	Angry 1	Angry 3	Angry 7	Joy 5	Angry 5	Disgust 5
21	Fear 3	Sadness 2	Acceptance 2	Sadness 4	Sadness 6	Anticipation 3
22	Fear 2	Joy 3	Angry 3	Angry 3	Acceptance 5	Angry 5
23	Surprise 2	Surprise 4	Joy 2	Disgust 4	Disgust 6	Joy 5
24	Angry 3	Fear 3	Surprise 5	Angry 4	Surprise 5	Neutral 0
25	Angry 2	Angry 4	Angry 5	Joy 5	Disgust 6	Angry 7

B.3 TCON Pilot 2 Results

TCON2 ID	P1	P2	P3	P4	P5	P6	P7
0	Acceptance 7	Neutral 0	Sadness 2	Neutral 0	Acceptance 3	Neutral 0	Neutral 0
1	Acceptance 7	Angry 3	Anticipation 3	Angry 3	Angry 7	Joy 4	Surprise 2
2	Anticipation 2	Disgust 3	Surprise 6	Disgust 3	Joy 4	Surprise 6	Anticipation 1
3	Anticipation 7	Joy 5	Anticipation 2	Anticipation 4	Anticipation 4	Fear 5	Joy 2
4	Angry 6	Sadness 4	Surprise 3	Joy 2	Sadness 4	Anticipation 4	Surprise 4
5	Angry 6	Disgust 3	Joy 3	Angry 7	Angry 7	Fear 3	Surprise 3
6	Fear 7	Surprise 3	Surprise 4	Surprise 4	Fear 5	Anticipation 3	Surprise 4
7	Surprise 6	Joy 5	Acceptance 6	Acceptance 6	Sadness 4	Angry 6	Joy 4
8	Disgust 2	Anticipation 3	Acceptance 4	Acceptance 4	Surprise 5	Angry 6	Disgust 3

TCON2 ID	P8	P9	P10	P11	P12	P13	P14
0	Neutral 0	Neutral 0	Acceptance 1	Neutral 0	Neutral 0	Neutral 0	Neutral 0
1	Disgust 2	Anticipation 3	Surprise 5	Disgust 2	Neutral 0	Disgust 1	Disgust 2
2	Surprise 6	Anticipation 3	Disgust 3	Disgust 4	Angry 3	Disgust 5	Surprise 6
3	Joy 5	Joy 2	Joy 6	Anticipation 2	Surprise 3	Fear 3	Anticipation 2
4	Joy 2	Sadness 4	Fear 3	Joy 2	Angry 3	Disgust 5	Sadness 4
5	Disgust 3	Disgust 3	Surprise 3	Angry 2	Surprise 1	Disgust 3	Surprise 3
6	Surprise 3	Surprise 4	Surprise 5	Surprise 4	Sadness 1	Disgust 4	Surprise 4
7	Joy 5	Acceptance 6	Sadness 6	Fear 3	Angry 4	Fear 4	Fear 3
8	Fear 7	Acceptance 4	Angry 6	Fear 4	Angry 3	Fear 4	Acceptance 4

TCON2 ID	P15	P16	P17	P18	P19	P20
0	Neutral 0	Acceptance 1	Neutral 0	Neutral 0	Neutral 0	Acceptance 1
1	Anticipation 6	Anticipation 3	Joy 3	Acceptance 2	Disgust 2	Angry 3
2	Angry 6	Surprise 6	Angry 4	Anticipation 3	Disgust 3	Anticipation 3
3	Anticipation 2	Surprise 4	Joy 4	Surprise 4	Joy 4	Joy 2
4	Disgust 3	Sadness 4	Disgust 3	Angry 5	Sadness 4	Joy 2
5	Anticipation 5	Anticipation 5	Angry 5	Fear 3	Disgust 3	Disgust 3
6	Joy 4	Angry 4	Angry 4	Disgust 3	Surprise 3	Surprise 3
7	Fear 3	Joy 5	Joy 4	Joy 4	Joy 4	Joy 5
8	Angry 3	Fear 7	Fear 4	Anticipation 3	Acceptance 4	Anticipation 3

B.4 Colour Pilot Results

Colour ID	P1	P2	P3	P4	P5	P6	P7
0	Surprise 6	Surprise 3	Joy 5	Joy 3	Acceptance 3	Neutral 0	Acceptance 5
1	Angry 7	Joy 3	Acceptance 2	Joy 2	Angry 6	Angry 6	Fear 4
2	Joy 7	Anticipation 2	Joy 4	Anticipation 3	Joy 4	Acceptance 5	Acceptance 7
3	Joy 7	Joy 1	Surprise 3	Joy 3	Surprise 3	Joy 5	Acceptance 7
4	Joy 7	Disgust 3	Joy 1	Joy 3	Joy 3	Joy 7	Acceptance 4
5	Acceptance 2	Joy 4	Neutral 0	Acceptance 3	Acceptance 4	Surprise 3	Joy 5
6	Acceptance 5	Acceptance 5	Sadness 3	Acceptance 5	Acceptance 3	Sadness 3	Acceptance 2
7	Fear 5	Sadness 5	Sadness 3	Disgust 5	Sadness 5	Disgust 5	Sadness 2
8	Acceptance 5	Acceptance 3	Acceptance 2	Acceptance 2	Sadness 3	Sadness 3	Anticipation 4
9	Acceptance 7	Disgust 3	Acceptance 4	Joy 1	Fear 3	Fear 3	Joy 1
10	Anticipation 7	Joy 3	Anticipation 5	Joy 3	Acceptance 4	Joy 5	Anticipation 1

Colour ID	P8	P9	P10	P11	P12	P13	P14
0	Surprise 4	Joy 5	Fear 4	Surprise 4	Joy 3	Anticipation 4	Joy 3
1	Joy 3	Acceptance 2	Angry 5	Angry 4	Joy 2	Disgust 4	Joy 2
2	Acceptance 5	Joy 4	Acceptance 3	Acceptance 5	Acceptance 3	Anticipation 3	Acceptance 5
3	Surprise 4	Anticipation 3	Joy 3	Joy 5	Fear 3	Acceptance 2	Joy 1
4	Joy 4	Acceptance 4	Joy 4	Joy 4	Fear 3	Anticipation 2	Joy 3
5	Anticipation 3	Sadness 5	Sadness 5	Anticipation 3	Sadness 3	Acceptance 3	Joy 5
6	Acceptance 2	Sadness 3	Fear 3	Acceptance 2	Sadness 3	Acceptance 5	Acceptance 5
7	Sadness 3	Fear 1	Sadness 5	Sadness 5	Sadness 3	Fear 1	Sadness 4
8	Sadness 4	Acceptance 2	Sadness 2	Sadness 3	Sadness 4	Acceptance 2	Acceptance 2
9	Joy 1	Fear 3	Acceptance 4	Fear 2	Angry 3	Fear 1	Fear 2
10	Joy 1	Joy 3	Anticipation 6	Fear 3	Joy 3	Fear 1	Joy 3

Colour ID	P15	P16	P17	P18	P19	P20
0	Fear 5	Surprise 4	Neutral 0	Joy 5	Surprise 3	Surprise 4
1	Angry 7	Joy 3	Angry 4	Angry 6	Angry 4	Acceptance 2
2	Joy 5	Joy 7	Joy 5	Acceptance 5	Acceptance 5	Acceptance 7
3	Surprise 3	Fear 4	Surprise 4	Anticipation 3	Joy 3	Joy 1
4	Surprise 6	Fear 3	Angry 4	Joy 3	Joy 1	Surprise 6
5	Anticipation 5	Joy 5	Surprise 3	Surprise 3	Joy 5	Anticipation 3
6	Fear 7	Acceptance 2	Sadness 3	Sadness 3	Acceptance 2	Acceptance 2
7	Sadness 7	Sadness 3	Fear 4	Sadness 4	Sadness 4	Sadness 7
8	Sadness 5	Acceptance 2	Sadness 3	Fear 4	Sadness 4	Acceptance 2
9	Disgust 3	Joy 1	Disgust 2	Fear 2	Acceptance 7	Joy 1
10	Anticipation 6	Fear 1	Acceptance 4	Joy 1	Fear 1	Joy 3

B.5 Main Study Stimuli

ID	Text Message	Touches	Color
0	Yay! Finally lol. I missed our cinema trip last week	None	None
1	At home by the way	None	None
2	No, but you told me you were going, before you got drunk!	None	None
3	Yay! Finally lol. I missed our cinema trip last week	Grin	None
4	At home by the way	Grin	None
5	No, but you told me you were going, before you got drunk!	Grin	None
6	Yay! Finally lol. I missed our cinema trip last week	Cry	None
7	At home by the way	Cry	None
8	No, but you told me you were going, before you got drunk!	Cry	None
9	Yay! Finally lol. I missed our cinema trip last week	None	Orange
10	At home by the way	None	Orange
11	No, but you told me you were going, before you got drunk!	None	Orange
12	Yay! Finally lol. I missed our cinema trip last week	None	Blue
13	At home by the way	None	Blue
14	No, but you told me you were going, before you got drunk!	None	Blue
15	Yay! Finally lol. I missed our cinema trip last week	Grin	Orange
16	At home by the way	Grin	Orange
17	No, but you told me you were going, before you got drunk!	Grin	Orange
18	Yay! Finally lol. I missed our cinema trip last week	Grin	Blue
19	At home by the way	Grin	Blue
20	No, but you told me you were going, before you got drunk!	Grin	Blue
21	Yay! Finally lol. I missed our cinema trip last week	Cry	Orange
22	At home by the way	Cry	Orange
23	No, but you told me you were going, before you got drunk!	Cry	Orange
24	Yay! Finally lol. I missed our cinema trip last week	Cry	Blue
25	At home by the way	Cry	Blue
26	No, but you told me you were going, before you got drunk!	Cry	Blue

B.6 Main Study Results

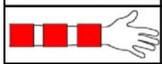
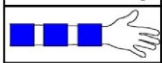
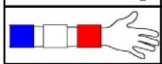
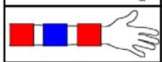
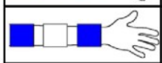
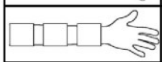
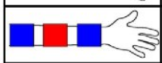
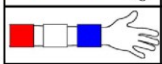
ID	P1	P2	P3	P4	P5	P6	P7	P8
0	Disgust 3	Neutral 0	Neutral 0	Anticipation 2	Joy 2	Joy 2	Neutral 0	Neutral 0
1	Joy 1	Neutral 0	Anticipation 1	Neutral 0	Neutral 0	Neutral 0	Neutral 0	Neutral 0
2	Angry 3	Acceptance 5	Fear 1	Angry 2	Disgust 2	Disgust 2	Neutral 0	Angry 1
3	Joy 3	Neutral 0	Surprise 3	Anticipation 3	Acceptance 2	Joy 3	Joy 3	Joy 1
4	Joy 6	Neutral 0	Anticipation 3	Anticipation 2	Joy 4	Acceptance 3	Neutral 0	Sadness 1
5	Angry 2	Neutral 0	Fear 1	Angry 2	Fear 2	Acceptance 2	Surprise 2	Sadness 1
6	Disgust 5	Joy 5	Surprise 5	Joy 3	Joy 1	Sadness 1	Disgust 7	Surprise 1
7	Anticipation 6	Joy 3	Anticipation 6	Angry 2	Surprise 2	Disgust 2	Angry 6	Disgust 4
8	Disgust 5	Angry 2	Fear 5	Angry 3	Disgust 5	Angry 3	Angry 1	Angry 3
9	Sadness 3	Anticipation 4	Surprise 2	Joy 3	Joy 4	Joy 3	Joy 5	Anticipation 1
10	Acceptance 4	Neutral 0	Anticipation 2	Neutral 0	Joy 2	Joy 3	Anticipation 2	Anticipation 4
11	Disgust 2	Neutral 0	Fear 1	Surprise 2	Angry 4	Disgust 1	Surprise 4	Acceptance 5
12	Disgust 2	Joy 5	Neutral 0	Anticipation 2	Neutral 0	Anticipation 1	Fear 4	Sadness 2
13	Joy 4	Acceptance 3	Anticipation 3	Neutral 0	Neutral 0	Sadness 2	Sadness 4	Neutral 0
14	Angry 3	Sadness 3	Fear 3	Angry 3	Fear 4	Disgust 2	Sadness 7	Neutral 0
15	Sadness 2	Surprise 6	Joy 2	Joy 3	Joy 7	Joy 5	Joy 6	Joy 3
16	Joy 4	Neutral 0	Anticipation 2	Neutral 0	Surprise 3	Joy 2	Anticipation 3	Acceptance 2
17	Angry 4	Anticipation 4	Fear 2	Surprise 4	Angry 2	Acceptance 5	Acceptance 5	Acceptance 1
18	Sadness 4	Anticipation 5	Surprise 3	Anticipation 3	Acceptance 3	Acceptance 1	Angry 3	Neutral 0
19	Joy 7	Joy 5	Anticipation 3	Anticipation 2	Acceptance 1	Fear 1	Disgust 3	Sadness 4
20	Surprise 4	Acceptance 5	Fear 2	Angry 2	Fear 1	Fear 1	Fear 6	Disgust 6
21	Sadness 6	Joy 4	Joy 4	Anticipation 6	Joy 6	Joy 1	Joy 5	Surprise 4
22	Joy 6	Fear 3	Anticipation 6	Angry 2	Angry 5	Disgust 1	Anticipation 7	Surprise 1
23	Disgust 6	Anticipation 5	Fear 5	Surprise 5	Disgust 7	Disgust 2	Surprise 7	Surprise 3
24	Disgust 6	Joy 6	Surprise 3	Joy 3	Neutral 0	Sadness 1	Disgust 2	Fear 1
25	Joy 7	Joy 4	Anticipation 6	Anticipation 4	Angry 2	Fear 3	Disgust 6	Disgust 3
26	Angry 6	Sadness 5	Fear 5	Angry 4	Surprise 3	Disgust 4	Fear 5	Fear 5

ID	P9	P10	P11	P12	P13	P14	P15	P16
0	Joy 2	Joy 2	Joy 1	Joy 5	Joy 1	Surprise 1	Joy 4	Anticipation 2
1	Acceptance 2	Neutral 0	Acceptance 1	Neutral 0	Neutral 0	Surprise 3	Angry 2	Sadness 3
2	Angry 1	Angry 2	Acceptance 2	Neutral 0	Neutral 0	Surprise 1	Disgust 3	Disgust 2
3	Anticipation 1	Joy 3	Joy 4	Joy 5	Anticipation 1	Surprise 1	Acceptance 4	Joy 2
4	Neutral 0	Neutral 0	Surprise 6	Neutral 0	Angry 1	Surprise 3	Angry 3	Anticipation 2
5	Disgust 1	Angry 1	Acceptance 3	Disgust 1	Surprise 1	Surprise 5	Disgust 4	Disgust 3
6	Joy 2	Joy 1	Joy 5	Surprise 2	Neutral 0	Surprise 4	Surprise 5	Joy 4
7	Angry 1	Surprise 1	Acceptance 5	Surprise 1	Angry 3	Surprise 4	Angry 6	Disgust 3
8	Angry 3	Surprise 3	Acceptance 6	Sadness 3	Angry 2	Surprise 2	Angry 4	Disgust 4
9	Joy 2	Joy 2	Joy 2	Joy 3	Joy 2	Neutral 0	Joy 5	Joy 4
10	Neutral 0	Surprise 1	Acceptance 2	Neutral 0	Anticipation 1	Surprise 2	Acceptance 3	Acceptance 3
11	Disgust 1	Surprise 2	Acceptance 4	Neutral 0	Surprise 2	Neutral 0	Acceptance 3	Anticipation 2
12	Joy 2	Joy 2	Joy 2	Joy 4	Neutral 0	Surprise 1	Fear 2	Anticipation 3
13	Neutral 0	Neutral 0	Acceptance 2	Neutral 0	Neutral 0	Joy 1	Sadness 3	Sadness 3
14	Sadness 1	Angry 1	Acceptance 2	Neutral 0	Sadness 1	Surprise 1	Disgust 3	Fear 2
15	Joy 3	Joy 6	Joy 5	Joy 3	Joy 2	Surprise 3	Joy 4	Acceptance 5
16	Acceptance 2	Neutral 0	Acceptance 2	Neutral 0	Joy 2	Surprise 5	Acceptance 2	Acceptance 3
17	Angry 2	Angry 1	Acceptance 4	Disgust 1	Surprise 3	Surprise 1	Acceptance 4	Acceptance 4
18	Neutral 0	Joy 4	Acceptance 3	Joy 4	Sadness 1	Fear 2	Acceptance 2	Anticipation 1
19	Angry 1	Disgust 1	Acceptance 3	Neutral 0	Sadness 1	Surprise 3	Angry 4	Sadness 4
20	Disgust 2	Angry 1	Anticipation 3	Disgust 2	Sadness 1	Surprise 2	Disgust 4	Acceptance 2
21	Joy 1	Joy 6	Joy 4	Surprise 4	Joy 3	Surprise 4	Fear 4	Joy 6
22	Fear 1	Surprise 3	Acceptance 5	Fear 2	Angry 3	Surprise 5	Angry 3	Surprise 4
23	Fear 2	Angry 3	Acceptance 5	Neutral 0	Angry 3	Fear 2	Acceptance 3	Acceptance 4
24	Joy 3	Joy 3	Joy 4	Surprise 4	Sadness 2	Surprise 4	Surprise 6	Surprise 3
25	Surprise 2	Surprise 3	Surprise 6	Fear 1	Sadness 3	Surprise 4	Angry 6	Surprise 2
26	Disgust 2	Angry 6	Surprise 5	Disgust 2	Sadness 3	Fear 1	Disgust 6	Sadness 3

Appendix C

Chapter 5 Patterns Data

C.1 Study Results

Thermal Pattern	Participant 1		Participant 2		Participant 3	
	Response	Rating	Response	Rating	Response	Rating
	1	0	4	3	1	3
	3	N/A	4	4	4	4
	8	5	4	5	8	5
	4	4	1	4	1	1
	2	4	4	4	7	1
	4	4	4	1	7	N/A
	8	4	7	3	8	5
	3	2	8	1	2	4
	5	5	1	5	8	1
	3	2	7	N/A	4	5
	8	5	7	3	6	5
	5	5	6	5	6	4
	5	3	8	1	4	3
	5	4	4	3	4	3
	1	0	4	4	5	4
	2	3	3	4	3	2

Appendix D

Chapter 5 Discrete Signalling Data

D.1 Study Results

Single Test

Thermal	P1 - M	P2 - M	P3 - M	P4 - F	P5 - M	P6 - M	P7 - M	P8 - M	P9 - F	P10 - M	P11 - M	P12 - M
Coolest	3	2	2	2	2	1	2	2	1	5	1	3
	2	1	1	1	1	6	1	1	2	4	2	3
	2	2	2	2	2	7	1	6	1	5	2	2
Cooler	1	2	3	1	2	3	1	2	1	6	3	2
	3	2	3	1	3	6	3	3	2	5	3	2
	3	2	3	2	2	3	1	6	2	5	3	4
Cool	4	5	4	1	3	6	3	4	2	4	4	3
	3	4	3	2	3	2	5	4	3	4	6	4
	4	3	3	3	3	5	3	5	3	6	5	4
Neutral	3	3	4	4	5	4	3	5	3	5	6	4
	4	5	5	3	3	5	4	2	4	7	6	4
	5	4	5	3	4	4	3	2	4	7	5	5
Warm	4	5	4	6	4	6	4	3	4	4	5	5
	5	5	5	4	5	5	4	2	5	6	6	5
	4	4	5	3	5	4	3	5	5	5	7	2
Warmer	5	6	6	2	6	5	4	2	4	6	2	5
	5	6	6	5	5	4	4	7	6	5	4	7
	5	6	6	2	6	4	5	2	6	6	5	6
Warmest	6	7	7	4	7	5	3	5	7	7	5	6
	7	6	7	5	6	5	4	6	6	6	5	7
	7	7	7	4	6	4	5	3	7	7	5	6

Amplification Test

Thermal	P1 - M	P2 - M	P3 - M	P4 - F	P5 - M	P6 - M	P7 - M	P8 - M	P9 - F	P10 - M	P11 - M	P12 - M
Coolest	2	1	2	1	2	7	1	1	1	2	1	1
	2	1	1	1	2	6	2	1	2	2	1	1
	1	3	1	1	2	2	2	2	1	2	1	2
Cooler	2	3	2	1	1	2	4	5	1	1	2	2
	5	3	2	2	3	6	3	1	2	3	1	2
	2	4	2	1	1	5	3	3	3	3	3	2
Cool	4	3	2	2	4	3	4	2	3	4	2	4
	2	3	3	2	3	4	3	3	3	4	3	3
	3	4	2	1	3	1	4	2	3	3	3	3
Neutral	5	4	5	6	4	3	4	4	4	3	3	4
	5	4	3	4	3	4	4	3	4	4	4	4
	4	3	4	2	4	4	4	4	4	5	4	4
Warm	4	5	4	5	6	4	4	3	4	4	4	5
	4	5	5	2	5	4	5	4	5	5	4	5
	5	5	5	3	5	4	4	3	4	3	3	4
Warmer	6	7	6	7	7	4	5	5	6	5	6	7
	5	6	6	7	6	4	5	5	6	6	5	6
	7	6	6	6	7	6	6	5	4	5	6	7
Warmest	7	7	7	7	7	6	7	7	7	7	7	6
	7	7	6	7	7	6	7	6	7	6	6	7
	7	6	7	6	7	7	6	7	6	7	6	7

Quantification Test

Thermal	P1 - M	P2 - M	P3 - M	P4 - F	P5 - M	P6 - M	P7 - M	P8 - M	P9 - F	P10 - M	P11 - M	P12 - M
Coolest	1	2	2	1	2	1	2	1	2	1	1	2
	2	2	2	1	2	2	2	3	6	1	1	2
	2	2	2	1	3	5	2	2	3	2	3	1

	2	2	3	2	2	5	2	6	2	2	1	2
Cooler	2	2	3	1	3	4	2	5	3	2	2	2
	3	3	3	2	3	2	2	1	5	5	2	1
	3	4	3	3	3	5	2	5	6	4	4	3
Cool	3	3	3	2	3	4	3	5	2	5	3	3
	3	5	3	2	3	4	3	2	6	4	4	3
	4	4	4	4	4	5	4	5	4	4	4	4
Neutral	3	3	4	4	4	5	3	2	1	4	4	3
	4	4	5	4	4	4	5	3	4	3	4	4
	5	5	4	7	6	4	5	3	4	4	5	5
Warm	5	5	4	6	6	7	4	4	7	4	5	4
	6	5	4	5	6	4	4	6	2	5	5	5
	7	7	5	7	6	5	6	6	4	7	6	6
Warmer	7	6	6	6	7	4	6	5	5	6	5	5
	6	6	5	6	6	4	5	5	3	7	5	6
	7	7	7	7	7	6	7	2	5	5	6	7
Warmest	6	6	7	6	7	6	6	6	6	7	6	7
	5	5	7	6	7	6	7	3	7	6	6	5

D.1 Study Time Logs (in milliseconds)

Single Test

Thermal	P1 - M	P2 - M	P3 - M	P4 - F	P5 - M	P6 - M	P7 - M	P8 - M	P9 - F	P10 - M	P11 - M	P12 - M
Coolest	2800	5400	6800	7900	13100	8900	8700	4000	6000	41100	N/A	N/A
	4400	2800	7300	8700	7800	6900	6600	3900	13000	10100	N/A	N/A
	6200	5300	6000	4100	4100	10800	5900	4500	6000	5000	N/A	N/A
Cooler	7700	8200	6900	6600	3400	11800	7700	4000	4100	8600	N/A	N/A
	11700	5100	6200	6200	5100	10800	13200	2700	5700	27700	N/A	N/A
	5400	4500	4500	11700	2900	6000	7100	4300	7000	9900	N/A	N/A
Cool	8500	5700	8500	6900	3800	10000	4500	2700	6900	12100	N/A	N/A
	3300	5400	2100	7100	3200	16000	8900	2900	4700	14200	N/A	N/A
	2700	7700	3400	6100	5400	16700	2800	4600	6900	8300	N/A	N/A
Neutral	5100	5000	2100	8600	3500	11900	3500	4600	4700	7300	N/A	N/A
	4400	3600	4200	8500	9000	7000	8300	4600	4700	4200	N/A	N/A
	2200	3900	3900	6000	7300	10200	7300	4100	4800	6400	N/A	N/A
Warm	8500	2800	6300	7600	5500	6300	6200	3800	4700	16200	N/A	N/A
	4100	3600	4200	8100	5300	11000	3900	4200	6800	8400	N/A	N/A
	5300	5400	2100	4200	11700	4700	3600	4500	6800	17700	N/A	N/A
Warmer	3800	4800	3800	13700	7000	9300	5900	4600	4100	8300	N/A	N/A
	10000	3800	5100	5900	9800	4700	3900	3500	4600	5400	N/A	N/A
	5700	3900	5200	11500	3000	7000	3400	3400	5300	10100	N/A	N/A
Warmest	6200	7400	4300	6800	3700	11000	4400	2900	5800	6400	N/A	N/A
	11000	4400	4500	6700	3800	9500	4600	3400	3500	6500	N/A	N/A
	6500	3000	6400	13700	3000	5800	4000	4300	4700	4100	N/A	N/A

Amplification Test

Thermal	P1 - M	P2 - M	P3 - M	P4 - F	P5 - M	P6 - M	P7 - M	P8 - M	P9 - F	P10 - M	P11 - M	P12 - M
Coolest	5800	3100	3200	4800	9100	15200	8200	5600	3800	6000	N/A	N/A
	4700	4100	5300	3200	10600	5500	9800	5300	3300	3000	N/A	N/A
	5400	2400	5300	6700	8100	12100	11600	4500	4100	2200	N/A	N/A
Cooler	5900	4400	4100	2800	14200	11800	17600	4700	4300	5500	N/A	N/A
	2900	2700	5400	10700	6800	6300	5100	7400	5100	2600	N/A	N/A
	5700	3700	4900	3100	5500	16000	17300	4200	3400	2200	N/A	N/A
Cool	9700	6800	3600	3800	5600	6000	9900	5600	3900	4700	N/A	N/A
	5100	4500	4100	3400	6200	10800	6600	8300	4900	6300	N/A	N/A
	5600	7400	7700	7200	7000	5200	8300	5900	4300	5900	N/A	N/A
Neutral	3700	7200	4400	3500	8700	3700	7200	6500	4100	1800	N/A	N/A
	10000	4000	4700	8800	5900	6700	14000	5900	3900	3700	N/A	N/A
	3200	2900	5300	7000	8200	8000	5800	6000	3900	1800	N/A	N/A
Warm	8800	6500	4800	7900	6300	6200	14200	4200	3900	15600	N/A	N/A
	4900	8000	4200	7500	5400	10400	7400	5200	4600	36000	N/A	N/A
	6800	4100	3600	5000	7600	4900	8300	4400	3900	4600	N/A	N/A
Warmer	5500	3600	4200	4200	8500	20700	6300	3000	5000	3700	N/A	N/A
	4500	7700	3600	20800	8600	7200	8000	3400	8800	28700	N/A	N/A
	9300	6400	9500	7600	13700	13000	4800	7400	3400	4000	N/A	N/A
Warmest	4200	6900	4400	5700	4200	8500	6800	4700	3500	10600	N/A	N/A
	2800	6200	4100	17200	4800	6700	6500	3800	6700	8200	N/A	N/A
	5600	10200	3800	6400	3100	3600	4600	3700	5800	7000	N/A	N/A

Quantification Test

Thermal	P1 - M	P2 - M	P3 - M	P4 - F	P5 - M	P6 - M	P7 - M	P8 - M	P9 - F	P10 - M	P11 - M	P12 - M
	3500	10700	11600	38600	7900	9300	7300	4900	4900	20100	N/A	N/A

Coolest	5000	18000	12600	10800	3100	4800	5500	6300	7100	11700	N/A	N/A
	4700	7900	7700	22200	5000	7600	8100	9300	7300	17800	N/A	N/A
	9000	6600	5000	3800	6400	19600	5300	2300	7100	25400	N/A	N/A
Cooler	8600	7600	6600	3700	2600	8000	10400	5100	7800	9900	N/A	N/A
	3900	4800	8000	4800	3100	6300	7700	2200	6300	16200	N/A	N/A
	11800	4500	4500	4600	4400	3700	7000	6500	4800	13400	N/A	N/A
Cool	7200	8700	6400	4600	2800	10200	7900	4300	4900	2900	N/A	N/A
	7300	5600	7300	6400	7700	14700	5100	4800	5300	4700	N/A	N/A
	3100	3200	9400	9100	6600	11400	7300	3700	4600	29900	N/A	N/A
Neutral	4800	6200	6300	15900	9100	3200	4300	2900	8600	4200	N/A	N/A
	4800	10300	5000	7000	3900	4700	5200	2700	4000	6000	N/A	N/A
	2000	3900	7000	4600	2900	9900	4300	6400	7300	25900	N/A	N/A
Warm	7200	4400	9400	11100	2400	9900	7700	4100	7700	3300	N/A	N/A
	10000	4500	5000	6500	5100	15000	4400	3700	5400	3600	N/A	N/A
	8900	4500	7300	12600	3900	17900	5000	4400	4600	4000	N/A	N/A
Warmer	10900	3700	7200	11200	5000	15500	4600	3500	4500	6800	N/A	N/A
	7700	3700	8600	8000	6100	7800	5700	4200	3500	7800	N/A	N/A
	8600	10200	3300	8100	2500	8500	7300	5200	4900	2300	N/A	N/A
Warmest	8200	3900	6900	8200	3800	3700	7800	3000	4000	4000	N/A	N/A
	6700	9800	4800	7300	1900	5300	7800	2700	4000	5000	N/A	N/A

Appendix E

Chapter 6 Continuous Signalling Data

E.1 Pilot 1 Results

Participant 1 - Male				
	Maze ID	Scale Multiplier	Completion Time	Moves
1st Maze	3	0	460.4	1220
2nd Maze	4	1	308.6	572
3rd Maze	1	2	2631.9	6572
4th Maze	2	3	NA	NA

Participant 2 - Male				
	Maze ID	Scale Multiplier	Completion Time	Moves
1st Maze	1	0	533.9	2204
2nd Maze	2	1	124.8	473
3rd Maze	3	2	120.2	512
4th Maze	4	3	171.6	708

Participant 3 - Female				
	Maze ID	Scale Multiplier	Completion Time	Moves
1st Maze	4	0	1134.4	3530
2nd Maze	1	1	1054.7	658
3rd Maze	2	2	635.4	677
4th Maze	3	3	NA	NA

E.2 Pilot 2 Results

Participant 1 - Male				
	Maze ID	Thermal?	Completion Time	Moves
1st Maze	2	No	418.3	1510
2nd Maze	1	No	600	2069
3rd Maze	4	Yes	600	2219
4th Maze	3	Yes	281.2	732

Participant 2 - Male				
	Maze ID	Thermal?	Completion Time	Moves
1st Maze	3	No	167.3	696
2nd Maze	1	No	200.7	852
3rd Maze	4	Yes	156.8	538
4th Maze	2	Yes	106.5	398

Participant 3 - Male				
	Maze ID	Thermal?	Completion Time	Moves
1st Maze	2	No	196	636
2nd Maze	3	No	324.4	1130
3rd Maze	1	Yes	600	1676
4th Maze	4	Yes	348	976

E.3 Study Results

Participant 1 - Female - 30	Maze ID	Thermal?	Completion Time	Moves
1st Maze	4	Yes	261.1	436
2nd Maze	3	Yes	263.5	382
3rd Maze	2	No	527.3	1816
4th Maze	1	No	225.9	772

Participant 2 - Male - 29	Maze ID	Thermal?	Completion Time	Moves
1st Maze	4	No	600	2361
2nd Maze	2	No	154.8	644
3rd Maze	3	Yes	460.1	1096
4th Maze	1	Yes	600	1789

Participant 3 - Male - 25	Maze ID	Thermal?	Completion Time	Moves
1st Maze	1	Yes	272.5	922
2nd Maze	4	Yes	168.7	658
3rd Maze	3	No	327.5	1404
4th Maze	2	No	249.4	1128

Participant 4 - Male - 27	Maze ID	Thermal?	Completion Time	Moves
1st Maze	4	No	231.3	908
2nd Maze	1	No	531.6	2086
3rd Maze	2	Yes	271.3	522
4th Maze	3	Yes	318.6	546

Participant 5 - Male - 39	Maze ID	Thermal?	Completion Time	Moves
1st Maze	2	Yes	330.2	690
2nd Maze	4	Yes	281.8	470
3rd Maze	1	No	600	1945
4th Maze	3	No	345.1	1188

Participant 6 - Male - 27	Maze ID	Thermal?	Completion Time	Moves
1st Maze	4	No	259.7	1172
2nd Maze	3	No	176.9	810
3rd Maze	2	Yes	149	610
4th Maze	1	Yes	96.8	418

Participant 7 - Male - 35	Maze ID	Thermal?	Completion Time	Moves
1st Maze	4	No	195.2	696
2nd Maze	3	No	197.8	742
3rd Maze	1	Yes	138.1	414
4th Maze	2	Yes	109.9	336

Participant 8 - Female - 30	Maze ID	Thermal?	Completion Time	Moves
1st Maze	3	No	265.4	896
2nd Maze	2	No	220.1	756

	Maze ID	Thermal?	Completion Time	Moves
3rd Maze	1	Yes	201.9	614
4th Maze	4	Yes	216.5	658

Participant 9 - Male - 25				
	Maze ID	**Thermal?**	**Completion Time**	**Moves**
1st Maze	4	Yes	191	740
2nd Maze	2	Yes	109.8	402
3rd Maze	3	No	223.6	972
4th Maze	1	No	474.2	2060

Participant 10 - Female - 46				
	Maze ID	**Thermal?**	**Completion Time**	**Moves**
1st Maze	1	Yes	215.8	382
2nd Maze	2	Yes	197	368
3rd Maze	4	No	600	2358
4th Maze	3	No	468	1810

Participant 11 - Female - 32				
	Maze ID	**Thermal?**	**Completion Time**	**Moves**
1st Maze	3	No	600	1578
2nd Maze	1	No	600	1845
3rd Maze	2	Yes	378.3	720
4th Maze	4	Yes	215.2	428

Participant 12 - Male - 35				
	Maze ID	**Thermal?**	**Completion Time**	**Moves**
1st Maze	1	Yes	320.8	346
2nd Maze	4	Yes	209.1	298
3rd Maze	3	No	567.8	2144
4th Maze	2	No	359.8	1412

E.4 Study Questionnaire and Answers

Q1: Was the temperature feedback useful?
A1: Yes, especially when it felt hot. At first I didn't pay attention to the temperature but didn't want to trace the whole maze in the end.

A2: Cold feels like hot- I only knew it was cold when I encountered a wall. So I learned it was a "wrong" sensation.
A3: Yes
A4: Yes, way faster. It was more accurate
A5: Yes
A6: Yes
A7: Yes
A8: Yes the cold and warm indicator helped me to understand if I am following the wrong direction.
A9: Yes, very.
A10: YES! Very useful.
A11: Yes, the temperature feedback helped me to "predict" where the target was
A12: Very Useful

Q2: Did you understand the feedback?
A1: Yes, I thought it would be biased due to the delay but it is not that bad.
A2: Yes
A3: Yes, very simple, just hot and cold. I got used to the length of time you use to test.
A4: Yes
A5: Yeah once I got used to it I went a bit slower. Initially I had trouble detecting cold but got used to it, but it took a while.
A6: At the beginning, no but at the end, yes
A7: Yes.
A8: Yes.
A9: Yes.
A10: Yes, definitely. Warm meant I was going in the right direction.
A11: I understood the feedback to some extent. But I did not know how it works exactly. For example, whether it is purely based on the path to the target or the the radius from the radius from the target
A12: Yeah. I felt it and it guided me.

Q3: Which was easier: With or without thermal feedback?
A1: Definitely with temperature
A2: With temperature
A3: With temperature.
A4: With temperature
A5: With temperature
A6: With temperature, it's like a guide to the right path.
A7: With feedback.
A8: With Thermal Feedback
A9: Much easier with feedback.
A10: Without a doubt, it was easier with the thermal feedback.
A11: With feedback
A12: With

Q4: Where the temperatures comfortable?
A1: Yes, but can't always rely on just temperature. It’s a "complimentary hint". I still need to trace the maze path in my head.
A2: Yes
A3: Yes. It's not too hot or cold but there's enough of a difference to tell them apart.
A4: Yes
A5: Yes, hot felt very hot but hot was more comfortable.

A6: Yes
A7: Yes. Hot could have been even hotter but was ok.
A8: Yes but sometimes couldn't distinguish the difference so I had to continue further to understand is it cold or warm?
A9: Yes.
A10: The temperatures were comfortable.
A11: It was comfortable to some extent. I would rate it on 5 on a 7-point Likert scale
A12: Yes it was in a level that lets you just feel it

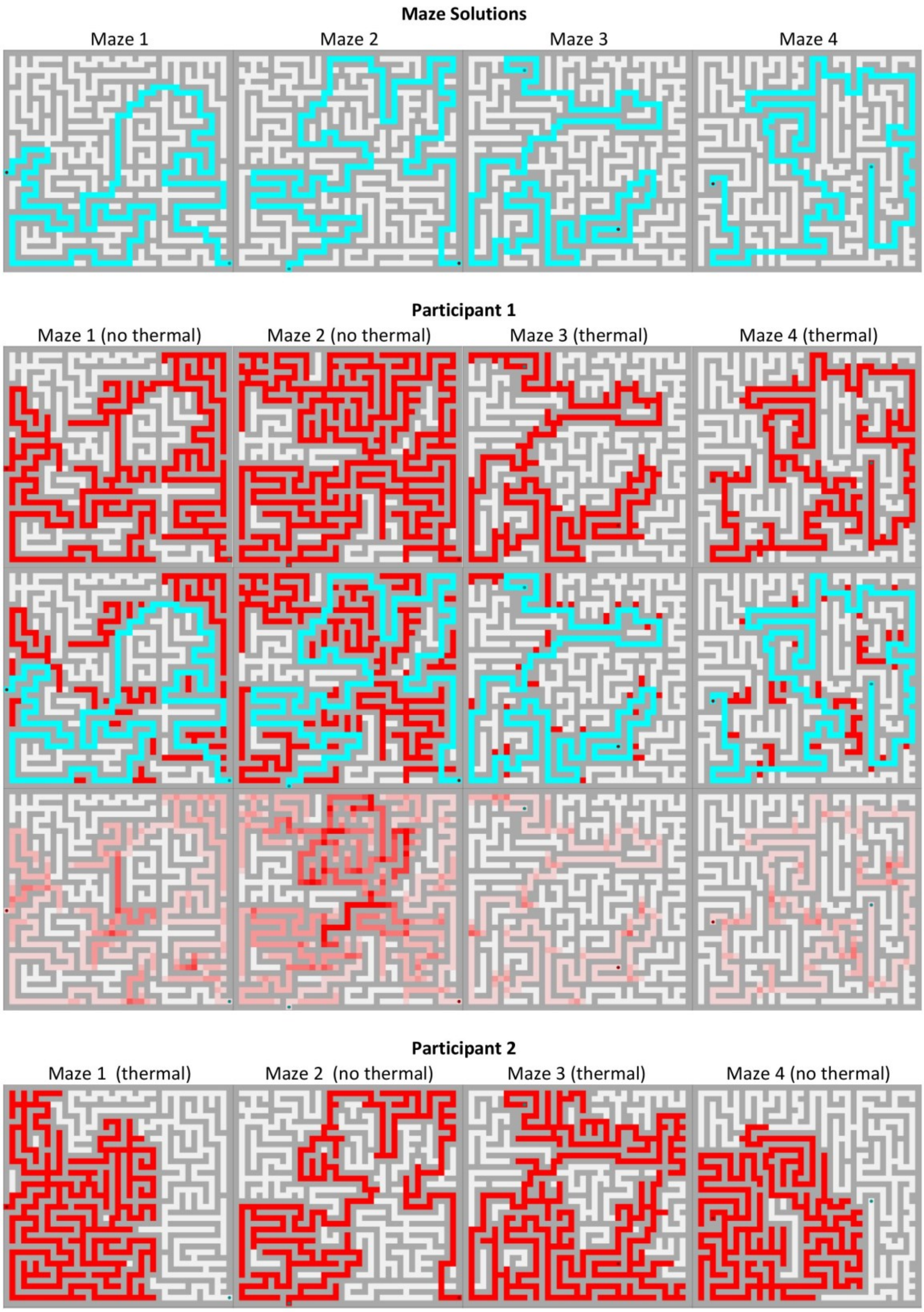
Q5: If this Technology could be worn, do you think it could useful for pedestrian naviagtion?

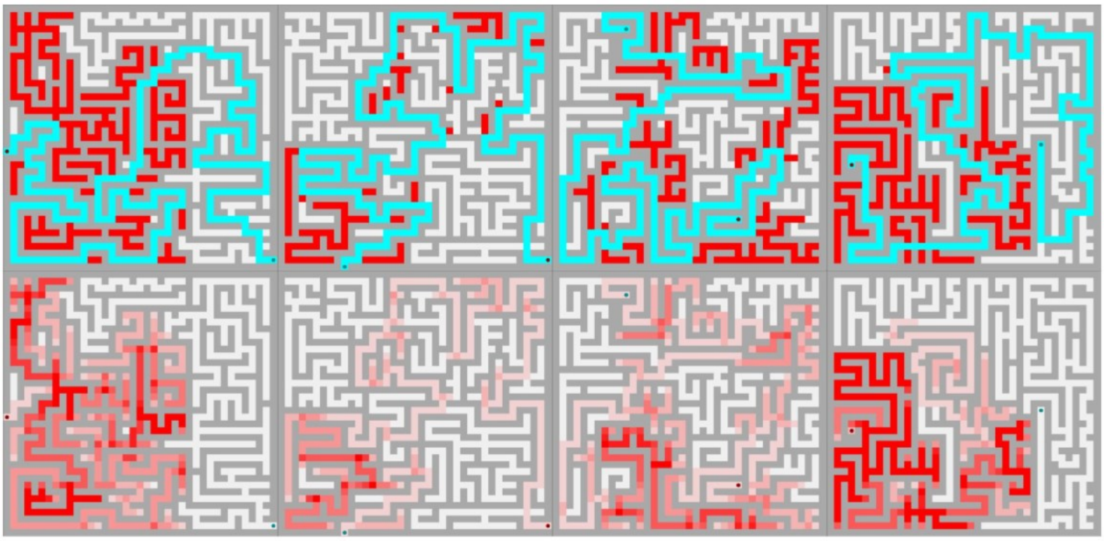
A1: It's possible, and its better than no feedback at all. Also adding vibrotactile feedback might be better.
A2: Still have to concentrate. Without temperature it is easier to concentrate on what you are seeing.

A3: Maybe, but it needs to take into account weather. Also with this system you will be able to look around.
A4: Yes
A5: Yes
A6: Yeah, but with a smaller device not a big one
A7: Yes, possibly, but not sure what benefits would be over vibration feedback. Might be too subtle to notice in busy environments when attention is elsewhere.
A8: With the respect of accuracy for direction and temperature difference, yes I do recommend this technology for the people with disability especially to the Blind one.
A9: If it was miniaturized then it might be useful. However, a vibrating signal might be easier to generate and to understand for the user.
A10: Yes, but I would want it to guide me in the right direction, not tell me that I'm in the right direction. I'd be annoyed if I had to keep turning around.
A11: Yes sure. If its simpler
A12: If it was designed to be felt effective. A watch like device may be too small.

Q6: What was your strategy for without temperature?
A1: I tried to remember were the paths were.
A2: I always took the path to the right.
A3: Keep trying to remember the maze. It's like blindness. I tried to get as much coverage of the maze as possible.
A4: Explore everywhere, and unlock each quadrant.
A5: Roughly cover areas of the screen and memorize them, corner by corner, then go to the middle. I tried to remember the junctions but it was too difficult to memorize.
A6: Just try all available paths. Some of the paths I visited them 3 or 4 times.
A7: Stay as long as possible on the path that I am on. When I reach a dead end I return to the last branch leading away from my path and try to stay as long as possible on that one etc.
A8: To go through all the pathways as fast as possible, for example at the junction of multiple way, instead of thinking which one can be correct, I go through all of them as fast as possible in order to make sure about the end.
A9: I think it was a combination of guessing and turning right whenever possible.
A10: I was trying to do the perimeter first, then work my way inwards to make sure I looked everywhere. It wasn't easy.
A11: Random
A12: Just try all the ways.

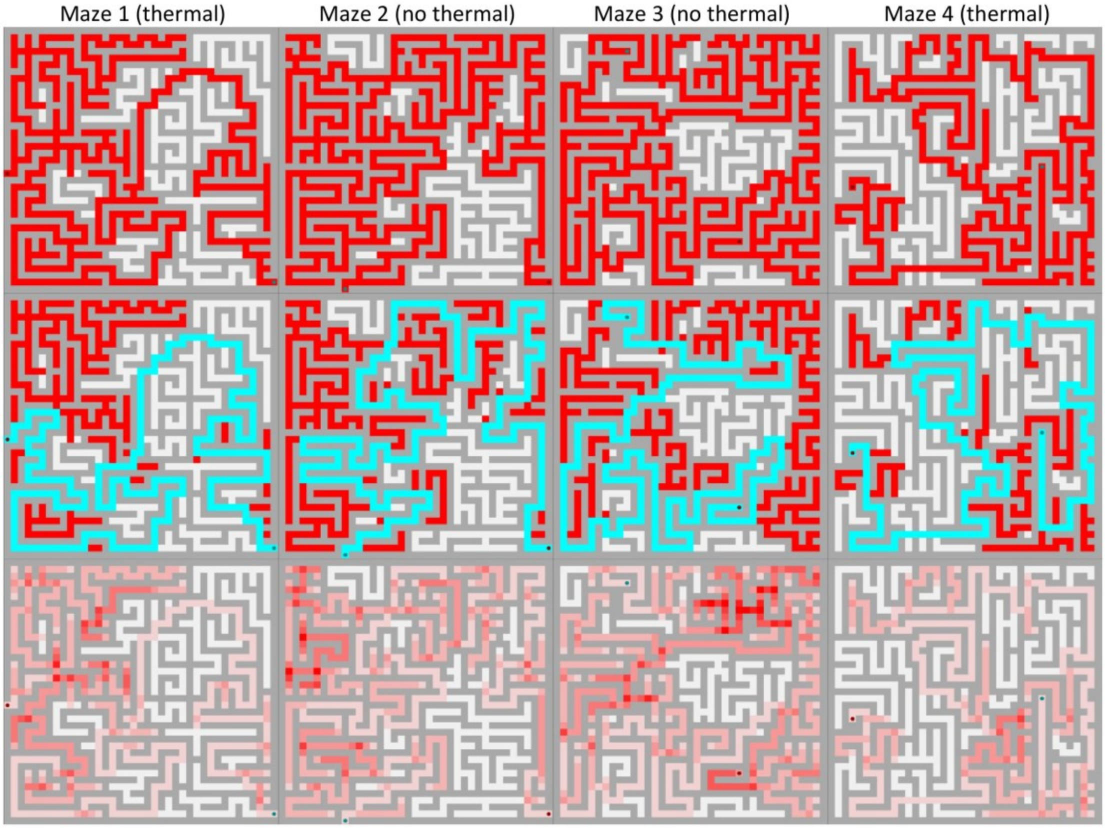
E.5 Heat Maps


Maze Solutions
Maze 1
Maze 2
Maze 3
Maze 4
Participant 1
Maze 1 (no thermal)
Maze 2 (no thermal)
Maze 3 (thermal)
Maze 4 (thermal)
Participant 2
Maze 1 (thermal)
Maze 2 (no thermal)
Maze 3 (thermal)
Maze 4 (no thermal)



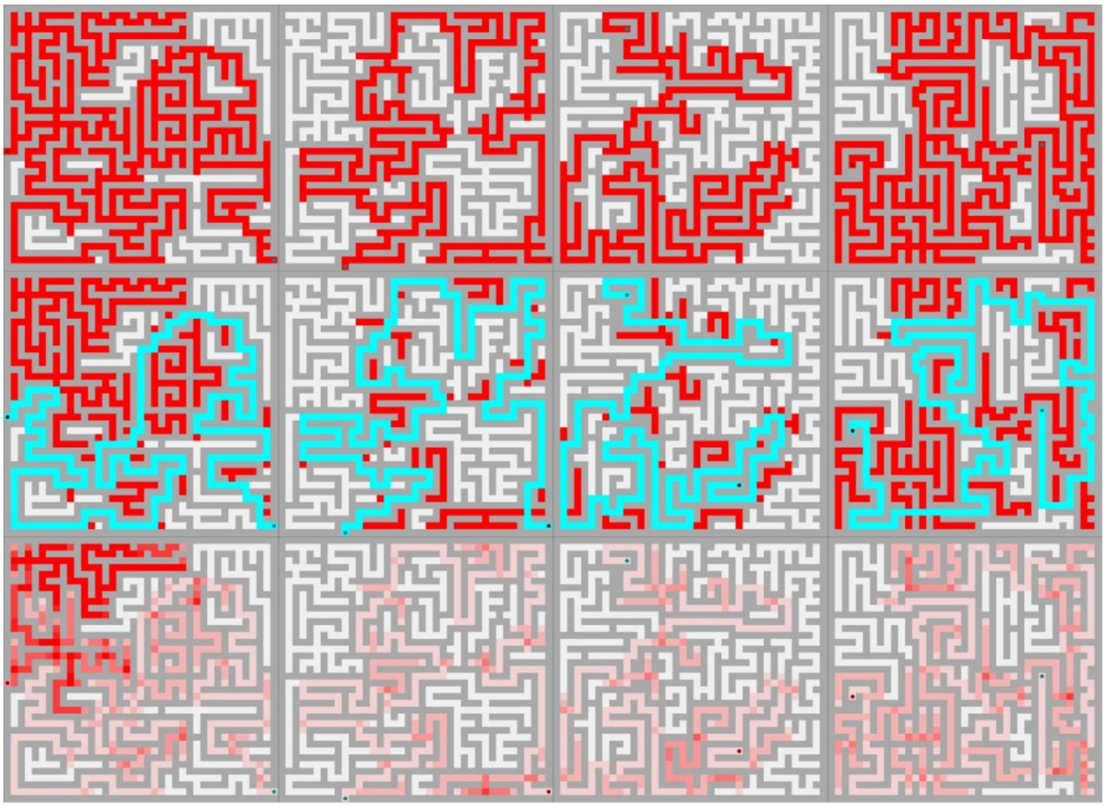
Participant 3

Maze 1 (thermal) Maze 2 (no thermal) Maze 3 (no thermal) Maze 4 (thermal)



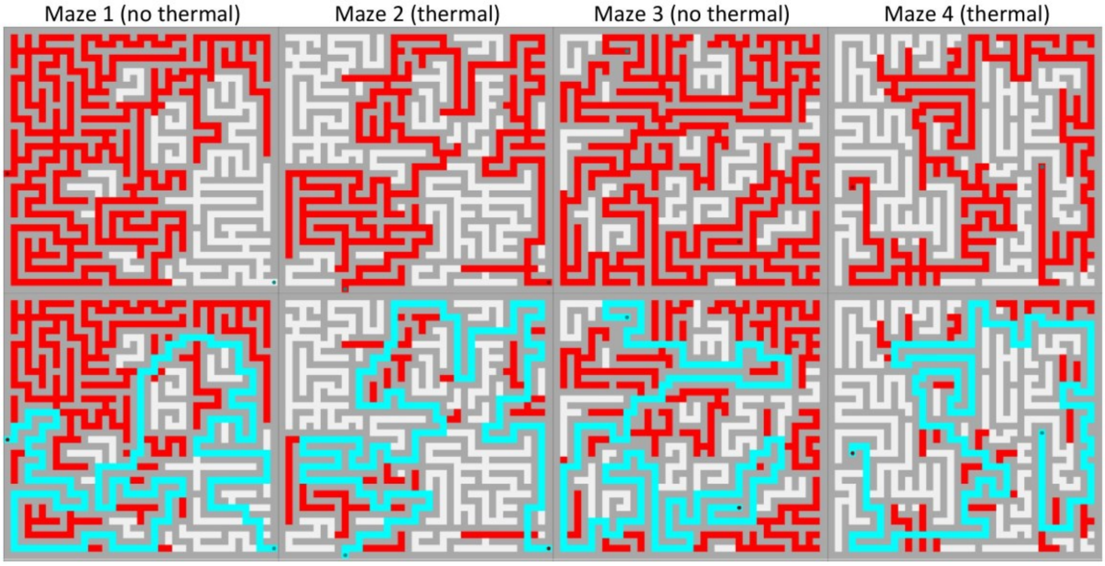
Participant 4

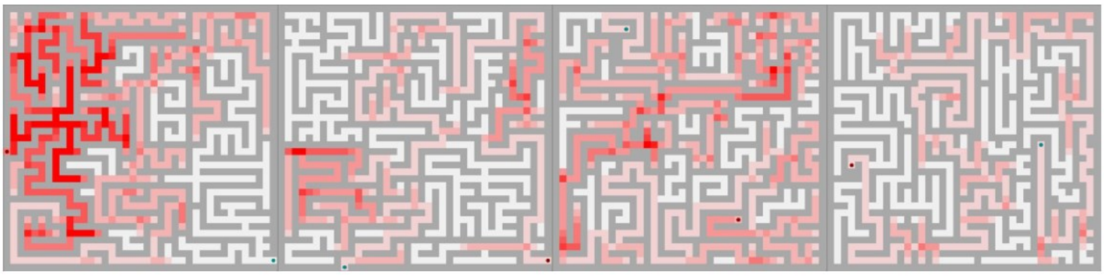
Maze 1 (no thermal) Maze 2 (thermal) Maze 3 (thermal) Maze 4 (no thermal)



Participant 5

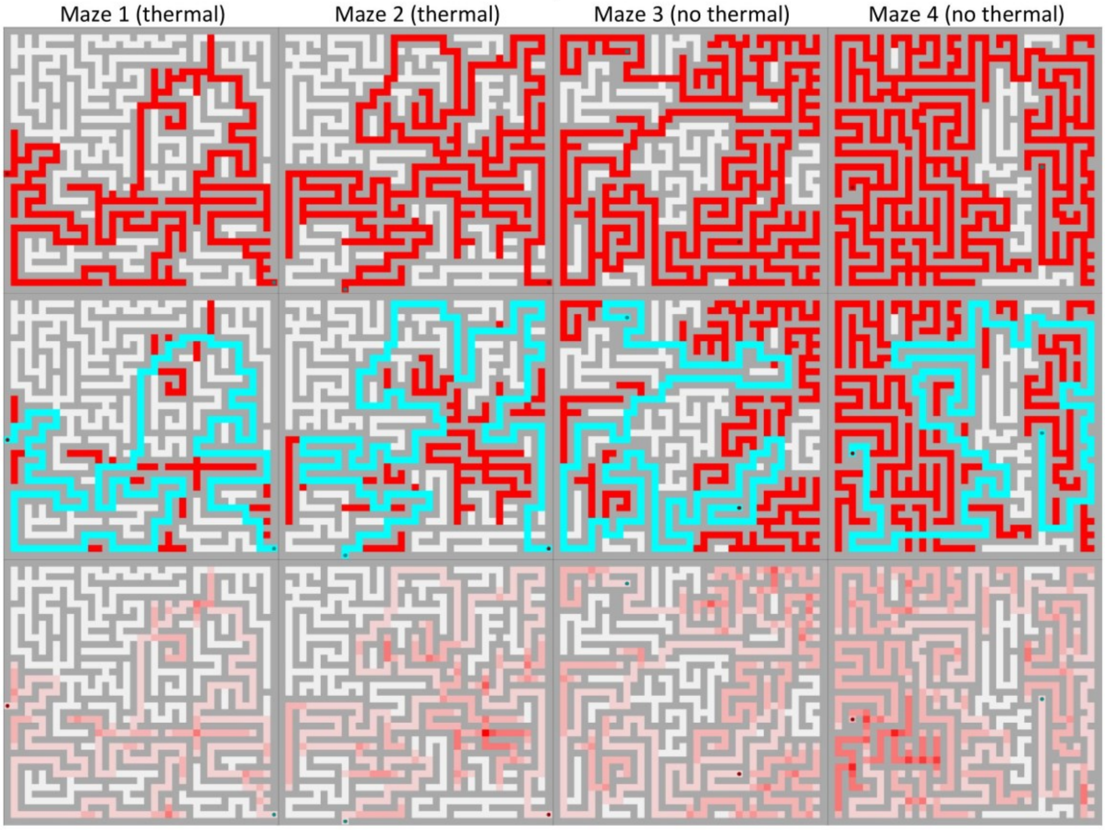
Maze 1 (no thermal) | Maze 2 (thermal) | Maze 3 (no thermal) | Maze 4 (thermal)





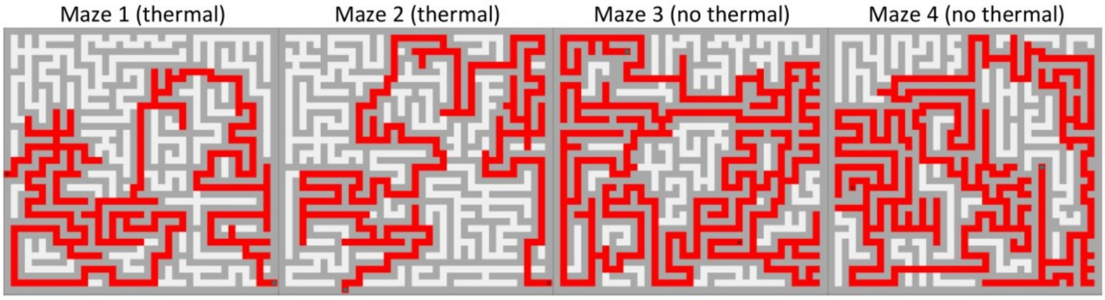
Participant 6

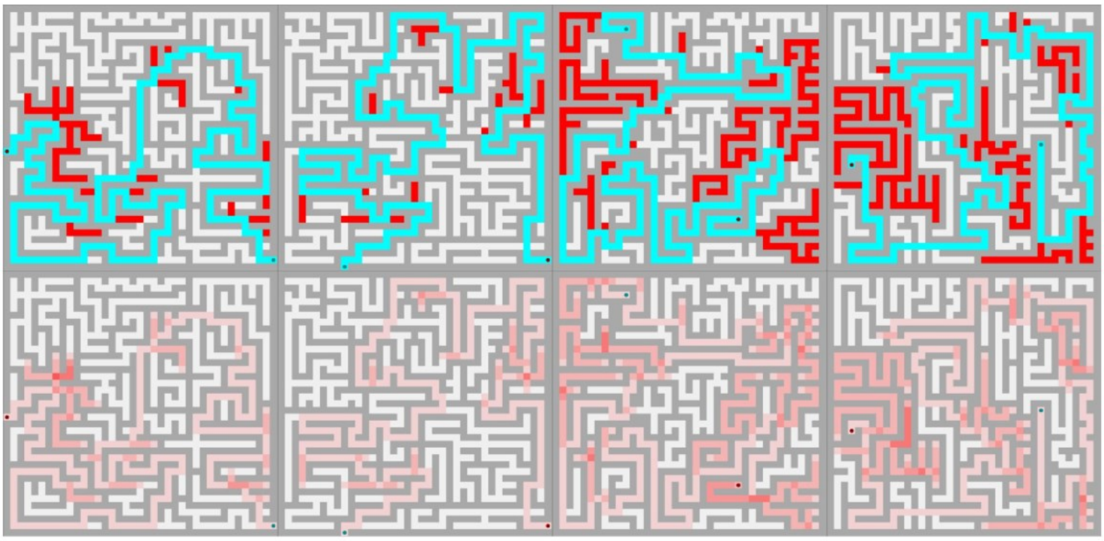
Maze 1 (thermal) Maze 2 (thermal) Maze 3 (no thermal) Maze 4 (no thermal)



Participant 7

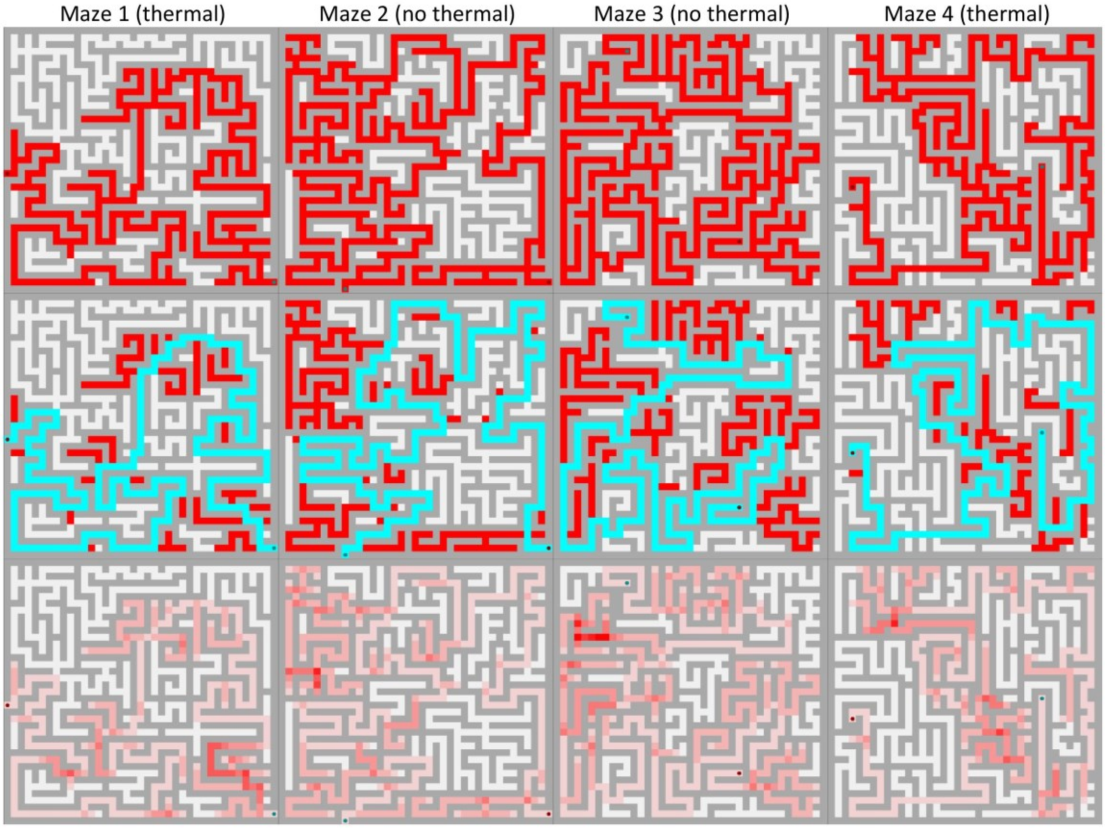
Maze 1 (thermal) Maze 2 (thermal) Maze 3 (no thermal) Maze 4 (no thermal)





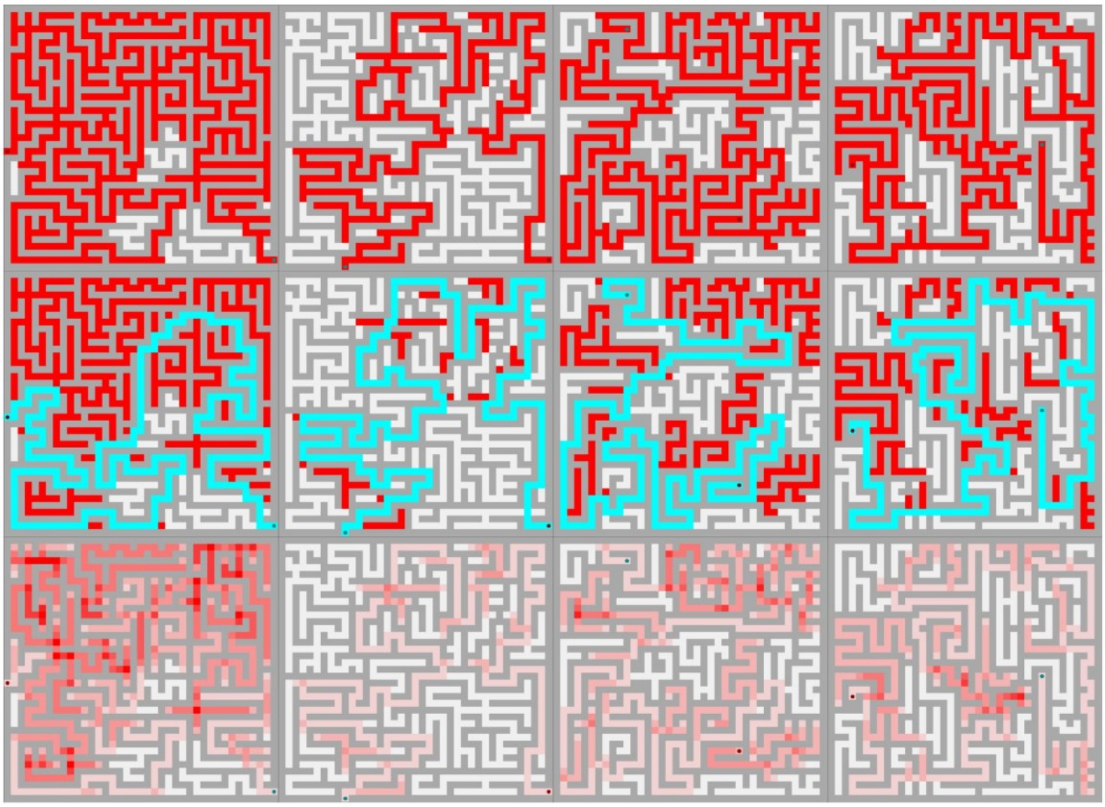
Participant 8

Maze 1 (thermal)	Maze 2 (no thermal)	Maze 3 (no thermal)	Maze 4 (thermal)



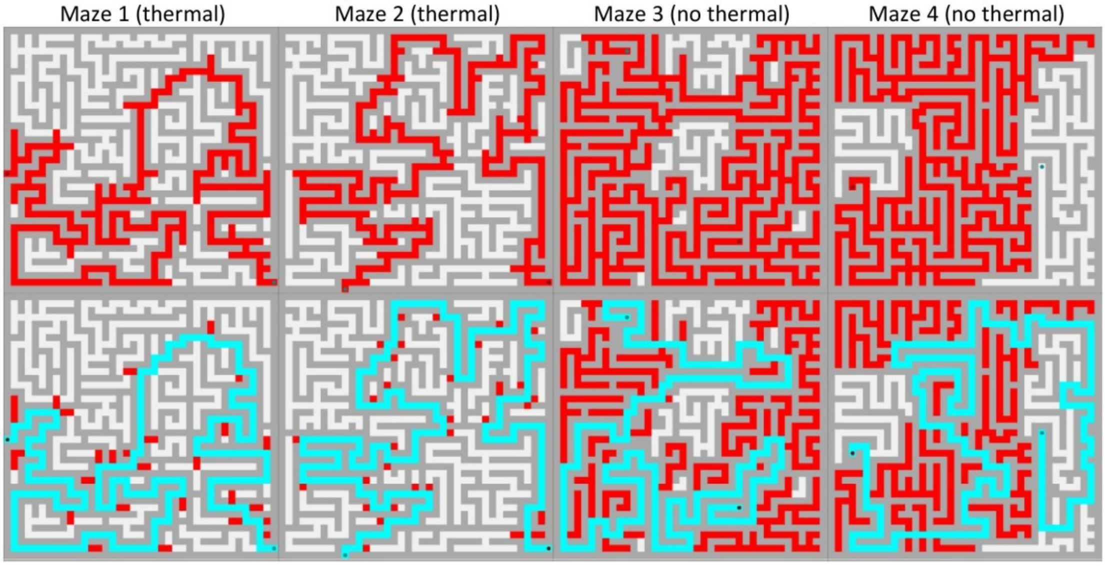
Participant 9

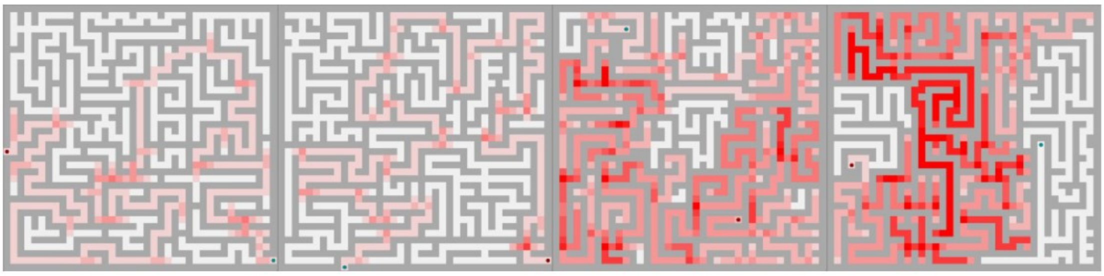
Maze 1 (no thermal)	Maze 2 (thermal)	Maze 3 (no thermal)	Maze 4 (thermal)



Participant 10

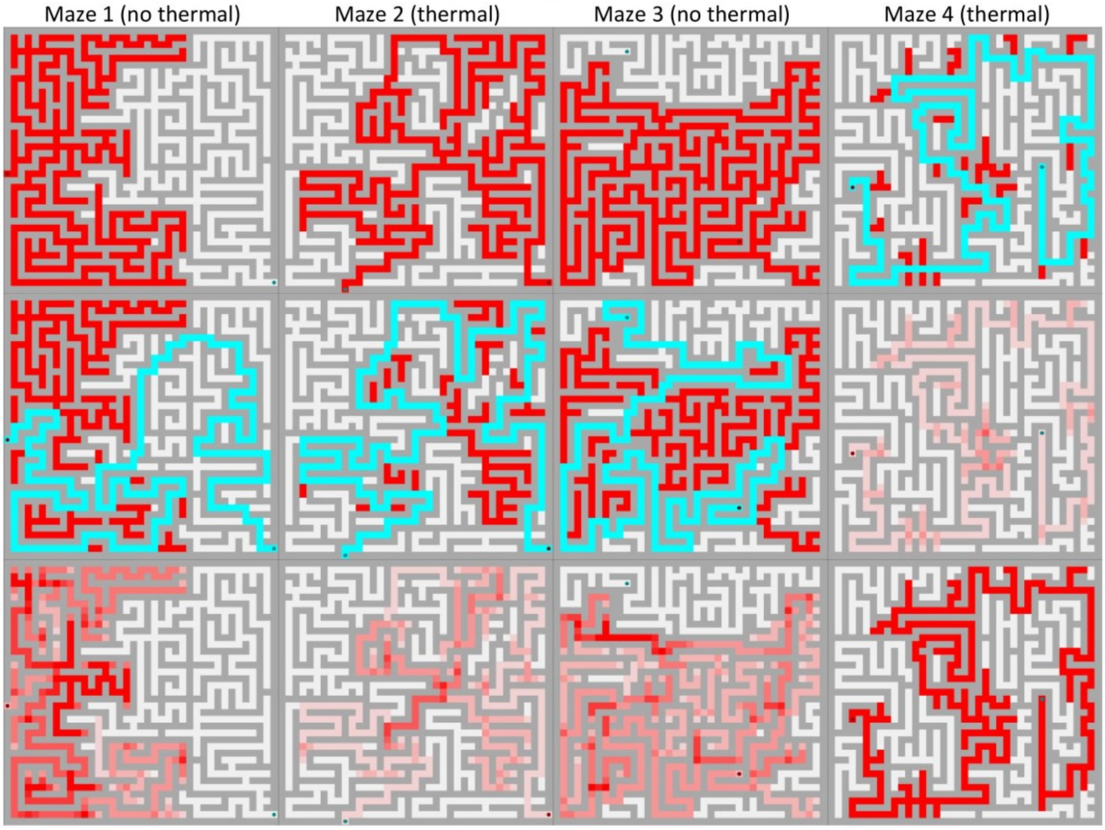
Maze 1 (thermal) | Maze 2 (thermal) | Maze 3 (no thermal) | Maze 4 (no thermal)





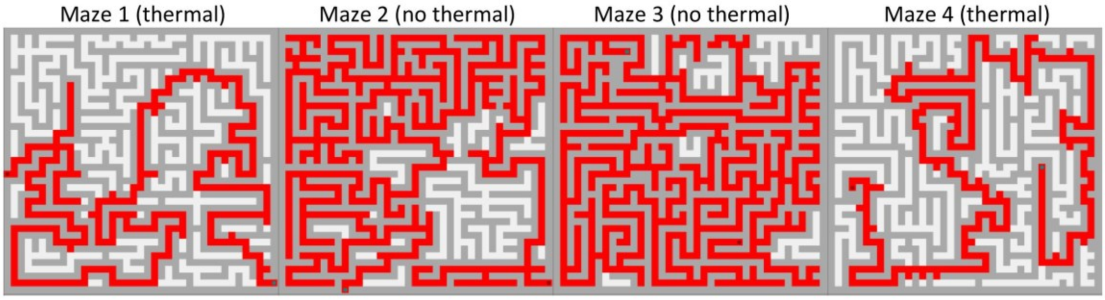
Participant 11

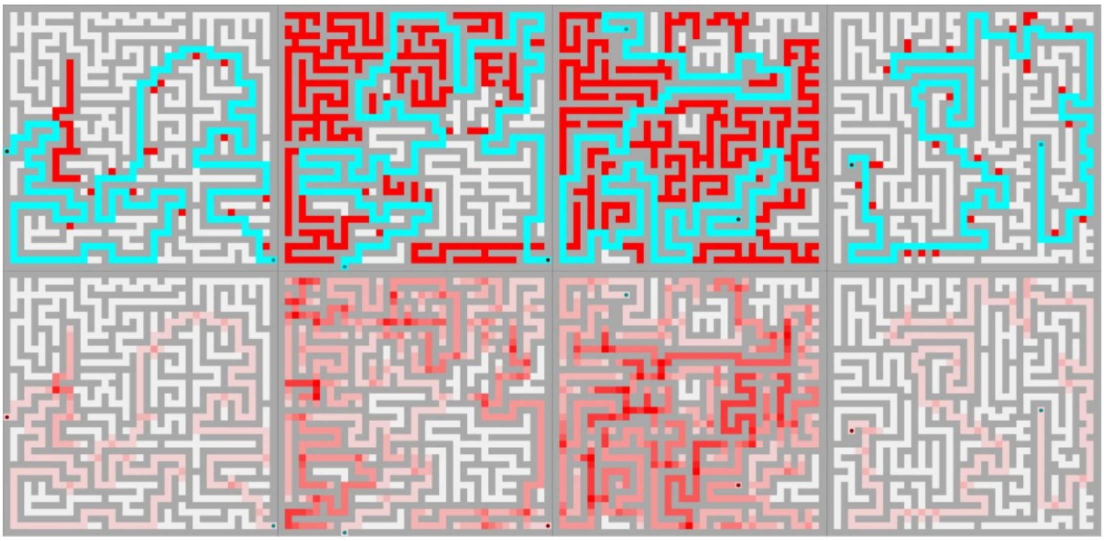
Maze 1 (no thermal) Maze 2 (thermal) Maze 3 (no thermal) Maze 4 (thermal)



Participant 12

Maze 1 (thermal) Maze 2 (no thermal) Maze 3 (no thermal) Maze 4 (thermal)





Appendix F

Chapter 7 Data

F.1 Pilot Messages

Type	TextID	Text Content	V_1	V_2	A_1	V_2
HV/HA	1	We'll be off and running to a lil' place called SILVERWOOD today! Can't wait! :)	9	9	8	8
	2	Happy happy happy new year to everybody!! I have optimistic hopes for 2016.	8	9	8	8
	3	OH EM GEE I LOVE MY SISTER SO MUCH! I WISH I WERE AS COOL AS HER!!!!!!!!!!!!! LIKE I CANT EVEN BELIEVE THAT I AM SO LUCKY TO HAVE HER AS MY SUPER DUPER AWESOME BIG SISTER!!!!!!! :DDDDDDD	8	8	9	9
	4	What a weekend? EAT, EAT and EAT some more, BBQ TIME!!!!	8	8	8	9
	5	i bought my wedding dress monday and i cant wait to have it on again!!!! its sooo	8	8	7	9
HV/LA	6	happy, got new friends, and lifes getting smoother.	8	8	2	1
	7	Thanks everyone for your birthday wishes another year is good thing blessed to have so many wonderful people in my life I love you all. P.S Tamika a birthday baby is a great gift thanks and much love to you all even you colts fans lol	8	8	3	1
	8	Life Gets Better from Here :)	8	8	3	2
	9	Blessed with a baby boy today...	8	7	1	3
	10	life is beautiful	7	9	1	1
LV/LA	11	i wasn't the son my father wanted	2	1	1	1
	12	you just killing me inside	3	2	1	1
	13	got a gun pulled on him last night	3	3	1	1
	14	My heart is broken for my sister. Her husband died today. She is a total mess, but I will help her get through this. I am strong enough. Maybe if I tell myself that enough, it will come true.	3	1	2	1
	15	well, we're in the hospital. my poor baby has had two spinal taps. we still dont know whats wrong....	3	1	2	3
LV/HA	16	At least 15 dead as israeli forces attack Gaza aid ahips!!!!!!! i hhhhhhate israil	2	1	8	8
	17	SICK AGAIN !!!! HATE IT !!!!!	3	2	8	9
	18	WTF WHY ARE YOU CHEATING IN A GAME OF THIS IMPORTANCE THAT WAS A CLEAN HIT ANYBODY COULD SEE THAT.YOU REFS COULDNT CALL A PLAY IF YOUR LIFE DEPENDED ON IT.WHEN A RECEIVER CATCHES A PLAY AND GET HIT THAT IS FOOTBALL.	3	2	9	8
	19	Is feeling especially racist against Americans today now that they've fXXked up skins!!THE IGNORANCE!!!!!!!!:'(	3	3	9	9
	20	HEADACHE!!!	3	3	9	9
NV/NA	21	i'm not dirty as yo think I am!	5	5	5	5
	22	School is about to start!	5	5	5	5
	23	is facing one of the most difficult decisions ever! The job offers are in: DC or Paris!	5	5	5	5
	24	i run over a fork on ur car, coz im a ninja!! lol	5	5	5	5
	25	And one careless match can start a forest fire but it takes a whole damn box to get a campfire going!	5	5	5	5

F.2 Pilot Valence Results

Message ID	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
1	3	4	4	3	3	4	3	4	4	3	5	4
	3	3	4	3	3	3	3	4	4	3	4	4
	4	4	4	4	3	3	3	4	4	3	4	4
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	4	4	4	4	4	3	4	5	4	4	4	4
7	4	3	4	4	3	4	4	5	4	3	4	3
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	4	4	4	4	3	3	4	4	4	3	4	3
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	2	2	2	2	3	3	1	1	2	3	1	1
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16	1	1	1	1	2	1	2	1	1	3	2	1
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	1	2	2	1	3	5	4	3	3	2	3	2

18	2	2	2	2	3	3	4	2	3	3	2	2
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Thermal	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
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Coolest	1	3	2	2	2	3	2	5	4	3	3	4
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	2	3	3	1	2	2	2	5	4	3	3	3
Cooler	1	2	3	2	2	3	2	4	4	3	4	4
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Cool	3	3	4	3	3	3	2	3	3	4	3	3
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	2	3	4	4	3	3	4	5	4	3	4	2
Neutral	3	3	2	4	3	3	3	3	3	3	3	3
	3	2	2	3	3	3	4	3	3	3	4	3
	3	3	2	3	3	4	3	3	3	3	4	2
Warm	2	3	2	3	3	3	4	3	3	3	3	3
	3	2	3	3	3	4	3	4	2	3	2	3
	4	4	4	3	2	4	3	3	2	3	2	2
Warmer	4	1	2	4	3	2	4	3	2	3	4	2
	4	4	2	4	2	2	3	2	3	3	4	2
	4	4	1	2	2	5	4	2	2	2	2	2
Warmest	4	2	1	3	2	5	4	2	2	2	1	1
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F.3 Pilot Arousal Results

Text ID	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
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24	4	2	3	4	3	4	1	4	3	3	4	2
	3	5	3	3	3	3	1	4	3	1	4	2
	3	3	3	3	3	3	2	3	4	3	4	2
25	1	3	4	1	3	4	1	1	3	3	1	4
	3	4	2	3	3	3	2	2	2	3	2	4
	3	5	3	3	3	2	2	2	4	3	4	4

Thermal	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
Coolest	4	2	2	4	4	2	4	4	4	3	1	4
	4	1	2	3	4	3	4	3	4	3	2	4
	5	3	2	4	3	2	4	4	2	1	2	5
Cooler	2	2	3	5	3	2	3	4	3	3	1	3
	5	2	4	4	3	4	3	3	3	2	2	4
	3	2	3	3	3	3	3	3	4	3	3	4
Cool	3	1	4	3	3	3	2	3	4	3	2	4
	3	1	3	3	3	4	2	3	2	1	1	4
	4	2	3	3	3	2	2	4	4	3	1	4
Neutral	1	1	2	2	3	3	2	5	2	3	1	3
	3	1	2	3	3	3	2	3	3	3	3	2
	2	1	4	3	3	3	2	3	3	3	2	4
Warm	3	2	3	3	3	4	2	3	2	3	3	2
	2	1	3	2	3	3	2	3	2	3	3	3
	3	1	3	3	3	3	1	3	3	3	3	4
Warmer	4	4	2	3	4	4	1	2	3	4	4	2
	4	3	4	3	4	4	3	3	3	4	4	1
	3	4	4	3	4	4	1	2	4	4	3	1
Warmest	5	3	4	4	4	4	3	2	4	4	4	1
	5	3	4	3	4	5	2	3	3	4	4	1
	4	4	2	3	4	4	3	2	3	4	4	2

F.4 Pilot Time Logs (in milliseconds)

Text ID	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
	8800	12500	8200	6500	5000	6300	5700	15800	6400	4500	15100	11600
1	7200	7100	3700	4200	3100	7000	3300	13000	6300	4800	10300	5200
	22300	5300	6600	5300	3500	4000	2900	12100	5800	5700	5300	3300
	8700	7800	6500	4700	3700	6300	5100	10700	5200	4200	7700	8900
2	6600	5800	3300	7400	3900	6500	3800	10900	7600	4900	7000	7000
	5300	5000	3600	4500	3400	3200	4300	5100	5600	6300	5800	6500
	13500	11600	11300	7400	9500	14000	6500	17100	9300	7500	14200	17900
3	4800	12600	11600	3500	4900	8200	4600	9800	8300	5800	9600	5000
	7500	7900	4500	3500	2900	7400	3400	12100	5200	4600	7700	9000
	12700	7300	6700	4600	6600	12100	4200	7200	6800	4600	12600	5200
4	4700	4300	3900	3900	5800	4500	4600	5700	5200	4000	5200	6200
	3600	4000	3500	3500	2900	5800	2600	5100	5000	5300	3900	8500
	13000	7500	7900	5400	3900	8800	5800	9800	6200	5800	10800	8200
5	5600	7200	4400	3700	3400	7900	3700	7600	5300	8100	8500	6500
	4400	5800	3500	3600	3400	11300	3000	6500	6500	6200	6300	6500
	8000	4900	7400	7400	5200	7600	4500	8400	5700	4700	8500	8500
6	5600	5100	9500	4800	3500	7600	3400	7400	4900	5500	6700	10400
	5100	4500	4400	7000	3400	6800	3800	6300	5200	3800	7900	4600
	20300	15900	10600	5600	11700	12900	8700	22400	9100	5700	11700	14300
7	10400	7500	5800	9300	7200	12600	3300	10600	5900	6500	7800	16400
	10000	9100	4000	3700	3800	17000	4700	12600	9700	5000	9100	14400
	5600	4900	6100	3900	3900	10400	4600	7300	5800	6000	6800	5900
8	4600	4400	5100	10000	2900	2600	3800	5400	4300	4900	5000	4800
	3700	4800	6000	3300	3200	3300	2500	5200	4800	3900	5200	5100
	5200	6900	4600	4300	6500	6000	3700	7100	5800	8300	8200	5700
9	3600	5700	4400	4000	3600	7400	3200	7000	4900	5900	5900	6600
	3500	3600	3500	4600	2900	3100	2300	6000	4900	7000	4700	4000
	9600	4200	3500	2800	3600	4700	5100	6100	4600	5200	11100	6100
10	4900	3900	3000	2700	6300	5600	3400	4700	4200	3100	5200	11000
	3300	3900	7900	4900	3000	6200	2800	4600	4000	3900	5300	8100
	21500	9000	4900	5900	3600	9400	6300	8500	5700	5700	9500	8600
11	9200	5600	4000	7000	3500	9800	3600	5600	6200	3600	9100	14000
	6600	4300	8000	7900	3200	3700	3000	4600	7300	3800	4400	3300
	8700	6000	8900	4800	5100	8900	4500	7200	5300	6500	8700	5100
12	5200	6400	7100	3800	3000	5500	3700	4900	8200	5500	6700	6500
	15400	3800	3600	3100	2000	2300	3100	4500	5300	3100	7000	3700
	6900	6100	8100	4800	4500	8300	6700	8800	5300	5900	13100	10100
13	6000	6400	5300	3100	3400	3900	8400	7000	7700	4000	6300	4400
	3600	3900	9200	3500	3700	3000	4700	5900	7500	3900	7500	3500
	6900	15800	12200	11400	8500	12800	6900	13900	10700	8700	17500	15400
14	12100	13000	5100	5100	7300	9600	3100	7600	8700	7200	9600	6300
	8500	9300	3700	4000	4200	5600	4400	9400	7700	4600	9200	10600
	7400	7900	10500	8900	5300	10500	6400	13800	8400	5800	10800	7200
15	5000	8000	4600	3900	4400	6800	3900	8200	7700	3600	7000	6200
	4800	6900	6200	3900	4900	5600	2800	7200	6400	3700	9000	4700
	9800	9900	8100	6000	5900	15500	7600	24900	8500	6500	13000	11000
16	9500	5300	6500	3800	5000	8100	6800	7300	6800	5700	7100	7200
	5700	4100	3600	3600	4800	4900	4300	5200	4600	6500	6200	5100
	6100	4700	5100	3200	6100	6000	4500	7400	6900	3600	8000	3800
17	5000	5500	5200	2500	6900	5500	4400	5400	6200	3700	6000	6400
	5900	4000	3500	3600	2600	6400	3300	5000	4900	3100	4300	7400
	17900	17600	14000	10500	10300	14500	10300	25300	11500	7100	20300	21500

18	6100	10400	6500	3000	5200	17500	4200	19300	7900	6400	7000	5200
	5900	10800	4500	3300	8000	6900	5000	9800	3400	5400	5900	8200
	19900	18100	7200	10600	8300	14400	7900	15800	9400	8000	16300	10400
19	7800	7200	5400	5300	4300	8100	5700	14300	6800	8800	10000	7100
	5400	6000	6600	4700	4800	7600	5700	10000	6100	4600	6300	4200
	11400	6900	4500	3100	4900	4700	3800	9400	4800	6000	7200	7500
20	7400	4100	34300	3400	5700	7000	2900	4700	3500	4800	7900	5400
	4500	4900	5800	3200	5800	5200	2500	8600	5600	3200	6500	6200
	9200	7400	9500	7400	3100	6900	7300	14300	5500	7100	10900	5500
21	7100	6500	26600	5000	2900	6400	3800	5400	5100	4300	7600	5000
	4800	5200	5200	2500	3300	3500	3400	6000	4200	3500	3300	4200
	7100	4400	5000	5000	4700	7000	5300	6100	4900	5500	6700	7500
22	4300	3700	3500	4400	3700	2700	3400	5900	25300	4300	4300	3100
	3200	4800	3200	3000	2800	7800	3500	4200	5800	3300	3800	4300
	13900	7300	17000	4600	6700	12700	5300	14500	17400	5100	14100	16200
23	6400	6500	4500	4000	7100	5900	3500	9300	7500	5200	5900	14000
	10500	4900	4600	6300	2900	3000	3600	6700	6300	3900	3900	12600
	7500	9100	8000	4500	8200	12200	7200	15100	8100	6700	8900	11200
24	6900	5700	4300	3100	3600	15000	7000	6200	7100	4300	4600	5600
	4400	5400	3400	3500	3400	3200	3800	10000	6800	3400	8700	3500
	11800	15600	22800	7100	11200	8500	7300	17000	7900	4700	21100	14600
25	6400	5500	8400	6400	4500	11100	4600	13500	12100	5100	8700	7600
	6500	7100	5800	4700	3800	4700	3100	7800	6700	5300	5800	5400

Thermal	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
	6200	5700	14000	5500	3600	6600	6800	77800	11500	4600	6200	7000
Coolest	8800	5300	8100	7400	3700	3600	4700	7100	3800	3300	7300	7300
	6500	6900	16300	5300	4900	7300	3900	4800	4900	4300	5200	5700
	6300	6700	8600	5300	6600	7900	4000	4800	4200	5100	8800	10800
Cooler	8000	5000	7200	6700	11700	6100	5400	4100	6400	3300	5000	5900
	11100	7700	14100	4900	5400	6800	3400	3600	7600	2900	3500	4800
	7000	6200	5400	9900	6900	6400	6700	4800	21400	3200	6000	8500
Cool	5600	6900	9700	8300	7000	5300	7900	3700	7700	4900	6300	9000
	14000	8100	4600	6400	7800	4600	5100	4700	7200	3000	5400	9800
	11300	6700	5400	5500	5800	6400	8000	6000	5600	4700	4100	6600
Neutral	4100	8700	14700	5900	7600	4900	7000	5900	4900	3700	7200	9200
	9500	7100	12900	6700	3700	5400	6700	3300	5300	2900	5500	7800
	15000	4100	7800	6400	7600	24500	7700	6500	7000	2600	6200	5800
Warm	7100	6200	17200	8300	4900	5400	5500	4400	4600	3100	5300	12900
	5300	5900	9900	5900	4100	6700	6200	5300	6000	3200	5700	7900
	7800	5000	9900	6600	5000	5600	8600	6100	7500	4700	4700	8800
Warmer	5700	5200	7200	5700	5500	7100	5800	6700	7700	4000	6700	6200
	9900	6000	7500	5000	5000	4500	5000	7000	6900	3900	5500	6500
	13300	3300	5600	6000	5800	5400	6300	8100	7900	3900	4900	6000
Warmest	14400	4400	5800	5700	4100	2700	6000	5400	4700	4300	4100	5600
	8000	7900	10500	6500	3400	4000	5400	6000	6300	4500	4200	5700

F.5 Main Study Valence Results

Text Type	Thermal	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
High Valence, High Arousal	Coolest	9	7	6	2	5	8	6	8	6	9	9	3
		9	8	4	4	5	8	6	7	6	8	4	5
	Cooler	9	8	6	3	5	8	7	8	6	9	5	4
		9	8	5	4	5	8	5	8	7	8	5	5
	Cool	8	8	6	4	5	8	6	8	6	8	9	6
		7	8	7	4	5	8	6	8	7	8	5	4
	Neutral	9	8	7	4	4	8	6	8	7	8	9	5
		7	8	6	4	5	8	6	8	6	8	5	3
	Warm	9	8	7	3	5	8	8	8	6	9	6	5
		6	9	5	4	5	8	6	8	7	8	9	2
	Warmer	3	8	6	5	6	8	7	9	8	9	5	4
		4	9	6	5	6	8	7	8	6	8	5	3
	Warmest	6	8	6	6	5	8	7	9	5	9	9	3
		4	9	6	6	5	8	7	7	4	8	3	3
	None	9	8	8	5	5	9	7	8	7	8	8	4
		9	8	7	5	5	8	7	8	7	8	6	4
High Valence, Low arousal	Coolest	9	5	6	5	6	7	6	7	7	8	9	4
		9	5	6	5	5	7	5	6	7	8	5	2
	Cooler	9	6	6	5	6	7	6	7	6	9	9	2
		9	6	6	5	5	7	6	6	3	8	7	2
	Cool	7	5	5	6	5	7	6	7	6	9	9	4
		7	6	5	5	4	7	6	6	7	8	5	4
	Neutral	9	5	7	5	5	7	6	6	7	9	9	6
		9	5	5	4	5	7	7	7	5	9	9	4
	Warm	9	5	7	5	5	7	6	8	7	9	9	6
		7	5	6	6	5	7	7	6	5	9	5	5
	Warmer	7	7	5	6	5	7	7	6	4	9	8	4
		7	6	7	6	5	7	7	7	4	8	6	4
	Warmest	5	7	7	6	4	7	7	6	6	8	9	3
		2	7	5	7	5	6	7	8	7	9	9	5
	None	9	6	8	4	6	7	6	7	8	8	8	1
		9	7	8	6	5	7	6	7	7	8	6	1
Low Valence, Low Arousal	Coolest	5	2	5	2	4	3	1	1	7	3	8	6
		3	5	5	2	4	4	3	2	3	2	5	4
	Cooler	5	4	5	3	5	4	2	3	5	2	2	4
		5	3	4	3	4	4	4	4	3	3	2	4
	Cool	4	4	3	4	4	4	4	5	5	2	7	3
		3	3	4	3	4	4	5	3	5	3	5	1
	Neutral	5	2	3	4	5	5	5	5	3	4	5	5
		2	4	4	4	4	3	4	3	4	2	4	2
	Warm	3	4	5	3	5	4	4	3	7	2	4	2
		3	3	4	4	4	4	4	2	7	2	2	4
	Warmer	4	4	5	4	4	4	3	3	4	2	4	4
		3	4	3	3	5	4	5	2	4	2	5	3
	Warmest	2	4	4	4	5	3	5	3	6	2	1	4
		2	3	4	3	4	4	5	1	3	2	4	5
	None	4	3	3	3	4	4	4	3	3	2	5	2
		1	3	4	3	5	5	3	4	3	2	5	3
	Coolest	2	2	4	2	4	3	3	1	5	2	3	2
		5	3	4	3	4	4	2	2	3	2	1	2
	Cooler	2	3	4	3	3	3	3	1	3	2	1	3
		3	2	4	3	4	3	1	1	6	2	3	1

Low Valence, High Arousal	Cool	5	2	5	3	3	3	4	1	3	2	4	2
		5	3	3	4	4	3	4	1	3	2	3	2
	Neutral	4	3	4	2	6	4	3	1	3	2	4	2
		3	2	4	3	4	3	3	2	2	2	4	1
	Warm	4	2	3	3	4	3	5	1	5	2	2	1
		4	1	4	3	4	3	2	1	5	2	6	2
	Warmer	3	3	3	3	4	3	4	1	2	2	4	4
		2	2	5	2	4	3	3	1	4	2	3	1
	Warmest	1	2	3	1	4	3	4	1	2	2	1	3
		1	2	3	2	4	3	5	1	3	2	4	1
	None	1	3	1	1	2	3	3	1	4	2	4	2
		1	2	2	2	3	3	3	1	3	2	3	2
Neutral	Coolest	6	7	4	4	5	3	4	7	3	5	5	3
		4	5	5	5	4	3	4	6	6	5	4	1
	Cooler	6	6	4	4	5	4	4	7	5	5	4	3
		5	6	4	5	5	3	4	6	6	5	4	5
	Cool	4	6	5	4	4	3	5	6	5	6	4	3
		4	6	4	4	4	3	5	7	3	5	5	4
	Neutral	3	5	4	6	4	3	5	5	5	5	5	6
		4	6	5	5	4	3	5	6	6	6	5	2
	Warm	5	5	5	6	5	4	5	5	7	5	9	4
		5	6	4	5	4	3	5	7	5	5	5	3
	Warmer	3	6	5	6	5	3	5	6	5	6	9	3
		4	6	4	7	4	3	5	6	7	5	8	5
	Warmest	1	6	3	6	4	3	5	6	3	4	8	9
		4	7	3	8	5	3	5	7	3	5	4	4
	None	5	6	6	8	5	8	4	5	5	5	8	2
		5	7	5	8	5	7	5	6	6	5	6	2
No Message	Coolest	6	6	4	2	6	6	2	3	3	8	6	4
		8	4	4	3	5	5	3	6	5	8	5	3
	Cooler	7	6	5	3	5	5	3	6	3	5	9	3
		6	5	5	4	5	5	2	5	5	6	5	2
	Cool	5	6	5	4	5	5	5	5	7	9	5	3
		6	6	5	6	5	5	5	6	6	8	5	3
	Neutral	5	6	5	5	5	5	5	5	5	8	5	5
		5	5	4	6	5	5	5	6	7	3	5	3
	Warm	4	5	4	5	5	5	5	5	6	8	4	5
		7	6	4	5	5	5	5	5	5	7	5	2
	Warmer	4	6	3	7	5	5	4	4	3	8	4	4
		5	7	5	8	5	5	6	6	3	5	5	2
	Warmest	2	6	4	7	4	5	8	4	3	8	4	2
		4	6	3	8	5	5	8	6	3	8	5	2

F.6 Main Study Arousal Results

Text Type	Thermal	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
High Valence, High Arousal	Coolest	1	6	4	2	5	7	5	5	7	8	2	3
		2	7	4	3	5	8	4	4	7	7	4	5
	Cooler	3	7	4	4	4	8	6	7	7	7	5	4
		1	7	5	2	3	8	4	6	7	8	4	4
	Cool	3	6	2	3	3	7	5	6	6	8	1	5
		3	7	2	2	5	8	5	4	6	7	6	3
	Neutral	1	8	3	2	4	8	5	5	6	7	2	4
		3	8	3	4	4	8	4	6	4	7	4	4
	Warm	4	8	2	3	4	8	6	5	3	6	5	4
		4	7	4	3	3	7	6	7	7	6	3	2
	Warmer	6	8	2	4	6	8	6	7	8	7	4	3
		6	8	4	6	6	7	7	7	6	7	4	2
	Warmest	5	7	3	5	6	8	6	6	2	8	2	2
		5	9	4	3	6	7	7	7	8	7	4	2
	None	1	8	5	5	3	8	7	7	7	8	1	3
		1	8	5	5	4	7	7	6	7	8	2	3
High Valence, Low arousal	Coolest	1	5	3	3	5	6	5	7	3	8	2	3
		5	4	3	3	5	6	3	6	5	6	5	2
	Cooler	1	5	2	3	5	7	5	7	3	7	4	3
		1	5	4	3	6	6	5	6	7	8	3	1
	Cool	3	5	4	5	5	6	5	4	3	7	2	3
		3	4	3	4	5	6	5	5	7	6	4	3
	Neutral	1	4	2	4	4	6	7	4	2	7	2	5
		2	4	3	5	4	6	5	5	5	8	1	4
	Warm	3	4	2	4	5	7	5	7	6	8	1	4
		3	4	3	5	4	7	6	5	4	8	4	4
	Warmer	4	6	4	5	4	5	6	5	7	8	2	3
		4	5	5	4	4	7	6	6	7	7	4	3
	Warmest	5	7	1	6	6	7	7	6	4	8	3	2
		7	6	4	7	6	6	7	7	8	7	2	4
	None	1	6	1	5	4	5	5	4	7	8	1	1
		1	6	1	4	4	5	6	3	4	8	3	1
Low Valence, Low Arousal	Coolest	5	4	4	4	5	4	1	6	7	2	1	5
		6	4	3	3	6	4	2	4	2	2	4	4
	Cooler	5	4	5	3	6	4	1	7	3	2	2	3
		5	5	3	5	5	4	3	3	7	2	3	2
	Cool	5	3	2	4	6	5	3	2	7	2	2	4
		6	5	5	5	4	4	3	2	3	2	4	1
	Neutral	5	5	4	4	4	5	4	5	3	3	4	5
		6	4	3	4	4	4	5	4	6	2	6	1
	Warm	7	4	4	5	4	4	2	5	7	2	3	2
		6	5	5	5	5	5	3	3	6	2	2	4
	Warmer	6	4	3	5	6	4	1	2	8	3	5	4
		6	4	6	5	5	4	3	6	8	2	6	2
	Warmest	6	3	4	5	6	4	3	7	6	2	6	3
		8	4	4	6	6	4	4	8	8	2	5	4
	None	7	5	2	4	7	5	2	2	7	2	1	2
		7	4	2	6	3	5	2	2	3	1	3	3
	Coolest	6	4	4	6	6	5	1	7	3	4	6	3
		5	6	5	6	5	4	2	4	7	2	6	2
	Cooler	6	5	4	5	5	4	3	8	3	2	3	3
		5	5	5	6	5	4	2	6	3	2	5	2

Low Valence, High Arousal	Cool	5 6	4 5	3 4	6 6	5 5	3 4	3 3	4 4	7 3	2 2	6 4	2 2
	Neutral	7 6	4 5	5 5	6 6	7 7	4 4	2 2	4 4	7 1	2 2	7 4	2 1
	Warm	6 6	3 4	5 4	7 6	6 5	4 4	4 2	6 6	5 4	2 2	5 2	1 3
	Warmer	6 7	4 6	5 4	5 7	4 6	4 4	5 4	8 4	7 9	3 2	4 6	3 1
	Warmest	7 9	4 6	4 4	7 6	7 5	4 4	3 4	8 8	8 8	2 2	3 5	2 1
	None	6 8	7 6	6 5	8 7	7 7	4 3	3 3	7 6	8 7	2 2	3 5	1 2
Neutral	Coolest	5 6	5 4	4 3	3 3	4 4	4 4	4 3	6 6	8 3	5 5	4 6	3 1
	Cooler	5 5	5 5	4 4	4 4	4 5	4 4	4 2	6 4	2 4	5 5	4 4	2 6
	Cool	6 6	5 5	2 4	4 4	4 4	4 4	4 4	6 5	4 7	4 5	5 7	3 4
	Neutral	6 6	5 5	4 4	5 5	4 4	4 4	5 4	5 1	5 6	5 5	4 6	6 2
	Warm	5 5	4 6	4 4	6 4	4 4	4 4	3 3	5 3	7 7	5 5	1 4	4 3
	Warmer	6 6	6 6	4 3	6 6	6 6	4 4	3 5	6 3	7 7	5 5	1 2	3 5
	Warmest	6 8	6 6	5 5	7 8	6 6	4 3	3 5	6 7	8 7	5 5	2 2	7 3
	None	5 5	6 6	3 3	7 5	6 4	5 5	4 2	2 2	3 5	6 5	1 2	2 2
No Message	Coolest	5 5	5 5	4 4	4 4	5 4	5 5	2 2	6 4	2 3	7 7	3 4	3 2
	Cooler	3 4	4 4	1 2	3 4	4 4	5 5	2 1	6 5	4 3	4 4	1 7	3 2
	Cool	5 3	5 5	2 3	4 6	5 4	5 5	5 4	4 5	6 3	6 6	2 2	1 3
	Neutral	5 5	5 4	3 4	3 5	3 4	5 5	3 5	5 1	5 5	6 3	4 3	5 3
	Warm	6 3	5 6	3 6	4 4	4 5	5 5	4 2	6 1	9 7	7 5	4 7	5 2
	Warmer	6 5	6 6	5 2	7 7	5 4	5 5	3 6	7 5	9 8	7 5	5 7	3 1
	Warmest	6 6	6 6	4 4	6 7	6 6	5 5	7 7	8 6	8 9	7 6	5 4	3 2

F.7 Main Study Time Logs (in milliseconds)

Text Type	Thermal	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
High Valence, High Arousal	Coolest	4500	15900	4500	6600	3500	7000	9100	8800	6000	5700	5200	6100
		3700	8200	5200	5800	4600	4800	12200	15600	5800	6700	5000	5900
	Cooler	7100	7500	5400	6000	4800	5000	14700	6000	9600	5900	4500	7700
		7200	14600	3800	4300	5000	4100	4000	7400	6100	6100	3900	6200
	Cool	6300	8700	4400	4400	4800	8400	6100	12000	6500	4700	5000	5400
		12700	8800	4500	4600	4100	6000	5800	7700	7100	6200	4500	4700
	Neutral	5700	4600	6500	5300	3200	6100	7100	7000	10000	9000	5000	5600
		4200	14200	4200	4600	2900	5400	3900	5700	7700	4200	3500	6300
	Warm	8800	6700	6700	5600	3000	6200	16400	9500	9200	9500	6100	11600
		9000	9100	4300	5500	4900	4200	7200	11300	6200	4100	4400	6000
	Warmer	5300	12000	6800	5300	4600	6400	9600	22800	12000	4600	4200	4000
		4400	6400	8400	6900	4100	6500	3600	6900	9800	4100	4400	8100
	Warmest	10500	5700	8300	4700	8000	6800	10800	8300	7800	5400	5800	5000
		7200	8600	4700	4700	4700	4200	8900	5600	6200	3200	3900	8700
	None	7300	6100	5700	25200	3400	6800	7900	3800	9800	3800	6900	5600
		7800	9000	6400	6600	3400	6000	8100	5800	9800	4900	7200	5900
High Valence, Low arousal	Coolest	5900	10900	4500	4600	3300	4700	3500	8400	6900	4200	5000	7000
		6800	11900	4000	4300	5000	4100	5200	10900	5400	5000	4100	4900
	Cooler	5100	7400	3600	5300	4300	5700	4800	15300	8500	6000	4000	4400
		5400	14200	3400	6200	7000	4800	4300	9900	7200	4900	4300	3500
	Cool	5300	13400	4800	3800	6800	7000	14100	14900	6500	6500	6000	7900
		8600	5800	5600	5700	4600	6000	11500	7600	5600	3200	7000	5000
	Neutral	6100	9700	7100	5500	3300	5400	4900	16600	7300	4100	3900	8200
		5300	10800	3800	4800	4400	4700	7400	14700	9900	3600	3600	7800
	Warm	13100	7500	5500	4900	4000	4600	9100	6000	13000	3800	4600	9700
		6700	8800	5200	4300	4300	5300	8500	4400	7400	3700	4100	10100
	Warmer	8300	9200	3800	7200	6400	5500	10000	8900	9000	4900	7000	4500
		5800	9900	3800	6300	3600	6700	4500	9400	8000	3600	3800	8700
	Warmest	4400	7400	6300	4300	4700	6900	4100	12000	8400	8000	5800	8900
		4700	5100	4200	4600	3900	6200	6000	6500	6700	4800	7400	9000
	None	9400	7500	12800	6100	6900	7700	12100	7600	8900	2700	5000	6900
		6800	5500	5900	8600	4100	6100	6600	8300	6200	3900	3600	7800
Low Valence, Low Arousal	Coolest	3700	10100	5300	6500	8600	5300	7100	7200	9500	5200	7100	8400
		6400	9400	3800	6500	3600	3800	5700	6100	8700	3400	4500	7900
	Cooler	7500	7200	6500	5500	3100	7400	6400	6400	12700	8700	5500	5800
		3700	13900	4100	5000	5800	6300	5700	5800	7800	5500	5700	7200
	Cool	10000	10000	7700	4100	5000	5600	5900	8900	7000	4100	13800	6000
		7700	11200	7300	5800	3500	4000	3500	7100	5700	5800	6000	6400
	Neutral	5800	8300	5500	5100	5100	6100	7300	7600	8000	13800	6100	8400
		5800	7800	4100	4700	3800	4300	8300	6800	6500	3600	5000	6900
	Warm	6600	8000	4500	6100	2800	5500	14800	9400	8400	4900	7900	5600
		5700	9600	4700	5400	4400	6000	7100	7900	8200	3900	5500	5300
	Warmer	7900	11900	8800	5900	3300	5300	9600	10500	9000	8000	6700	7800
		4500	8000	4600	8600	5700	4400	4800	5200	8000	3000	3800	7200
	Warmest	5200	8200	5000	5400	5000	6600	9800	16400	11500	4900	5300	7800
		4500	13300	3700	5900	3800	3500	11100	5200	6700	3400	5500	7500
	None	23900	10500	11000	7200	8700	10700	8500	12800	9100	3700	6700	5200
		10700	10500	6800	7000	7400	7700	4900	6100	11200	5000	4600	8000
	Coolest	14300	21300	5100	7100	4700	8900	4600	10500	8600	25100	9800	10300
		4700	7800	3600	5500	5700	9200	4400	7800	6800	8000	8300	12200
	Cooler	7600	8400	4000	9900	4000	6400	18700	8800	8300	5800	14400	6000
		14600	15400	5000	4600	5300	4900	6000	11300	7200	3100	6500	7200

Low Valence, High Arousal	Cool	8300	15100	5300	5700	6600	6100	16600	16300	13300	4900	7500	11200
		10900	7600	7600	5200	3400	4300	3900	10100	12600	3900	4600	6100
	Neutral	8700	10900	6900	7500	5800	7500	9400	17300	12800	7200	9800	10100
		8500	9400	4800	5600	6600	3900	5100	12900	7900	3600	5200	5000
	Warm	14400	15400	5300	6100	3700	6800	9000	6300	11900	6000	9200	7500
		6700	24700	4000	5600	6200	5000	16200	7500	8100	4800	6400	6700
	Warmer	5600	19800	4500	5900	3300	5900	13600	5500	7600	6300	6900	6800
		6900	10800	3900	5900	4100	3400	15900	8500	7400	6600	7000	6700
	Warmest	5900	14100	7100	6200	4200	6600	9000	15900	8000	4900	9700	7000
		5500	12600	7200	6500	4200	4900	6000	5100	6400	3800	7400	7300
	None	10200	16900	14600	10500	9100	15200	10100	8200	7400	4500	5200	7900
		8700	14400	5000	8100	7400	9300	3800	6000	7500	4200	4800	9900
Neutral	Coolest	7600	18100	8400	6800	8000	5000	11900	16900	8000	3800	5100	11700
		5400	16900	6000	6800	5900	7600	12000	8800	6600	4600	6300	6100
	Cooler	9100	5400	5700	6500	4800	9000	9800	14000	10300	23500	4700	10500
		6800	11400	4400	6400	2900	5100	8000	12000	10800	13700	3500	10900
	Cool	8800	10700	8100	6100	4600	5900	17500	22400	11400	6900	3100	12300
		6600	11800	3600	6600	3000	10100	5100	10300	7600	4600	4700	5900
	Neutral	9500	13000	5800	4700	5800	6000	7600	12300	15400	5600	10600	7300
		8600	11800	5800	4500	7600	3300	5700	15400	15200	8100	4200	6900
	Warm	7300	14800	4000	5300	4200	8200	20300	16300	12700	6900	9000	7600
		8100	5600	3500	6800	6200	3800	9800	6600	8100	5200	4700	8100
	Warmer	11700	11100	5800	6200	8100	4600	12300	13400	10700	7900	12700	6600
		7700	12700	4300	4200	2800	4700	7900	8100	12500	3400	4900	6600
	Warmest	6900	10800	5700	5300	4600	6500	8900	18300	18000	8300	5100	13300
		5900	9100	4100	3900	3600	6900	5300	7900	10200	6600	8600	8400
	None	12500	9900	16000	14800	9800	17600	18800	15200	11700	3600	9600	6600
		5200	9300	12400	9300	8800	8600	6800	11800	10300	4400	8500	5500
No Message	Coolest	17200	11000	7800	6000	5100	4900	7800	10600	5800	11000	5800	10500
		4000	12400	4200	5100	4100	3100	4500	7500	7900	4800	4300	5200
	Cooler	5000	11400	8900	5500	5100	6100	8900	8400	9100	7200	9800	8200
		5200	16300	6100	4600	3600	6300	3900	7800	6800	7900	5600	5100
	Cool	6000	7200	5700	5700	5600	3200	7400	18000	7000	7100	6800	5900
		5200	19200	3900	4200	3700	3500	4700	9300	5400	4900	6400	4900
	Neutral	5500	10900	3800	4900	4600	4900	8700	6300	14400	14500	4900	5600
		3800	8400	4600	4400	3100	5100	7000	9700	8500	3700	3400	6100
	Warm	8300	13200	4100	5300	10000	4800	8300	11100	7400	4400	3300	6500
		5700	9100	5000	6600	3400	3600	7200	9500	8100	4700	3700	5700
	Warmer	6700	9600	3900	4500	3900	3200	7900	14400	7600	4000	2900	7500
		6900	12600	4000	5100	3100	4500	4600	8700	7000	5700	4900	6000
	Warmest	5600	5800	4400	5500	6500	5600	7200	14800	7600	7900	5400	6700
		5600	4500	4600	4000	6000	6400	6000	13300	6300	4700	7000	4400

Appendix G

Experiment Instructions

G.1 Chapter 2 Smell Pilot Instructions

You will be presented with a smell. Rate the emotional feel of the smell by clicking on the emotion wheel. Select what you think the predominant emotion is from one of: surprise, joy, anticipation, acceptance, sadness, disgust, anger and fear. Rate the strength of the emotion from weak (1) to strong (7) by clicking the corresponding circle in the emotion wheel. However, if you think the smell is emotionally neutral then click the neutral circle at the centre of the wheel. When you have emotionally rated the smell click the next button at the bottom of the screen. When you are ready click the OK button below.

G.2 Chapter 2 Message Pilot Instructions

You will be shown a text message at the top of the screen. Rate the emotional feel of the message by clicking on the emotion wheel below the message. Select what you think the predominant emotion is from one of: surprise, joy, anticipation, acceptance, sadness, disgust, anger and fear. Rate the strength of the emotion from weak (1) to strong (7) by clicking the corresponding circle in the emotion wheel. However, if you think the message is emotionally neutral then click the neutral circle at the centre of the wheel. When you have emotionally rated the text message click the next button at the bottom of the screen. When you are ready click the OK button below.

G.3 Chapter 2 Main Study Instructions

You will be shown a text message at the top of the screen along with a smell. Rate the emotional feel of both by clicking on the emotion wheel below the message. Select *what you think the predominant emotion is from one of: surprise, joy, anticipation, acceptance, sadness, disgust, anger and fear. Rate the strength of the emotion from weak (1) to strong (7) by clicking the corresponding circle in the emotion wheel. However, if you think the message and the smell are emotionally neutral then click the neutral circle at the centre of the wheel. When you have emotionally rated the text message and the smell click the next button at the bottom of the screen. When you are ready click the OK button below.*

G.4 Chapter 3 Vibration Pilot Instructions

You will feel vibration touch from the ring. Rate the emotional feel of the vibration by clicking on the emotion wheel. Select what you think the predominant emotion is from one of: surprise, joy, anticipation, acceptance, sadness, disgust, anger and fear. Rate the strength of the emotion from weak (1) to strong (7) by clicking the corresponding circle in the emotion wheel. However, if you think the vibration is emotionally neutral then click the neutral circle at the centre of the wheel. When you have emotionally rated the vibration click the next button at the bottom of the screen." When you are ready click the OK button below.

G.5 Chapter 3 Colour Pilot Instructions

You will see colours from the ring. Rate the emotional feel of the colour by clicking on the emotion wheel. Select what you think the predominant emotion is from one of: surprise, joy, anticipation, acceptance, sadness, disgust, anger and fear. Rate the strength of the emotion from weak (1) to strong (7) by clicking the corresponding circle in the emotion wheel. However, if you think the colour is emotionally neutral then click the neutral circle at the centre of the wheel. When you have emotionally rated the colour click the next button at the bottom of the screen." When you are ready click the OK button below.

G.6 Chapter 3 Main Study Instructions

You will see colours and feel vibration from the ring with a text message on the phone. Rate the emotional feel of all three by clicking on the emotion wheel. Select what you think the predominant emotion is from one of: surprise, joy, anticipation, acceptance, sadness, disgust, anger and fear. Rate the strength of the emotion from weak (1) to strong (7) by clicking the corresponding circle in the emotion wheel. However, if you think the colour, vibration, and message are emotionally neutral then click the neutral *circle at the centre of the wheel. When you have emotionally rated all three click the next button at the bottom of the screen." When you are ready click the OK button below.*

G.7 Chapter 5 Experiment Instructions

The purpose of this experiment is to test if you can recognize thermal feedback patterns. We have attached our thermal feedback apparatus to your arm. This device consist of 3 stimulators that will stimulate heat and cold sensations on your arm. During the test you will be presented with 8 different thermal patterns which will be sent one at a time to your arm. After the pattern is sent to your arm, you will be presented with 8 diagrams depicting different thermal patterns like the picture on the right. Each of the blocks corresponds with one of the 3 stimulators on your arm. Blue means cold. White means neutral (no change). Red means hot. You must choose which of the 6 diagrams you think best matches the thermal feedback you received. You will have 15 seconds to make your choice. You cannot edit your choice after you've made your decision or if the timer runs out. After each choice, the device will reset itself back to neutral temperature for 20 seconds. The monitor will display a status bar showing progress during this. During this time you may feel some warming and/or cooling sensations. This is just the device resetting the temperature for the next pattern and is not part of the test. You will be notified when this is completed and the next pattern is sent.

G.8 Discrete Signalling Experiment General Instructions

Thank you for agreeing to participate in our experiment. This experiment should take about an hour to complete. If at any point during the experiment you need to stop for whatever reason, please notify the lab monitor so that he can safely detach the device and allow you to leave. The purpose of this experiment is to validate a thermal display prototype.

The device consists of 3 stimulators that will generate heat and cold sensations on your arm.

The temperatures are safe, but if you feel the device is too uncomfortable, please notify the lab monitor and you can quit the experiment at any time. The experiment consists of 3 tests. Each test will have its own set instructions that you should read carefully. After you have completed a test, you will be given a 5 minute break. Before each test *you will first be given a quick "calibration" session. The purpose of this is to familiarize yourself with the device and the user interface in front of you. After this, you will be treated to a test session where you will be asked to make a selection. If you have any questions now, please ask the lab monitor. Otherwise please enter your name below. Once you have typed in your name, please notify the lab monitor so he can attach the device to your arm. Once the device is attached, please press the "Next" button to begin the first test*

G.9 Discrete Signalling Experiment Single Method Calibration Instructions

You will become acquainted with the temperatures generated by the stimulator attached to your arm. The calibration session is a 2 step process: First, the device will reset the temperature of your arm to room temperature. Then the device will generate a temperature for you. You will be presented with a user interface showing this process. You are to read the instructions as you are given and observe how the interface changes with respect to the temperature you are given. During this part of the experiment, feel free to ask the lab monitor any questions you may have as this is not a test. Press the "Begin Calibration" button to begin calibration.

G.10 Discrete Signalling Experiment Amplification Method Calibration Instructions

You will become acquainted with the temperatures generated by three stimulators attached to your arm. The calibration session is a 2 step process: First, the device will reset the temperature of your arm to room temperature. Then the device will generate a temperature sent to all stimulators at once. You will be presented with a user interface showing this process. You are to read the instructions as you are given and observe how the interface changes with respect to the temperatures. During this part of the experiment, feel free to ask the lab monitor any questions you may have as this is not a test. Press the "Begin Calibration" button to begin calibration.

G.11 Discrete Signalling Experiment Quantification Method Calibration Instructions

You will become acquainted with the temperatures generated by one, two, or all the stimulators attached to your arm. The calibration session is a 2 step process: First, the device will reset the temperature of your arm to room temperature. Then the device will generate a temperature sent to one, two, or all the stimulators at once. You will be presented with a user interface showing this process. You are to read the instructions as you are given and observe how the interface changes with respect to the temperatures. During this part of the experiment feel free to ask the lab monitor any questions you may have as this is not a test. Press the "Begin Calibration" button to begin calibration.

G.12 Discrete Signalling Experiment Post Calibration Instructions

You will now take the test portion of this part of the experiment. This will be exactly like the user interface before, except it is now up to you to rate the temperatures on the scale. After you have made a selection, a "Next Pattern" button will appear. Once you are confident of your selection, click this button, which will take you back to the interface for resetting your arm temperature. The process will repeat itself until all patterns are exhausted. If you have any questions now, please ask the lab monitor. As this is now a test, you will not be permitted to speak with the lab monitor for advice. When you are ready to begin the test, please press the "Begin Test" button.

G.13 Continuous Signalling Experiment Instructions

When you click the button below you will be presented with a maze like that on the right. Most of the maze is covered in a black "fog". You can only see the area around your current position which is designated as a red dot. White areas are paths you can you take, whereas grey areas designate walls. Your job is to find the goal, which is designated as a green dot hidden somewhere in the maze. You will use the arrow keys on the keyboard to move the red dot. You can move up, down, left, or right. As you advance through the maze, the area around you will be revealed, like a spotlight. During the experiment, you may be asked to wear the temperature device on your arm. You can use this to help guide you toward the goal. If you are moving in the right path, you will fell a WARM sensation on your arm. If you take a wrong path, you will feel a

COOL sensation on your arm. Please note that it takes a few seconds to change the temperature, so you may not feel feedback immediately. You will have 600 seconds to complete each maze. You will be able to see a timer in the upper right corner for how many seconds have passed. The number of moves you make will also be recorded so try to make as few moves as possible in the quickest time. During all tests you will be asked to wear earplugs. Once you have put on your earplugs, notify the lab monitor, and press the "Next" button to begin the test. The test will start as soon as you press the button, so get ready to use the arrow keys to move the dot! If you are wearing the temperature device there will be 10 second break to allow the device to warm up before the test starts. Do your best!

G.14 Chapter 7 Message Pilot Study Instructions

In this part of the study, we are interested in how people respond to Facebook message posts sent from friends. You will be shown such message posts at the top of the screen, and you will be rating each post in terms of how it made you feel while viewing it, as if you had been sent the message from your friends on Facebook. There are no right or wrong answers, so simply respond as honestly as you can. Underneath the text message, you will see 2 sets of 5 figures, each arranged in a row. We call this set of figures SAM, and you will be using these figures to rate how you felt while viewing each text message. SAM shows two different kinds of feelings: The first row shows Unhappy vs. Happy and the row underneath it shows Calm vs. Excited. You can indicate your selection by pressing the radio button under the figure for each row. Each SAM figure varies along each scale. In the first row is the first SAM scale, the unhappy-happy scale, which ranges from a smile to a frown. The extreme right of this scale denotes that you felt happy, pleased, satisfied, contented, and hopeful. The extreme left of the scale denotes you felt completely unhappy, annoyed, unsatisfied, melancholic, despaired, bored. If you felt completely neutral, neither happy nor sad, choose the figure in the middle of the scale. The second row shows the second SAM scale, the calm-excited scale. At the right extreme of the scale you felt stimulated, excited, frenzied, jittery, wide-awake, aroused. On the other hand, at the other end of the scale, you felt completely relaxed, calm, sluggish, dull, sleepy, unaroused. If you are not at all excited nor at all calm, select the figure in the middle of the row. Some of the pictures may prompt emotional experiences; others may seem relatively neutral. Your rating of each picture should reflect your immediate personal experience, and no more. Please rate *each one AS YOU ACTUALLY FELT WHILE YOU READ THE MESSAGE. It is very important not to dwell on your ratings of the pictures. There are no right or wrong answers; so rate every picture on all two dimensions. Once you are satisfied with your selections, press the next button at the bottom of the screen to continue to the next message. If you have any questions now, please ask the lab monitor.*

As this is now a test you will not be permitted to speak with the lab monitor for advice. When you are ready to begin the test, please press the "Begin Test" button below.

G.15 Chapter 7 Thermal Pilot Study Instructions

In this part of the study, we are interested in how people respond to temperature emotionally. You will be asked to wear the temperature device now which will provide thermal feedback sensations on your arm. You will be rating each thermal sensation in terms of how it made you feel while perceiving it. There are no right or wrong answers, so simply respond as honestly as you can. Like the previous test with texts, you will see the SAM set of figures, with 2 sets of 5 figures, each arranged in a row. You will be using these figures to rate how you felt while perceiving each thermal sensation. SAM shows two different kinds of feelings: The first row shows Unhappy vs. Happy and the row underneath it shows Calm vs. Excited. You can indicate your selection by pressing the radio button under the figure for each row. Each SAM figure varies along each scale. In the first row is the first SAM scale, the unhappy-happy scale, which ranges from a smile to a frown. The extreme right of this scale denotes that you felt happy, pleased, satisfied, contented, and hopeful. The extreme left of the scale denotes you felt completely unhappy, annoyed, unsatisfied, melancholic, despaired, bored. If you felt completely neutral, neither happy nor sad, choose the figure in the middle of the scale. The second row shows the second SAM scale, the calm-excited scale. At the right extreme of the scale you felt stimulated, excited, frenzied, jittery, wide-awake, aroused. On the other hand, at the other end of the scale, you felt completely relaxed, calm, sluggish, dull, sleepy, unaroused. If you are not at all excited nor at all calm, select the figure in the middle of the row. Some of the pictures may prompt emotional experiences; others may seem relatively neutral. Your rating of each picture should reflect your immediate personal experience, and no more. Please rate each one AS YOU ACTUALLY FELT WHILE YOU PERCEIEVED THE TEMPERATURE. It is very important not to dwell on your ratings of the pictures. There are no right or wrong answers; so rate every picture on all two dimensions. Once you are satisfied with your selections, press *the next button at the bottom of the screen to continue to the next temperature. If you have any questions now, please ask the lab monitor. As this is now a test you will not be permitted to speak with the lab monitor for advice. When you are ready to begin the test, please press the "Begin Test" button below.*

G.16 Chapter 7 Main Study Instructions

In this study, we are interested in how people respond to simultaneous Facebook message posts sent by friends and temperature feedback. You will be asked to wear the temperature device which will provide thermal feedback sensations on your arm. You will also be shown message posts at the top of the screen. You will be rating each pair of a message post and a thermal sensation in terms of how they made you feel while viewing and perceiving them simultaneously. The message post should be treated as if one of your friends on Facebook had posted it. There are no right or wrong answers, so simply respond as honestly as you can. During some of the trials, you may not see a message post. In this case, just rate how the temperature made you feel with the scales. Underneath the message post area, you will see 2 sets of 9 figures, like below, each arranged in a row. We call this set of figures SAM, and you will be using these figures to rate how you felt while perceiving each temperature and message pairing. SAM shows two different kinds of feelings: The first row shows Unhappy vs. Happy and the row underneath it shows Calm vs. Excited. You can indicate your selection by pressing the radio button under the figure for each row. Each SAM figure varies along each scale. In the first row is the first SAM scale, the unhappy-happy scale, which ranges from a frown to a smile. The extreme right of this scale denotes that you felt happy, pleased, satisfied, contented, and hopeful. The extreme left of the scale denotes you felt completely unhappy, annoyed, unsatisfied, melancholic, despaired, bored. If you felt completely neutral, neither happy nor sad, choose the figure in the middle of the scale. The second row shows the second SAM scale, the calm-excited scale. At the right extreme of the scale you felt stimulated, excited, frenzied, jittery, wide-awake, aroused. On the other hand, at the other end of the scale, you felt completely relaxed, calm, sluggish, dull, sleepy, unaroused. If you are not at all excited nor at all calm, select the figure in the middle of the row. Some of the messages/temperatures may prompt emotional experiences; others may seem relatively neutral. Your rating of them should reflect your immediate personal experience, and no more. Please rate each pair AS YOU ACTUALLY FELT WHILE YOU READ THE MESSAGE AND PERCEIVED THE TEMPERATURE.

It is very important not to dwell on your ratings of them. There are no right or wrong answers; so rate every message/temperature pairing on all two dimensions. Once you are satisfied with your selections, press the next button at the bottom of the screen to continue to the next trial. If you have any questions now, please ask the lab monitor. As this is now a test you will not be permitted to speak with the lab monitor for advice. When you are ready to begin the test, please press the "Begin Test" button below.

Appendix H

Participant Permission Forms

H.1 Chapter 2 Study Consent Form

Smell Experiment : Participation Agreement

I confirm that I am a fluent Japanese speaker.

I also confirm that:

- I have a normal sense of smell
- I have no history of olfactory dysfunction
- I am not currently suffering from cold/flu or other temporary respiratory problems
- I do not suffer from asthma or any form of air-born allergy
- I have normal or corrected-to-normal vision.
- I understand that I can stop the experiment at any time .

Date ____

Signed____

H.2 Chapter 3 Study Consent Form

Ring*U Experiment: Participation Agreement

I confirm that I am a fluent Japanese speaker.

I also confirm that:

- I have a normal sense of touch.
- I have normal or corrected-to-normal vision.
- I understand that I can stop the experiment at any time.

Date ______________________________

Signed______________________________

H.3 Chapter 5 + 6 Study Participant Information Sheet

Participant Information Sheet

City University London, Centre for Human Computer Interaction Design

Identifying Distinguishable Temperature Feedback Patterns Using Controlled Parameters Sent From an Arm Mounted Temperature Display Device

We would like to invite you to take part in a research study. Before you decide whether you would like to take part it is important that you understand why the research is being done and what it would involve for you. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information.

What is the purpose of the study?

We are examining how humans might perceive warm and cool sensations sent from a computer. In order to measure this, we have constructed a device that you will wear on your arm that generates warm and cool temperatures on the skin. You will be asked to identify which temperature you think is being sent as well as its intensity using the PC that will be situated in front of you while you are wearing this device.

Why have I been invited?
You have been selected among 12 participants. You have been invited because you have been deemed healthy to participate and fall within the target age group. No other exclusion criteria were used. If you possess Peripheral Neuropathy or any disease resulting in hypersensitivity to heat you should not participate. Simply state your refusal to do so, you do not need to mention why.

Do I have to take part?
Participation for this study is voluntary. You may withdraw at any stage, even after agreeing to take part, and you can be assured that you will not be penalized should you choose to withdraw. If you are a student, taking part in the research will not affect your grades. It is up to you to decide whether or not to take part. If you do decide to take part you will be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason.

What will happen if I take part?

- You will take part in an experiment that will last an hour.
- The study will be held in room A212 in the HCID Centre, College Building.
- During the duration of the study, you will be asked to wear a haptic apparatus developed here in the lab. The device will generate warm and cool sensations on your arm. You will be seated during the experiment.
- You will be instructed to use the computer in front of you while wearing the apparatus.
- There will be 3 tests to perform. Before each test you will be given a chance to familiarize yourself with the user interface for test recording as well as the temperatures.
- The entire experiment is automated, with two 5 minute breaks between each test. You can get up and walk around the room if necessary.

Payments

- Upon completion of the experiment you will be given £10 cash to thank you for your time.

What do I have to do?
You will be asked to make some rankings with Likert scales with the user interface. You will have to wear an unproven prototype of a haptic device on your arm and make judgements of the temperature it generates.

What are the possible disadvantages and risks of taking part?

- The device sends temperatures within a safe range to your arm. It has the potential to generate dangerous temperatures if left unmonitored, however, this is unlikely as you will be monitored throughout the entire experiment. Temperature changes are very slow so in the event of failure the device can be shut down and detached from your arm before it poses such a danger.

- You may experience some minor discomfort during the experiment. However, if you feel you cannot tolerate wearing the device, notify the lab monitor and you may quit the experiment.

In case of a technical failure, the lab monitor, Jordan, will activate a safety switch which will disable the device and protect you from any harm.

What are the possible benefits of taking part?
You will contribute to an emerging area of HCI research that might have a significant effect on how we communicate, play games, or interact in the real world ambiguously using temperature.

What will happen when the research study stops?
The data collected after the experiment ends will be stored securely on a PC in the HCID department behind lock and key. It is only accessed by the investigators and will not be shared externally. It will be de-identifiable, and will be destroyed in 10 years.

Will my taking part in the study be kept confidential?
- Only Jordan, the Principal Investigator, and his supervisors, will access the data.
- No information can be used to identify that the data is yours. It will be de-identifiable.
- All data will be specific to actions you take during the experiment.

What will happen to results of the research study?
The data will be analysed and reported in a paper submitted to a top tier HCI conference, as well as Jordan's current thesis. Your anonymity will be maintained in any published work. If you wish to see the results of your test you may contact Jordan via his email.

What will happen if I don't want to carry on with the study?
You are free to withdraw from the study without an explanation or penalty at any time.

What if there is a problem?
If you have any problems, concerns or questions about this study, you should ask to speak to a member of the research team. If you remain unhappy and wish to complain formally, you can do this through the University complaints procedure. To complain about the study, you need to phone 020 7040 3040. You can then ask to speak to the Secretary to Senate Research Ethics Committee and inform them that the name of the project is:

Identifying Distinguishable Temperature Feedback Patterns Using Controlled Parameters Sent From an Arm Mounted Temperature Display Device

You could also write to the Secretary at:
Anna Ramberg
[redacted]
Email: [redacted]

City University London holds insurance policies which apply to this study. If you feel you have been harmed or injured by taking part in this study you may be eligible to claim compensation. This does not affect your legal rights to seek compensation. If you are harmed due to someone's negligence, then you may have grounds for legal action.

Who has reviewed the study?
This study has been approved by City University London Computer Science Research Ethics Committee

Further information and contact details
Jordan Tewell, PhD Student
[redacted]

George Buchanan, Primary Supervisor
[redacted]

Jon Bird, Second Supervisor
[redacted]

Thank you for taking the time to read this information sheet.

H.4 Chapter 5 + 6 Study Consent Form

Consent Form

City University London, Centre for Human Computer Interaction Design

Title of Study: *Identifying Distinguishable Temperature Feedback Patterns Using Controlled Parameters Sent From an Arm Mounted Temperature Display Device*

1.	I agree to take part in the above City University London research project. I have had the project explained to me, and I have read the participant information sheet, which I may keep for my records. We will need your consent to attach the device to your arm before any testing can commence. I understand this will involve: • Testing a new haptic feedback technology which is unproven but will be carefully monitored during the study. • Wearing a device on my arm that warms up and cools down. • Being subjected to various mild temperatures that will be perceived as warm and cool. • Using a computer to make selections based on the feedback I receive. • Sitting at a desk for periods of excess of 15 minutes at a time.	
2.	This information will be held and processed for the following purpose(s): • For submitting to a top tier HCI conference • For the PhD student's own work. I understand that any information I provide is confidential, and that no information that could lead to the identification of any individual will be disclosed in any reports on the project, or to any other party. No identifiable personal data will be published. The data will not be shared with any other organisation. AND I understand that I will be given a transcript of data concerning me upon my request if needed.	
3.	I understand that my participation is voluntary, that I can choose not to participate in part or all of the project, and that I can withdraw at any stage of the project without being penalized or disadvantaged in any way.	
4.	I agree to City University London recording and processing this information about me. I understand that this information will be used only for the purpose(s) set out in this statement and my consent is conditional on the University complying with its duties and obligations under the Data Protection Act 1998.	
5.	I agree to take part in the above study.	

Name of Participant	Signature	Date
Name of Researcher	Signature	Date

H.5 Chapter 7 Study Participant Information Sheet

9. Participant Information Sheet

City University London, Centre for Human Computer Interaction Design

Using Temperature Feedback to Augment Text Messages Sent From an Arm Mounted Temperature Display Device

We would like to invite you to take part in a research study. Before you decide whether you would like to take part it is important that you understand why the research is being done and what it would involve for you. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information.

What is the purpose of the study?

We are examining how humans might emotionally perceive warm and cool sensations sent from a computer as well as text messages, which may or may not be paired with such thermal feedback. In order to measure this, we have constructed a device that you will wear on your arm that generates warm and cool temperatures on the skin. You will be asked to emotionally rank how the temperature and messages feel to you using the illustrated manikins which will appear on the screen in front of you while you are wearing this device.

Why have I been invited?

You have been selected among 12 participants. You have been invited because you have inquired about participating earlier, have been deemed healthy to participate, and fall within the target age group (18-50 years of age). No other exclusion criteria were used. However, if you possess Peripheral Neuropathy or any disease resulting in hypersensitivity to heat you should not participate. Our device creates temperature differences on the arm and may trigger urticaria (Hives) for those with a medical history of such allergies. For all other reasons, simply state your refusal to do so, you do not need to mention why.

Do I have to take part?

Participation for this study is voluntary. You may withdraw at any stage, even after agreeing to take part, and you can be assured that you will not be penalized should you choose to withdraw. If you are a student, taking part in the research will not affect your grades. It is up to you to decide whether or not to take part. If you do decide to take part you will be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason.

What will happen if I take part?

- You will take part in an experiment that will last an hour.
- The study will be held in room A222 in the Interaction Lab, College Building.
- During the duration of the study, you will be asked to wear a haptic apparatus developed here in the lab. The device will generate warm and cool sensations on your arm in the range of 29℃-35℃. You will be seated during the experiment.
- You will be instructed to use the computer in front of you while wearing the apparatus.
- The entire experiment is automated. You can get up and walk around the room if necessary before and after the test, as well as any break you are allocated during the test.

Payments

- Upon completion of the experiment you will be given a £10 Amazon voucher to thank you for your time.

What do I have to do?

You will be asked to make some rankings with illustrated manikins in the user interface. You will have to wear a prototype of a haptic device on your arm and make judgements of the temperature it generates along with text messages, which will appear on the screen in front of you along with the illustrations.

What are the possible disadvantages and risks of taking part?

- The device sends temperatures within a safe range to your arm. It has the potential to generate dangerous temperatures if left unmonitored, however, this is unlikely as you will be monitored throughout the entire experiment. Temperature changes are very slow so in the event of failure the device can be shut down and detached from your arm before it poses such a danger.
- You may experience some minor discomfort during the experiment. However, if you feel you cannot tolerate wearing the device, notify the lab monitor and you may quit the experiment.

In case of a technical failure, the lab monitor, Jordan, will activate a safety switch which will disable the device and protect you from any harm. Additionally, the software also can trigger a shutdown in case it detects a danger.

What are the possible benefits of taking part?

You will contribute to an emerging area of HCI research that might have a significant effect on how we communicate and interact in the real world ambiguously using temperature.

What will happen when the research study stops?

The data collected after the experiment ends will be stored securely on a PC in the HCID department behind lock and key. It is only accessed by the investigators and will not be shared externally. It will be de-identifiable, and will be destroyed in 10 years.

Will my taking part in the study be kept confidential?

- Only Jordan, the Principal Investigator, and his supervisors, will access the data.
- No information can be used to identify that the data is yours. It will be de-identifiable.
- All data will be specific to actions you take during the experiment.

What will happen to results of the research study?

The data will be analysed and reported in a paper submitted to a top tier HCI conference, as well as Jordan's current thesis. Your anonymity will be maintained in any published work. If you wish to see the results of your test you may contact Jordan via his email.

What will happen if I don't want to carry on with the study?

You are free to withdraw from the study without an explanation or penalty at any time.

What if there is a problem?

If you have any problems, concerns or questions about this study, you should ask to speak to a member of the research team. If you remain unhappy and wish to complain formally, you can do this through the University complaints procedure. To complain about the study, you need to phone 020 7040 3040. You can then ask to speak to the Secretary to Senate Research Ethics Committee and inform them that the name of the project is:

Using Temperature Feedback to Augment Text Messages Sent From an Arm Mounted Temperature Display Device

You could also write to the Secretary at:
Anna Ramberg
[redacted]
Email: [redacted]

City University London holds insurance policies which apply to this study. If you feel you have been harmed or injured by taking part in this study you may be eligible to claim compensation. This does not affect your legal rights to seek compensation. If you are harmed due to someone's negligence, then you may have grounds for legal action.

Who has reviewed the study?

This study has been approved by City University London Computer Science Research Ethics Committee

Further information and contact details
Jordan Tewell, PhD Student
[redacted]

George Buchanan, Primary Supervisor
[redacted]

Jon Bird, Second Supervisor
[redacted]

Thank you for taking the time to read this information sheet.

H.6 Chapter 7 Study Consent Form

10. Consent Form

City University London, Centre for Human Computer Interaction Design

Title of Study: *Using Temperature Feedback to Augment Text Messages Sent From an Arm Mounted Temperature Display Device.*

1.	I agree to take part in the above City University London research project. I have had the project explained to me, and I have read the participant information sheet, which I may keep for my records. We will need your consent to attach the device to your arm before any testing can commence. I understand this will involve: • Testing a new haptic feedback technology which will be carefully monitored during the study. • Wearing a device on my arm that warms up and cools down. • Being subjected to various mild temperatures that will be perceived as warm and cool. • Reading text messages on the computer screen which may be upsetting or unpleasant in content. • Using a computer to make selections based on the feedback I receive. • Sitting at a desk for periods of excess of 15 minutes at a time.	
2.	This information will be held and processed for the following purpose(s): • For submitting to a top tier HCI conference • For the PhD student's own work. I understand that any information I provide is confidential, and that no information that could lead to the identification of any individual will be disclosed in any reports on the project, or to any other party. No identifiable personal data will be published. The data will not be shared with any other organisation. AND I understand that I will be given a transcript of data concerning me upon my request if needed.	
3.	I understand that my participation is voluntary, that I can choose not to participate in part or all of the project, and that I can withdraw at any stage of the project without being penalized or disadvantaged in any way.	
4.	I agree to City University London recording and processing this information about me. I understand that this information will be used only for the purpose(s) set out in this statement and my consent is conditional on the University complying with its duties and obligations under the Data Protection Act 1998.	
5.	I agree to take part in the above study.	

____________________ ____________________________ _____________

Name of Participant Signature Date

____________________ ____________________________ _____________

Name of Researcher Signature Date

Appendix I

Published Works

Emotional Priming of Mobile Text Messages with Ring-Shaped Wearable Device using Color Lighting and Tactile Expressions

Gilang Andi Pradana
School of Informatics
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Adrian David Cheok
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City University London

Masahiko Inami
Graduate School of Media Design
Keio University

Jordan Tewell
School of Informatics
City University London

Yongsoon Choi
Department of Art and Technology
Songang University

ABSTRACT

In this paper, as a hybrid approach to place a greater emphasis on existing cues in Computer Mediated Communication (CMC), the authors explore the emotional augmentation benefit of vibro-tactile stimulation, color lighting, and simultaneous transmission of both signals to accompany text messages. Ring U, A ring-shaped wearable system aimed at promoting emotional communications between people using vibro-tactile and color lighting expressions, is proposed as the implementation method. The result of the experiment has shown that non-verbal stimuli can prime the emotion of a text message, and it can be driven into the direction of the emotional characteristic of the stimuli. Positive stimuli can prime the emotion to a more positive valence, and negative stimuli can invoke a more negative valence. Another finding from the experiment is that compared to the effect on valence, touch stimuli have more effect on the activity level.

Keywords

Verbal and Non-Verbal Communication, Emotion, Vibro-tactile, Color

1. INTRODUCTION

Our ability to express and accurately assess emotional states is important to our life. Being able to perceive a variety of emotions also has potentially important applications in Computer Mediated Communication (CMC) [7]. Research in Social Presence Theory states that less rich CMC environments inhibit communicating emotional expression, while in much richer environments in which non-verbal cues are available, a full range of emotional information can be communicated due to greater social presence [17].

This paper has experimentally determined the emotional priming of mobile text messages using color and touch stimuli. Non-verbal stimuli can prime the emotion of a text message, and it can be driven into the direction of the emotional characteristic of the stimuli. By implementing these findings into a real life application, the authors hope that it can help a better emotional state assessment in computer mediated communication. The sending user can augment non-verbal cues to strengthen their verbal message and the receiving user can feel more emotion in receiving more than just a message.

2. LITERATURE REVIEW

Many research has been done worldwide to examine the relationship between emotions and nonverbal behaviors. For example, the area of haptic (touch based) interaction in Human Computer Interaction (HCI) has grown rapidly over the last few years. One example of a system that uses tactile information is "inTouch" [2] first described in 1997. It introduced the method of applying haptic feedback to interpersonal communication by providing a physical haptic link between users separated by distance. Another related field called Affective Haptics focuses on the study and design of systems that can enhance the emotional state of a human by means of the sense of touch. One example is in "Huggy Pajama", which aimed at promoting intimate physical interaction between parent and child [20].

Modern interpersonal communication technologies adopt characters in text to share their information. There was also a need to study such related research about how emotion is assessed in text-based communication, where nonverbal cues thought to carry emotional information are eliminated. One example is a study from Gill, et. Al. , where they study about emotion rating from short blog texts [7]. They explored the text-based communication of emotion in CMC, and examined whether emotion can be accurately classified on the basis of asynchronous short blog text extracts derived from real emotional blogs.

Another approach to support the emotional assessment in CMC environments is to adopt colors on the system. For centuries artists have been exploring color to express emotions and color-emotion relationships have been increasingly researched in recent years. Some research have attempted to create an emotional communication device by utilizing ambient multi-color glows, like in ”LumiTouch” [3]. Considering the strong relationship between color and emotion, the authors believe that this approach can be adopted as an extra channel to strengthen the cues in CMC environments. ”Cubble” has tried to adopt this hybrid approach by creating colors and haptic tap patterns as ambiguous and self-assignable messages and emotional templates for intimate communication in the form of a cube [10]. However, this research does not address how this hybrid approach is beneficial to the emotional state assessment, which is important in interpersonal communication.

3. OUR IMPLEMENTATION: RINGU

We explored the emotional augmentation benefit of vibro-tactile stimulation, color lighting, and simultaneous transmission of both signals to accompany text messages using RingU. RingU is the name of our ring-shaped wearable system which can promote emotional, remote communication between people using vibro-tactile and color lighting expressions. There was a need to implement our idea into a compact wearable device to place a greater emphasis on existing cues by developing a new strategy in a CMC environment, since the aim was to study the relationships and benefits of utilizing both verbal and non-verbal channels on emotional responses in CMC.

Traditionally a ring has been used as a symbolic present to deliver a message from the sender (the one who gives a present), to the receiver. A ring is one of the fashion accessories between couples to represent their relationships. A ring is an unbroken circle, which many cultures understand as the representative of eternity, which symbolizes the eternal promise between them on their engagement and wedding. The ring can act as both a reminder and as an outward symbol to others that a person is currently on an eternal commitment. A ring also has a meaning as a source of unity for everyone and not just for couples. People wear rings to join others and symbolise that they are in the same cause. We can see some examples of the use of a purity ring, or when a group of supporters wear rings after the victory of their team. Using this metaphor, the authors believe that a ring is a perfect symbol of something emotionally close and connected, which fits well with our aim to create a communication system that makes users feel even more connected and emotionally close. Several research like ”EyeRing”[12], ”Magic Ring”[9], or ”Nenya”[1], have adopted ring-shape devices as the implementation method for their system. These devices focus to create a new interaction by creating a ring that acts as an input device to interact with the environment. On the other hand, our system focuses more in creating emotional communication using vibro-tactile stimulation and color lighting expressions.

The RingU system consists of a wearable ring-shaped device and a smart phone. When a user squeezes the ring, a signal will be sent via Bluetooth low energy to his/her smartphone and then sent through the internet to his/her partner’s phone and consequently to their partner’s ring. The result is that their partner feels a squeeze akin to a virtual mini-hug and can see an accompanying color on their ring. For that very instant, they will feel each other’s warm presence. (Figure 1)

As described in the previous section, ambient, multi-color

Figure 1: Squeezing the ring to send a lighting and a vibro-tactile signal to the paired partner.

glows have been adopted in some research to create a certain mood and emotional feeling. The same approach was implemented into RingU, along with the vibro-tactile stimulation which acts as a non-verbal cue in the communication channel (Figure 2). This proposed interface is used to conduct our study about the relationships and benefits of utilizing both verbal and non-verbal channels on emotional responses in Computer Mediated Communication.

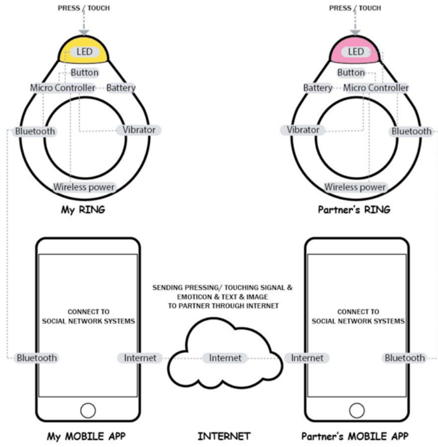

Figure 2: RingU System Scheme

4. SYSTEM IMPLEMENTATION

Several prototypes have been developed as an implementation of RingU. The first prototype of RingU system is designed for the proof of concept and it consists of an Arduino Fio, a push button, an RGB LED, a vibration motor, an XBee module, and a battery. For the prototype, the push button, the LED, and the vibration motor were built into the ring. A separated box that is connected with wire to the ring has been designed to contain comparatively bigger modules such as an Arduino Fio board, the Xbee, and the battery (Figure 3). With this prototype, users can send each other a single, pre-programmed color and vibration by pressing the top of their ring within range of the Xbees.

Figure 3: RingU first prototype

For the second prototype, adapted for our experiment, a single ring unit was constructed. An Arduino UNO was used in place of the Ardunio Fio used previously. We connected our ring to a PC via serial port which allowed the authors to program a software that can connect to a message database server to simultaneously send text messages along with a specific vibro tactile stimulation or color stimuli. A different electronic circuit was designed to adapt the change of the microcontroller, since they are using a different pin scheme. For this study purpose, a web based application was developed to load a specific text message from the database and to show the emotion wheel to enable participants to rate their emotional responses and save their responses to the database.

5. SCIENTIFIC STUDY

In this scientific study, the authors explore the emotional augmentation benefit of vibro-tactile stimulation, color lighting, and simultaneous transmission of both signals to accompany text messages. In our proposed interface, a text message acts as a verbal cue, while color and vibro-tactile stimuli act as non-verbal cues. This is a hybrid approach in attempt to place a greater emphasis on existing cues in a CMC environment. The hypothesis of this study is that augmentation of vibro-tactile stimuli, color, or both stimuli together can prime the emotion of a text message. The emotional perception of a text message can be driven to a higher valence with a positive stimuli, and lower valence with a negative stimuli.

5.1 Evaluation Settings

Two experiments: a pre-evaluation experiment and a main lab based experiment were conducted for this scientific study. In each of these tests, each participant was assigned to rate their emotional responses corresponding to the message received, vibro-tactile stimuli, and color lighting stimuli using an emotion wheel evaluation system.

The authors expand the classification of emotion from positive and negative into eight main categories as proposed by the literature [6] [14]. The emotion wheel covers joy, surprise, fear, anger, disgust, sadness, acceptance, anticipation, and neutral feeling, with 7 different strengths of each emotion. All participants used the activation-evaluation wheel. Evaluation (valence) is placed on the x-axis, with positive values on the right and negative values on the left. Activity level lies on the y-axis, with high activity level at the top for emotions like surprise or anger, and low activity at the bottom for emotions like acceptance or sad. The strength of the emotion perceived corresponds to the distance from the center of the circle (between 1 and 7), with the center of the circle used to score 0 or 'neutral' emotion (Figure 4). This model is considered well suited to computational work [4], has previously been used for rating emotion in speech [11], and allows comparison with findings for valence [8]. Alternative approaches to emotion are described in [5] [15]. Two different groups of 20 participants were gathered for the pre-evaluation experiment and the main lab based experiment.

5.2 Pre-Evaluation Experiment

The pre-evaluation experiment was conducted in order to sort out the colors, vibro-tactile stimuli, and messages that were linked to invoke a specifically positive, negative, or neutral valence feeling when accessed to an individual. This experiment consists of three individual parts: Emotional rating of texts, emotional rating of color, and emotional rating of touch. Selected stimuli from the result were used as the stimuli for the main experiment.

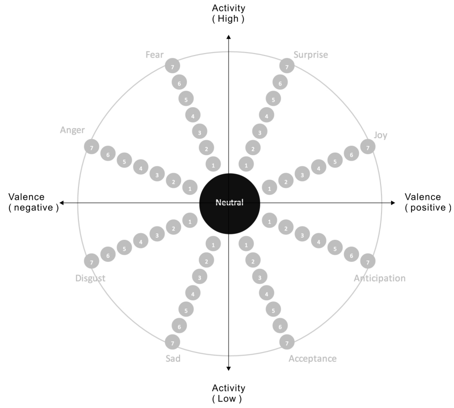

Figure 4: Emotion Wheel

5.2.1 Emotional Rating of Text Messages

A list of text messages gathered by a previous study was being used in this experiment [19]. 110 of the most appropriate text messages that were fully understandable and non-offensive was chosen. To narrow down the messages, we analyzed the emotional responses of the messages using two methods. The first method was to count the number of responses based on the category of positive, neutral, and negative valence. Based on the emotion wheel, the positive value of valence consists of emotions located on the right side of x-axis, and the negative value of valence consists of emotions located on the left side of x-axis. We ignored the strength of emotion rating (1-7) for this method. The second method used was the valence analysis method. In this method, we take the strength of each emotional response (range 1 to 7), and multiply negative valence emotion scores by -1, score neutral as 0 and then sum the scores for each text message. The result of the narrowed down messages is as follows:

Table 1: Emotional rating of texts experiment result

Message	+	O	-	Value
Yay! Finally lol. I missed our cinema trip last week	20	0	0	96
At home by the way	6	6	8	-6
No, but you told me you were going, before you got drunk!	1	0	19	-62

5.2.2 Emotional Rating of Colors

A set of 11 colors was selected from a previous research conducted by Manning, et. Al., who examined the relationships between color and emotion [24]. Similar to the emotional rating of text, a web script would randomize the order of which color to send to the testers and displayed them one by one on the RingU. After the color light was displayed, the tester was asked to rate them using the emotion wheel. The goal of this was to narrow down to two most dominantly invoked emotion-specific colors to be used in the main lab based experiment: one color for each of the positive and negative emotions. We did not select the neutral category for color because the color stimuli will be used to augment the emotional perception of a text message, so it needs to have a certain emotion.

To narrow down the colors, we have analyzed the emotional responses of the color using two methods of categorizing responses and valence analysis used in the previous emotional text rating experiment. The results of the emotional response of 11 color stimuli is as follows:

Table 2: Emotional rating of colors experiment result

Color	+	O	-	Value
White (Hex: FFFFFF)	16	2	2	55
Red (Hex: CC0000)	9	0	11	-36
Orange (Hex: FF9900)	20	0	0	94
Light Orange (Hex: FFCC00)	18	0	2	54
Yellow (Hex: FFFF00)	16	0	4	49
Green (Hex: 009900)	16	1	3	46
Cyan (Hex: 00CC99)	12	0	8	12
Blue (Hex: 0000FF)	0	0	20	-81
Dark Blue (Hex: 000066)	10	0	10	-9
Purple (Hex: 660099)	9	0	11	0
Pink (Hex: CC0066)	16	0	4	52

Table 3: Emotional rating of touch experiment 1 result

Duty Cycle	Length (sec)	+	O	-	Value
0%	0	1	14	5	-8
20%	1	8	1	11	-8
40%	1	9	2	9	-1
60%	1	11	1	8	10
80%	1	17	0	3	50
100%	1	9	0	11	-11
20%	2	9	0	11	-3
40%	2	12	0	8	12
60%	2	11	0	9	0
80%	2	12	1	7	17
100%	2	12	0	8	18
20%	3	5	0	15	-35
40%	3	9	0	11	-8
60%	3	9	0	11	-18
80%	3	4	0	16	-48
100%	3	7	0	13	-34
20%	4	4	1	15	-41
40%	4	7	3	10	-5
60%	4	11	0	9	19
80%	4	10	0	10	-9
100%	4	6	0	14	-34
20%	5	5	0	15	-42
40%	5	9	1	10	-2
60%	5	11	1	8	2
80%	5	6	1	13	-17
100%	5	7	0	13	-30

5.2.3 Emotional Rating of Touch

Lastly, a test of different types of vibrations from our ring device to the participants was conducted. There were two parameters we controlled: The time duration from 1 second to 5 seconds at 1 second intervals, and the intensity of the vibration, which was achieved by altering the duty cycle of the Pulse Width Modulation wave sent to the vibration motor inside the ring. Duty cycle describes the proportion of how much power is currently running: a low duty cycle corresponds to low power, because the power is off for most of the time, and a high duty cycle corresponds to high power. Duty cycle is expressed in percent, 100% being fully on. This was set at 20%, 40%, 60%, 80%, and 100% duty cycles. From these 5 values for two parameters, 25 unique combinations which each user tested were obtained. A vibration with a zero duty cycle and a zero second duration was used as a 26th neutral vibration. These vibrations were randomized and sent to the user sequentially after the users made their choices on the emotion wheel. After the test, two vibrations for each emotional category of positive and negative were selected. To narrow down the vibro-tactile stimuli, we have analyzed the emotional responses of the stimuli using two methods of categorizing responses and valence analysis used in the previous emotional rating of texts experiment. The result of this touch experiment is shown on Table 3.

This result has shown that only controlling two parameters of length and intensity is insufficient, and resulted in bias. There are too few comparatively dominant results to be selected for the main experiment. The authors decided to adopt the tactile pattern mapped to emotional expression introduced by Shin, et. Al in their study [16]. This set of patterns was used, together with the two most dominant results of the first touch experiment and 0 vibration, to get more clear result. To implement these patterns in RingU, a timer was set to alter the duty cycle of the motor after a certain period of time. Similar to the emotional rating of text and color, a web script would randomize the order of which patterns to send to the testers and displayed them one by one on the RingU. After the pattern was sent, the tester was asked to rate them using the emotion wheel. The goal of this was to narrow down to two most dominantly invoked, emotion-specific vibro-tactile patterns to be used in the study: one pattern for each of the positive and negative emotions. We also did not select the neutral category for touch because the touch stimuli will be used to augment the emotional perception of a text message, so it needs to have a certain emotion. The result of this touch experiment is shown on Table 4.

Table 4: Emotional rating of touch experiment 2 result

Pattern Name	+	O	-	Value
0	5	14	1	11
80% PWM in One Second	10	1	9	13
80% PM Four Seconds	11	0	9	12
Grin (Quick, Light and Regular Vibration)	18	0	2	56
Cry (Slow Moving Vibration : High, weak,mid, and weak stress)	7	0	13	-33
Anger (One strong vibration)	7	0	13	-28
Surprise (One vibration of thick and mid-stress)	13	0	7	20
Kiss (Being strong gradually and continuously)	12	0	8	27
Sleepy (Slow and Regular Vibration)	9	0	11	-15

5.3 Main Experiment

In the main lab based experiment, the participants were assigned to examine how touch and color can augment the emotional perception to a text message, or how both can affect them at the same time using an emotion wheel evaluation system. We asked 20 participants to join this experiment, and the experiment took about 10 to 15 minutes.

From the pre-evaluation experiment, we had selected dominantly invoked, emotion-specific stimuli from each category: Three messages, one for each positive, neutral, and negative emotion, two colors, one for each positive and negative emotion, and two vibro-tactile patterns, one for each positive and negative emotion. In this experiment, we examined the emotional augmentation benefit of vibro-tactile, color lighting, and simultaneous transmission of both signals to accompany text messages. Each of the selected stimulus from the pre-evaluation experiment was combined to be transmitted simultaneously to accompany text messages. For each category of text message, we have 9 possible combinations: A text only stimuli, texts with positive and negative touches, texts with positive and negative colors, text with positive touches and positive colors, texts with positive touches and negative colors, texts with negative touches and positive colors, and texts with negative touches and negative colors. We have three different text categories, which result in total of 27 combinations of stimuli to be examined in this main experiment. Participants were asked to wear the ring on their hand while holding an iPhone, which shows the set of messages they are going to rate (Figure 5). The participants were asked to focus on the iPhone screen and the RingU, and were told that there will be messages coming. After receiving each stimuli, they were asked to rate their emotional response in our online emotion wheel rating system, which was used in the pre-evaluation experiment. These were recorded into a database entry. Our application would present the user with a button to proceed to the next stimuli once they have recorded the emotion on the emotion wheel rating system.

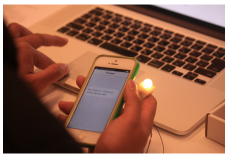

Figure 5: Participant wears the ring while holding an iPhone.

The emotional responses result for each stimuli is shown on the figure 6 to 10. Standard deviation σ_x for valence and σ_y for activity level is also calculated to show how much variation or dispersion from the mean for each type of stimuli.

5.3.1 *Emotional Responses in Text Only Stimuli*

Figure 6 shows the emotional responses in text only stimuli for each message category. Blue squares show responses for positive messages, gray circles show responses for neutral messages, and red diamonds show responses for negative messages. Each asterisk symbol in corresponding color shows the mean for each message category. This graph shows that most of the responses for positive messages are mapped on the positive valence area, in slightly high activity level. The mean value for the positive message is mapped in positive valence area with slightly high activity level. For neutral messages, most of the responses concentrate in the centre of the graph, with some of the responses are mapped in a slightly positive or negative valence. The mean value for neutral messages is mapped almost close to the centre of the graph. For negative message, most of the responses are mapped on the negative valence area, in slightly high, or low activity level. The mean value for the negative message is mapped in negative valence area with slightly low activity level.

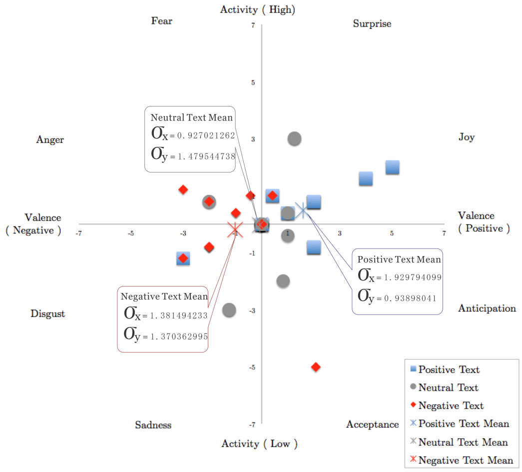

Figure 6: Emotional responses in text only stimuli

From the result 9 possible combinations, p-value testing, introduced by Karl Pearson [13], was used as the method for the statistical significance testing. When the p-value turns out to be less than a certain significance level, often 0.05 [18], the null hypothesis can be rejected, which indicates that the observed result would be highly unlikely under the null hypothesis and the statistical data is reliable.

5.3.2 *Emotional Responses in Text and Touch Stimuli*

The result of this experiment can be summarized in Figure 7, which shows the tendency of emotional responses changes to touch stimulus. For a positive message with positive touch stimuli, the graph shows a that this stimuli can drive the response to a slightly more positive valence, but still can be higher or lower activity level. On the other hand, with negative touch stimuli, the graph shows a consistent result that this stimuli can drive the response to a slightly less positive valence, and significantly higher activity level.

For a neutral message, positive touch stimuli can drive the response to a slightly higher activity level, in less significant change in the valence when it is combined together with color stimuli. On the other hand, with negative touch stimuli, the graph shows a consistent result that this stimuli can drive the response to a slightly less positive valence, and significantly higher activity level.

For a negative message, positive touch stimuli can drive the response to a slightly more positive valence, but still can be higher or lower activity level. When it is combined with negative color stimuli, it does not have a significant change both for the activity level and valence. On the other hand, with negative touch stimuli, the graph shows a consistent result that this stimuli can drive the response to a slightly less positive valence, and significantly higher activity level, except for when it is combined with negative color. The effect of touch stimuli has a less significant effect in negative message compared to in the positive and neutral message.

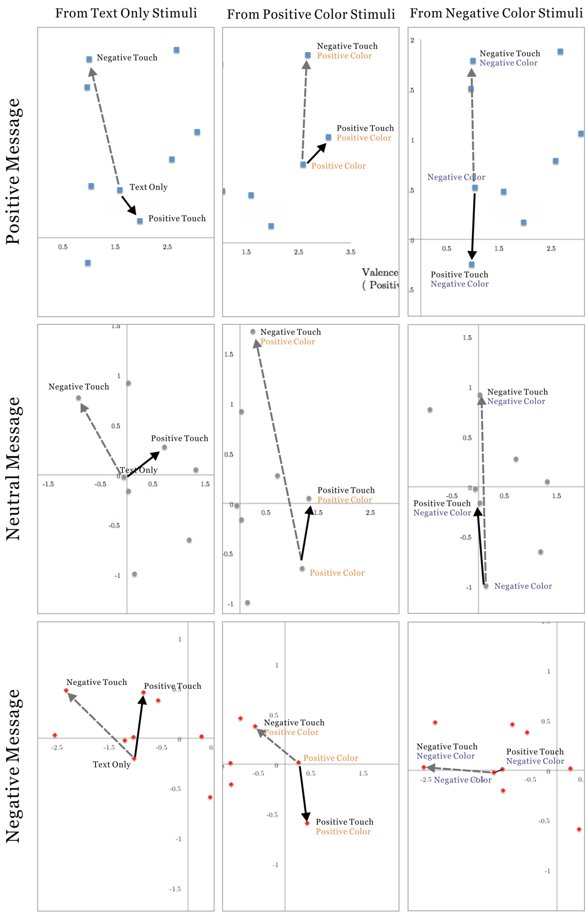

Figure 7: Emotional responses changes to touch stimuli

5.3.3 *Emotional Responses in Text and Color Stimuli*

Figure 8 shows the tendency of emotional responses changes to color stimulus. For a positive message, with positive color stimuli, the graph shows a consistent result that this stimuli can drive the response to significantly more positive valence and a slightly higher activity level. On the other hand, with negative color stimuli, the graph shows that this stimuli can drive the response to a slightly less positive valence, but still can be higher or lower activity level.

For a neutral message, with positive color stimuli, the graph shows that this stimuli can drive the response to significantly more positive valence, but still can be higher or lower activity level. With negative color stimuli, the graph shows that this stimuli can drive the response to a slightly higher or lower activity level, with no significant change on the valence.

For a negative message, with positive color stimuli, the graph shows that this stimuli can drive the response to significantly more positive valence, but still can be higher or lower activity level. With negative color stimuli, the graph

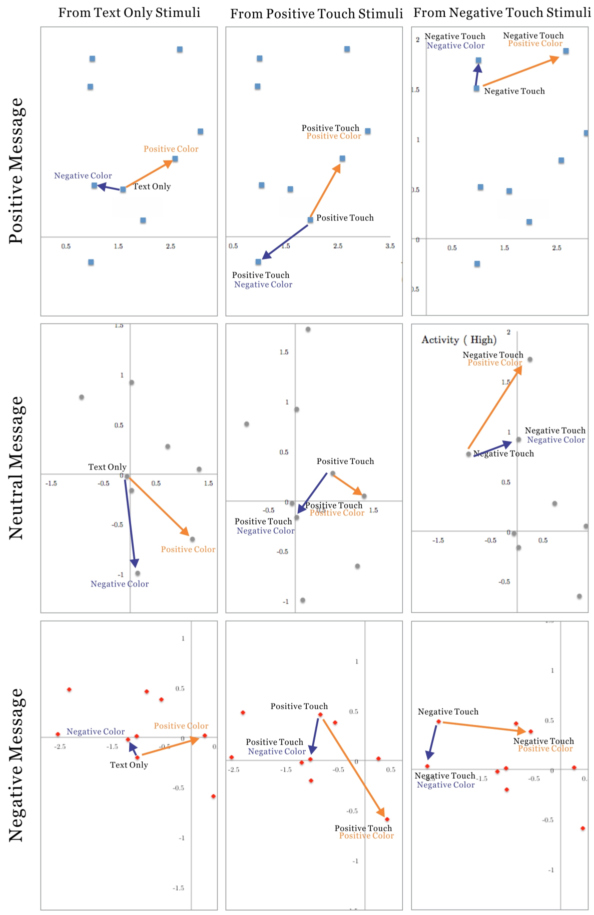

Figure 8: Emotional responses changes to color stimuli

	Text Only Stimuli			
	Positive Touch		Negative Touch	
	Change to Valence	Change to Activity	Change to Valence	Change to Activity
Positive Message	More Positive	Lower	More Negative	Higher
p-value	0.085484127	0.041589959	0.005940416	0.018879067
Neutral Message	More Positive	Higher	More Negative	Higher
p-value	0.022558282	0.078354818	0.00108509	0.037777055
Negative Message	More Positive	Higher	More Negative	Higher
p-value	0.048686828	0.033527947	0.041056502	0.026123686
	With Positive Color Stimuli			
Positive Message	More Positive	Higher	Almost no change	Higher
p-value	0.038703047	0.009869798	0.007155797	0.010947217
Neutral Message	More Positive	Higher	More Negative	Higher
p-value	0.144547557	0.01686781	0.002000521	0.026599393
Negative Message	More Positive	Lower	More Negative	Higher
p-value	0.040253955	0.00506044	0.004458957	0.002580583
	With Negative Color Stimuli			
Positive Message	Almost no change	Lower	Almost no change	Higher
p-value	0.025358695	0.038293697	0.012684849	0.009392258
Neutral Message	Almost no change	Higher	Almost no change	Higher
p-value	0.006710313	0.021023756	0.000880276	0.015490619
Negative Message	More Positive	Almost no change	More Negative	Almost no change
p-value	0.027721979	0.011925908	0.024219872	0.003274681

Figure 9: Emotional responses changes to touch stimuli with p-value

shows that this stimuli can drive the response to a slightly less positive valence, but still can be higher or lower activity level in a less significant way. The tendencies shown on Figure 7 and Figure 8 can be summarized and are shown on Figure 9 and Figure 10 along with p-value for each stimuli.

	Text Only Stimuli			
	Positive Color		Negative Color	
	Change to Valence	Change to Activity	Change to Valence	Change to Activity
Positive Message	More Positive	Higher	More Negative	Almost no change
p-value	0.044612063	0.107593882	0.030646831	0.083292038
Neutral Message	More Positive	Lower	Almost no change	Lower
p-value	0.15103246	0.047333039	0.089623994	0.061111628
Negative Message	More Positive	Higher	More Negative	Higher
p-value	0.079081783	0.026572705	0.119666356	0.015708449
	With Positive Touch Stimuli			
Positive Message	More Positive	Higher	More Negative	Lower
p-value	0.038703047	0.009869798	0.025358695	0.038293697
Neutral Message	More Positive	Lower	More Negative	Lower
p-value	0.144547557	0.01686781	0.006710313	0.021023756
Negative Message	More Positive	Lower	More Negative	Lower
p-value	0.040253955	0.00506044	0.027721979	0.011925908
	With Negative Touch Stimuli			
Positive Message	More Positive	Higher	Almost no change	Higher
p-value	0.007155797	0.010947217	0.012684849	0.009392258
Neutral Message	More Positive	Higher	More Positive	Higher
p-value	0.002000521	0.026599393	0.000880276	0.015490619
Negative Message	More Positive	Almost no change	More Negative	Almost no change
p-value	0.004458957	0.002580583	0.024219872	0.003274681

Figure 10: Emotional responses changes to color stimuli with p-value

6. DISCUSSIONS

In the result shown on the previous section, we can see the dispersion difference of emotional responses from participants for each different condition. In text-only stimuli trials, we can see that almost all responses for each message category are mapped in their valence area. If we compare the responses for positive touch stimuli, we can see that the results are more dispersed, especially for positive text. By looking at the standard deviation, we can see significant rise in σ_y, meaning that the responses on the activity level are really dispersed. Touch stimuli may have resulted in different interpretations to participants on the activity level, but did not particularly drive the perception into the opposite direction of the valence.

The standard deviation value also helped the authors to recognize how consistent a stimuli affects emotional perception to a certain category of messages under different conditions, for example where a positive color stimulus has more consistent effect on neutral text. We can also see similarities in other conditions, where neutral texts has comparatively less value of standard deviation. This also proves that emotional perception of neutral text can easily be driven to the direction of stimuli, compared to positive or negative text. Higher dispersion is shown when the stimuli emotional characteristic is in contradiction with the text message emotion category. In this condition, participants may have a different perception of which direction is stronger for them: the emotion of the text message, or the emotion of stimuli.

In the result shown on Figure 7 to 10, we can see that the effect of augmentation of both color stimuli and touch stimuli has a different effect depending on which category the message belongs to, and what stimuli comes together with it. We can also see that certain stimulus has a consistent effect on driving the emotional response into a certain direction across all different categories of message, while some others may change depending on the message category.

Positive touch stimuli, in most cases, will invoke a slightly higher activity level and slightly more positive emotion, except for when it is used with other negative factors: either a negative color, or the negative text message itself. Negative touches shows the most consistent tendency among other stimuli. Statistical significance analysis has also shown that negative touch stimuli generally has the least p-values in all conditions, meaning that it is the most reliable data. Negative touch stimuli can invoke a higher activity level and slightly more negative emotion, often not so significant. The combination of two contradictory categories of emotion in different factors may have resulted in the effect difference, compared to when the stimuli is combined with same emotion category, or the neutral emotion. This may be the reason why touch stimuli is most effective when it was used to accompany a neutral message, as it is seen on Figure 7.

Positive color stimuli, in most cases, will invoke a slightly higher or lower activity level and a more positive emotion. Negative color stimuli invokes a lower activity level and a slightly more negative emotion, often not so significant. In color stimuli, we can also say that the combination of two contradictory categories of emotion in different factors may have resulted in the effect difference, compared to when the stimuli is combined with same emotion category, or with the neutral emotion. This may be the reason why color stimuli is also most effective when it was used to accompany a neutral message, as seen on Figure 8.

Based on these findings, we can say that both positive touch and positive color stimuli can invoke a more positive valence. For the positive emotion, the results have shown that positive color stimuli has more effect to convey positive emotions. On the other hand, both negative touch and negative color stimuli can invoke a more negative valence, in a less significant way compared to the positive stimulus. Another finding is that touch stimuli has more effect on the activity level, especially for the negative touch stimuli, which has most tendency compared to other stimuli to invoke a higher activity level and a slightly more negative valence.

These findings can be implemented into the CMC environment, to support the assessment of the user's emotional state. For example, to invoke a higher activity emotional level and more positive emotional valency, we can use positive color stimuli, combined with negative touch stimuli, as a hybrid approach that is proposed in RingU system. As a contribution for the future application, this paper has proven the idea that non-verbal stimuli can change the emotional perception of a verbal cue in text message, and it can be driven into the direction of the emotional characteristic of the stimuli. By implementing these findings into a real life application, the authors hope that it can help better emotional state assessments in computer mediated communication. Senders can augment non-verbal cues to strengthen their verbal message and receiver can feel more emotion in receiving just a message.

7. CONCLUSION AND FUTURE WORK

In this paper, RingU, a ring-shaped wearable system aimed at promoting emotional, remote communication between people using vibro-tactile simulations and color lighting expressions is proposed as a hybrid approach in attempting to place a greater emphasis on existing cues by developing a new strategy in CMC environments. From the scientific study, we can conclude that:

- Both positive touch and positive color stimuli can invoke a more positive valence, especially in positive color stimuli, where it has more effect to convey a positive emotion.

- Both negative touch and negative color stimuli can invoke a more negative valence, as it is expected in the hypothesis.

- Another finding from the experiment is that compared to the effect on valence, touch stimuli has more effect on the activity level, especially for the negative touch stimuli, which has most tendency compared to other stimuli to invoke a higher activity level and a slightly more negative valence.

These findings have proven that touch and color stimuli is effective to invoke and change the emotional perception to a text message.

There are still a lot of improvements needed in the RingU system. In the implementation part, by implementing the system into a real compact ring, we may get a more interesting and more suitable result, especially for the user evaluation of the system.

For future possible applications, other than the use by couples or families to do intimate remote communication, another possible use is in the entertainment industry, for example where an artist can send a squeeze through the ring to all of his/her fans. For the scientific study part, emotional response is still subjective and may need deeper research to conclude the best result. By conducting the study with more extensive patterns of stimuli, a bigger sample population, and different emotional measurements, one possible application that can be developed is emoticons for vibrotactile stimuli and color patterns that represents different types of emotions and can be used in various systems.

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H.2 Ring*U: A Wearable System for Intimate Communication using Tactile Lighting Expressions

Ring*U: A Wearable System for Intimate Communication using Tactile Lighting Expressions

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Abstract
In this paper we describe Ring*U which is a ring-shaped, wearable system for sharing intimate, interpersonal interactions remotely through subtle colored lighting and tactile expressions. We present an overview of the Ring*U system. We also describe our next objectives for future work.

Author Keywords
Ring; tactile; lighting; pairing communication; emotion

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

Introduction
Love, closeness, and intimacy are important for people's psychological well-being. Nowadays, however, couples are often forced to live apart. Accordingly, there has been a growing and flourishing interest in designing technologies that mediate a feeling of relatedness when being separated, beyond the explicit verbal communication and simple emoticons available technologies offer [1].

Traditionally, a ring has been used as a symbolic present to deliver a message from the presenter to the receiver of the ring to sow their relationship. An example of this is its use as a fashion accessory between couples to represent their relationships and to eternize the promise between them on their engagement and wedding.

We developed Ring*U, a ring-shaped, wearable system that uses colored lighting and tactile expressions controlled remotely to share intimate and emotional interpersonal communication. We explored the lighting and tactile effects in social interactions and describe the overall design of Ring*U system. We then present the future research issues how natural our tactile "mini-hugs" can be generated from the rings and how they help people's emotional connection in remote.

Related Study

Colored lightings play important roles in reinforcing people's special perception, activity, mood setting, emotion, judgments, and even social relationships [2][3]. The effects of lighting expressions have been researched by architecture, interior, and theatre designers to set atmosphere, evoke feelings and moods, and heighten the emotional engagement.

From a neurological aspect, touch has a strong emotional impact. A psychologist, Harry Harlow (1958) [4] conducted a controversial study involving rhesus monkeys and observed that monkeys reared with a "terry cloth mother", a wire feeding apparatus wrapped in softer terry cloth which provided a level of tactile stimulation and comfort, were considerably more emotionally stable as adults than those with a mere wire mother. His work proposes that maternal touch was helpful to the development of emotions on target.

The physical touch may also continue throughout life as a scaffold upon which we build our social judgments and decisions. This has been shown in various psychological studies exploring how touch is essentially not just important for complex sensory motor tasks, but also can offer a deeper neural sensation for evoking recognition and judgment [5].

Thanks to the development of fashion technology, touch expressions have been used beyond the texture functions on the garments and new types of interaction in many projects have been realized. The tactile feelings of hugging from such garments were researched in the Hug Over a Distance project (2005) [6], Hug Shirt™ (2006) [7], and the Huggy Pajama (2007) [8]. Those have similar concepts to transfer the tactile feel of hugging to the remote place.

The Overview of Ring*U system

The Ring*U is a ring-shaped wearable system that enables people to communicate emotionally no matter how far you are from each other using the subtle tactile and lighting expressions (Figure 1).

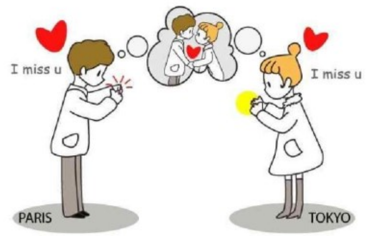

Figure 1: The concept of Ring*U system.

The wearer can communicate with his or her paired partner through the wireless communication using his or her smart phone that is connected with the Ring*U. When a user squeezes the ring, a signal will be sent over the internet and onto the partner's smart phone, which actuates a mini-hug and color on the paired ring.

The ring will start subtle vibration and shining in the RGB LED colors (Figure 2). By using Ring*U, people can convey warm feelings and messages to the paired partner more closely beyond the spatial restrictions.

The user can send 14 different combinations of lighting and 3 levels of vibration intensity through the setting of RGB color control (e.g. red, green, blue, red+green, red+blue, green+blue, red+green+blue) and vibration control (e.g. vibration on and off) using the smart phone app in current Ring*U system.

Figure 2: Pressing the top of the ring to send a lighting and a vibration signal to the paired partner through the Internet using smart phone app.

Once the user sets the value of lighting and vibration expression, then she can send it to the partner through pressing the button from the smart phone app or squeezing the ring. The pressure exerted determines the intensity of the color and the vibration.

For the natural interaction for the Ring*U system, the authors have developed a wireless communication between the rings. It utilizes the Bluetooth 4.0 protocol which is tiny and uses comparatively lower power consumption in the ring. This will allow the rings to also communicate with our complementary smart phone app which transmits the touch message over the Internet (Figure 3).

Figure 3: The system configuration of new Ring*U system.

Future Research

Based on the first prototype of the Ring*U system, the authors researched how the Ring*U system can convey the people's intimacy and emotional communication messages through the subtle lightings and tactile

Figure 4: The prototype of new Ring*U design expressions and its more natural interaction ways in remote.

For the emotional interaction, the authors are studying about the correlation of the emotional feedback and the various lightings and tactile expressions from the Ring*U system. They also are researching how tactile feedback from the ring can accompany a more meaningful transfer of emotion compared to a mobile phone.

Currently the authors are developing a new design of the ring since current design is not small and beautiful enough to wear in our daily lives as a fashion accessory. The authors are rebuilding the hardware and ring design toward the aesthetic as shown in Figure 4.

Conclusion

The Ring*U system is a wearable system that enables physical interaction in remote communication between loved ones. The key contribution is the ability to reproduce a mini-hug experience between two paired people remotely in a natural, physical manner. Based on this system, future works include studying and analyzing how natural mini-hugging can be generated and if it helps people's intimate interactions while being physically separated.

Acknowledgements

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The Heat is On: A Temperature Display for Conveying Affective Feedback

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ABSTRACT
Previous research has investigated whether temperature can augment a range of media including music, images and video. We describe the first experiment to investigate whether temperature can augment emotion conveyed by text messages. A challenge in prior work has been ensuring users can discern different thermal signals. We present an improved technique for thermal feedback that uses an array of three thermal stimulators. We demonstrate that the Thermal Array Display (TAD) increases users' ability to identify temperatures within a narrower range, compared to using a single thermal stimulator. While text messages dominate valence in the absence of context for temperature, the TAD consistently conveys arousal, and can enhance arousal of text messages, especially those that are emotionally neutral. We discuss potential applications of augmenting text with temperature.

Author Keywords
Thermal feedback; thermal haptics; affective computing

ACM Classification Keywords
H.5.2. User Interfaces – Haptic IO.

INTRODUCTION
An emerging trend in CHI research is using temperature to augment. Recent studies have examined temperature conveying qualities, such as emotion, activity level, and social distance [18][40][26].

Human performance in perceiving temperature and its rate of change potentially limits the application of this approach. Cutaneous sense of temperature is carried on nerve endings with slow response times [23] and incorrect perception of temperature results in sensory illusions such as 'synthetic heat' as illustrated by placing a hand on interlaced warm and cool bars [5]. Thermal signals must be sufficiently intense, otherwise they may be difficult for users to perceive correctly, if at all [42]. Along with human factors are limitations of thermal electric coolers (TECs), the technology used in thermal feedback research. Depending on which TECs are used, they can have high power consumption, high latency, and low accuracy.

We demonstrate latency can be mitigated using an array of TECs. The Thermal Array Display (TAD) is a device worn on the arm that displays patterns of warm, cool, and neutral temperatures using three TEC stimulators. Individually, the TECS are heated and cooled over a small thermal range, but as a group, they signal a wide temperature span. Multiple stimulators also increase stimulated skin area, easing perception of the thermal signal for users.

There are three contributions in this paper. First, we conducted a pilot study to detect if participants could identify warm and cool patterns on their arm. The difficulty of discerning patterns led to investigating if the TAD could instead increase user discrimination of temperature. Results showed participants could identify thermal cues signalled with an array of TECs better compared to the case where only one TEC was used. Second, we conducted another study to demonstrate how thermal cues signalled with the TAD can communicate arousal. Lastly, we proceed to demonstrate that, while text messages dominate valence in the absence of context for temperature, the TAD consistently affects arousal, especially arousal of more emotionally neutral text messages.

BACKGROUND
While vibrotactile feedback (VTF) research is more common to convey information, Suhonen *et al.* reported instances where VTF was misunderstood emotionally [32]. Alternatively, they claimed that temperature could communicate emotional meanings with warmth and coolness, thanks to its bi-directional and continuous advantage over VTF.

HCI literature has investigated whether thermal cues can convey qualities, such as social presence and proximity, [10][26], supporting behaviour such as musical performance, [25] and therapy [35]. AffectPhone [18] mapped arousal to temperature on the recipient's phone, and Lovelet [8] conveyed situation by sensing body temperature and sending it to the other partner. These examples, however, focused on output form novelty and lacked extensive, empirical studies to verify hardware design or the feedback. As noted in the Introduction, human physiology limits effectiveness of thermal communication, and a more detailed examination is needed.

Thermal Feedback System Design

A direction thermal HCI has taken is examining specifics of designing effective sensory output systems. Wilson *et al.* [42] noted 1°C/sec rates of change were appropriate for thermal displays and did not produce stimuli more difficult to detect than 3°C/sec or greater changes. 1°C change magnitudes, on the other hand, were harder to detect than 3°C and 6°C changes and resulted in longer time-to-detections. Users found it harder to detect thermal changes in a mobile setting than when they were seated [42], when wearing stimulators over clothes instead of directly on the skin [15], and when using stimulators outdoors due to ambient temperature interference [13]. Wilson *et al*. combined thermal cues with VTF [39] and examined practical uses of thermal feedback, such as assigning temperatures to activity levels and reviewing restaurants [40]. While results revealed users could detect different levels of temperature, it was not clear, indeed doubtful, if those levels could be discriminated accurately.

Problems of discrimination are primarily due to nonlinear temperature effects that occur when areas of skin in close proximity are exposed to differing temperatures. Due to the low ability of people to discern detailed spatial resolution of the skin's sense of heat, adjacent stimulations affect one other, creating perceptual temperature illusions. These physiological limitations create potential barriers to the effective use of thermal displays.

A key physiological phenomenon in thermal feedback design is *referral*. This occurs when stimulation at one point on the skin is experienced at another location. Green [11] demonstrated this when participants placed their index, middle, and ring fingers on three TECs set to hot and cold patterns. He noted strong sensations outweighed weak ones. Participants found the middle sensation strongest when adjacent stimulators were the same temperature – a form of referral. Referral also occurred when stimulation of the ring and index finger created a sense of temperature applied to the middle finger. When adjacent stimulations mixed hot and cold, users had a (mild) burning sensation termed *synthetic heat*.

Oron-Giland *et al.* [27], created a thermal display comprised of three TEC stimulators worn on the arm. They investigated synthetic heat and primarily looked at spatial configurations of two stimulators turned on in pairs of hot and cold. They found great variance in detection times among participants, and that the thermal detection threshold varied more for hot temperatures than cold. However, their use of multiple TECs only focused on synthetic heat, and they did not examine potential of three-stimulator feedback to communicate thermal patterns to invoke emotion.

Other researchers have used multiple stimulators to explore thermal sensitivity of different body locations. Watanbe *et al.* [36] used two stimulators mounted on a surface that the user's arm rested on. They sent mixed pairs of hot (40°C), cold (20°C), and neutral (33°C) temperatures to participants, who reported the sensations at each stimulator. A major discovery was that extent of referral increases for warm sensations nearer the elbow, or towards the body centre, and cold stimulation has greater referral distance near the hand, or towards the periphery. Participants could judge correctly when both stimulators were set to the same temperature, but had trouble distinguishing if one was set to neutral because of referral. Synthetic heat was also perceived asymmetrically- the wrist does not perceive it, or more generally, thermal referral, as well as if the stimulation occurred nearer the elbow. Thus, stimulator location influences user detection accuracy and perception for hot, cold, or synthetic temperatures.

Multiple stimulators have also been used to address the problem of the time it takes users to discern temperature stimuli. Sato and Maeno [31] found that, although distinguishing thermal stimuli patterns is difficult, multiple stimulators can reduce latency. They created a device consisting of a small 2x2 matrix of TECs that participants placed their fingertips on that exploited the skin's low spatial resolution. Participants could only identify TEC positions at 50% chance levels, but could guess correctly whether the stimulus was hot or cold. Sato and Maeno also demonstrated that patterns of all hot or all cold lowered detection response times compared to mixed patterns. Akiyama *et al.* [1] used two TECs side by side, placed under the hand to 'prime' the skin before sending a hot and cold stimulus. They claimed this reduced detection times up to 28% and 24% for hot and cold, respectively.

Affective Thermal Feedback

Giving someone the cold shoulder or giving them a warm welcome are popular metaphors for communicating abstract concepts that humans harbour toward each other. Concrete experiences, such as sensing temperature, ground such concepts when they are co-experienced, such as affection. This demonstrates a "systemic inter-dependence among language, perception, and social proximity" [17, pp 1214].

Because of this, temperature could be used to alter one's physical state to regulate underlying emotions. Thermoception has both enteroceptive and affective aspects, as both temperature and emotion are processed in the limbic system. Medical studies utilizing PET and fMRI imaging of the brain have shown cooling a patient's right hand linearly correlates with activity in the insular cortex, which regulates internal feelings such as panic, anxiety, sadness, and sexual arousal [6]. Warm stimulation activates distributed regions of the brain associated with affective responses and could induce subjective awareness, such as inner body feelings and emotionality [33].

Social perception involves physical and perceptual content. Lawrence and Bargh described 'Psychological Warmth' to influence a first impression of others. They primed participants by asking them to hold warm and cold beverages before meeting a stranger. Participants primed with warm beverages perceived the stranger more positively than those who held cold beverages [37]. A similar experiment demonstrated that warm beverages induced greater social proximity, and warm, ambient temperatures enabled participants to describe social events more concretely [17]. Subsequently, 'Psychological Cold' influences social exclusion, [43] as excluded participants gave lower estimates of room temperature and craved hotter foods than those not excluded in their study.

As discussed earlier, thermal stimulator prototypes have been used in HCI research to invoke emotional responses, but few have examined the effect of temperature on emotion thoroughly. Salminen *et al.* examined two methods for conveying temperature to invoke emotional responses [30]. In both methods, warming up was sensed as more arousing, dominating, and motivational. Temperature did not affect ratings in pleasantness (valence) and acceptability. Lee and Lim [21] [22] asked participants to investigate information conveyed with wrist worn thermal devices. They found thermal feedback only has meaning in context, but has a unique emotional value which allows for an unobtrusive, casual method of communicating. Heat worked better on a visceral, unconscious level than cognitive, as humans have no legacy for communicating information with heat. Wilson *et al.* [41] examined thermal responses on valence, arousal, and domination. They found useful parameters for temperature to elicit emotional responses but only few emotions were elicited from temperature alone. However, they did not look at thermal augmentation.

Research utilizing thermal augmentation has been used on images and movies, but have only focused on novelty with no significant work relating specific emotions with the stimuli. Hannah *et al.* [16] augmented videos displayed on a television by heating a remote device during happy scenes and cooling it for sad ones. They proposed information could be embedded within the metadata of a movie file for more practical applications. AmbiPad [24] was an Android tablet modified with coloured lighting around the frame and TECs on the back to enhance contents of the screen when it played a movie.

The most intensive research in augmentation was carried out by Halvey *et al.* [12]. They studied the effect of temperature on subjective perceptions of images and music to evoke emotional responses. Images were selected from the International Affective Picture System, and music was selected based on audio dynamics and volume levels. They found temperature could significantly enhance or dampen affective experiences with images. However, no significant differences were found pulsing temperature dynamically with music. They only used three temperatures, and only varied the rate of change as a parameter.

No similar research has augmented text with temperature. Though Thermal Hug Belt [10] examined how temperature could mediate a sense of social presence when subjects used IM chat, they did not examine how temperature could elevate or decrease emotion, as text was not controlled.

To summarize the literature review, research has shown that temperature can effectively communicate meanings, such as emotional state. [32][18][8] demonstrated temperature eliciting such reactions from participants. Furthermore, studies have examined key parameters for designing thermal feedback, such as Wilson *et al.*'s work, [42][15][13][39][40]. Green [11], Oran-Giland *et al.* [27], Watanabe *et al.* [36], Sato and Maeno [31], and Akiyama *et al.* [1] incorporated multiple stimulators into their work to investigate perceptual aspects of temperature. However, they focused on physiological aspects and were not necessary HCI related. Thus, gaps in the knowledge remain:

- Can multi-stimulator thermal devices relay more complex patterns akin to vibrotactile patterns [3]?
- Can users' thermal sensory acuity be boosted further than previous work [31][1]?
- Can temperature augment emotion when paired with social media messages?

HARDWARE OVERVIEW

We constructed the Thermal Array Display, or TAD, to investigate these knowledge gaps. First, we examined how accurately users could distinguish thermal patterns. The TAD device, shown in Figure 1, is worn on the arm and can signal thermal patterns using three stimulators.

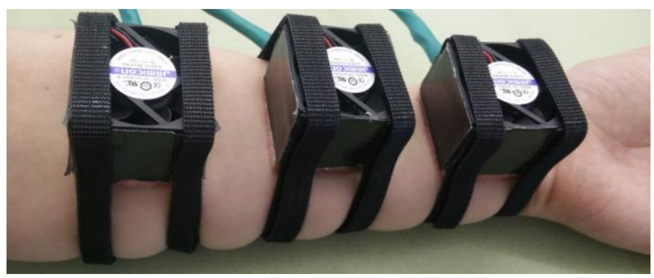


Figure 1. The Thermal Array Display

Most modern thermal output systems use TECs: flat, rectangular, thermoelectric components that cool down and heat up on either side depending on how current is applied. By varying voltage using Pulse Width Modulated (PWM) signals from a micro-controller, one can control how much heat is transferred from the cool side to the warm side, depending on rise time of the signal. When polarity is reversed to a TEC, the heat transfer direction reverses, allowing either side to warm up or cool down. This behaviour can be moderated using an H-Bridge circuit, which is implemented in motor drivers. By using a Proportional-Integral-Derivative (PID) controller, one can set the temperature of the TEC by reading current temperature using a thermistor and appropriately updating output and direction of the current to the TEC.

In our system, an Arduino Mega 2560 is used to control three TECs independently. Each TEC (MCPE1-01708NC-S, Multicomp) is connected to a thermistor (MC65F103A, Amphenol Sensors) that is polled in the Arduino main loop. As Arduino pins are rated at only 40 mA, the TECs are driven by a motor driver (MC33926, Pololu), which draws power from a 6V, 10A mains supply. Each TEC is connected in series with an inductor to 'smooth' the PWM signal from the motor driver to appear as a DC current source. This signal is pulsed at 490 Hz, as it produced the most stable temperature behaviour compared with other frequencies attainable on the Arduino.

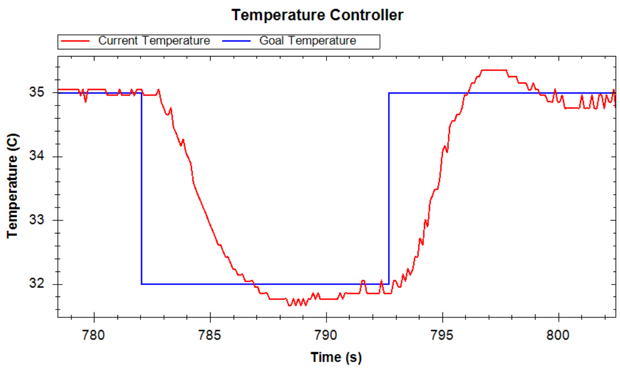


Figure 2: Temperature Plot

Maintaining a fixed rate of change is difficult using a PID controller. After careful tuning, we achieved, on average, 1°C/s rates of change using tuning parameters of K_p=50, K_i=2, and K_d=0, the proportional, integral, and derivative constants, respectively. Figure 2 shows a time plot of temperature changes using the system, first cooling from 35°C to 32°C and then warming up back to 35°C.

Figure 3 shows the stimulator pad construction. Design is based Oron-Giland *et al.*'s device [27], the only instance of an arm-worn, three-stimulator display in literature. Each stimulator consists of a TEC, attached to a heat sink (BGA-STD-115, ABL) using double-sided thermal tape. A 5V DC fan is attached on top of the heat sink by gorilla tape. Fans are driven from an external power supply using BD137 NPN transistors. Both heat sinks and the fans are needed to extract heat away from the TECs. Otherwise, the efficiency of the TECs decreases as they heat up, potentially posing a safety hazard. The participant was insulated from the heat sink using a panel of cardboard and Styrofoam glued together. Double-sided Velcro was glued to both sides of the heat sink, which allows users to wear the stimulators by strapping them around the arm.

Oron-Giland *et al.* used a thin, 3mm thick, metal plate at the point of contact between the skin and the TEC itself. This involved drilling a hole in one of the plate's four lateral surfaces to insert the temperature probe into. This is an alternative to mounting the sensor directly on top of the TEC, as is done in most systems reported and allows the stimulator to be comfortably worn. It also protects the sensor from exposure to the ambient environment, which may result in less reliable readings. Instead of using aluminium for the plate however, we used C101 copper due to its superior heat transfer properties. Before inserting the probe, the hole was filled with thermal grease (MX-4, Artic). After insertion, it was sealed with epoxy.

Figure 3: A Single Stimulator- Bottom (Left) and Top (Right)

Software consists of Arduino firmware and a PC user interface. The Arduino monitors temperature from the thermistors, connected as part of a voltage dividing circuit that feeds into the Arduino's analog pins. This raw voltage input is converted into degrees Celsius using the Steinhart-Hart thermistor equation. The PC software interfaces with the Arduino using the USB serial library CMDmessenger [7]. The basic functionality sets the temperature of each TEC separately, monitors safety, reads parameters from files, and logs participant data in real-time.

PILOT STUDY

The initial aim of the TAD was developing a pattern-based, thermal-tactile language. We conducted a short pilot to see if users could identify patterns of three stimulators set to warm, cool, or neutral temperatures.

- Participants wore the TAD and were shown visual representations of eight thermal patterns.
- Participants were instructed to select one they believed was 'displayed' to them.
- Each pattern was used twice.

Oron-Giland *et al.* [27] proposed patterns of three alternating thermal stimuli but no study was conducted. Wilson discussed the ideas of area stimulation and 'thermal waves' [38], like unidirectional vibro-tactile rhythms [3]. However, he did not pursue it due to perceptual problems and technological issues. This research carried out a pilot study to investigate this further.

As the TAD uses three stimulators, 27 patterns are achievable with warm, cool, and neutral temperatures. A taxonomy was devised to categorize such patterns. Each had a 'mechanical' device setting and a 'perceived' effect derived from physiological illusions [11] and the anticipated spatial direction the temperature would travel [36]. Two parameters were used: the temperature direction (hot, cold, and neutral) and TEC arm positioning, (elbow, middle of the forearm, and wrist). Table 1 illustrates a few of these.

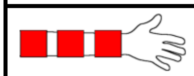
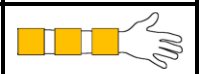
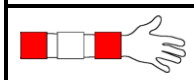
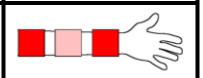
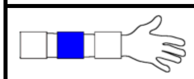
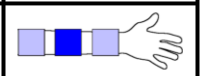
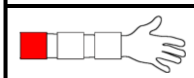
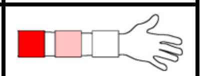
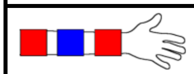
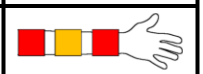
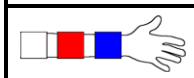
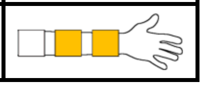
Mechanical	Description	Perceived
	Enhanced Hot	
	Inward Referred Hot	
	Outward Referred Cold	
	Proximal Referred Hot	
	Synthetic Heat	
	Distal Optimal Synthetic Heat	

Table 1: Thermal Patterns

Pilot studies revealed similar findings to Sato and Maeno [31]: participants could not easily identify temperature of the individual TECs when presented simultaneously. We therefore investigated whether the TAD could improve ability of users to accurately identify single temperature states. The TAD increases the skin area that is stimulated which could potentially enhance signal intensity, making perception of temperature easier to discriminate.

Two further studies were conducted with the TAD. The first compared two methods of signalling temperature with three stimulators and compared accuracy of users' responses to the case where only one stimulator was used. Participants recorded responses on a 7-point Likert scale (Figure 4), where each point, illustrated as a radio button, corresponded to a temperature state of the TAD (Table 2). The second study investigated if thermal cues could convey emotion by measuring valence and arousal when participants viewed positive, neutral, and negatively rated Facebook messages on-screen with temperature.

EXPERIMENT 1

Participants were asked to identify seven thermal stimuli using three methods: Single, where only one stimulator was used, Amplification, where all stimulators were set to the same temperature, and Quantification, where the target temperature was represented by setting one, two, or all three stimulators to the warmest or coolest temperature.

- The Single, Amplification, and Quantification tests were presented in random order.
- Each test had a calibration session beforehand to acquaint participants with stimuli.
- During each test, seven temperature stimuli were presented three times each, and the skin temperature returned to neutral before each was presented.
- Participants made selections on a 7-point Likert scale.
- There was a five-minute break in between each test.

Stimuli Design

Three parameters were considered when designing the temperature stimuli: neutral temperature; temperature range; and the temperature difference between stimuli. We discuss each in this section and then describe how we signalled temperature using the TAD.

Since skin adapts to stimulation, consideration was made which temperature to use as the neutral stimulus or baseline temperature. This neutral temperature varies from person to person, but it is thought to be in the range of 20°C - 40°C [19]. Within this range, skin will adapt slowly to reduce the sensation of stimulation until full re-adaptation has taken place and the user no longer perceives any sensation. Temperatures closer to the middle of this range are easier to adapt than at the extremes [14]. Beyond this range, temperatures feel persistently cold or hot [20]. Such extreme temperatures are not commonly used as they are uncomfortable and painful. We chose a conservative temperature of 32°C as was used in Wilson and Halvey *et al.*'s work [39][42][13][25].

The use of wide temperature ranges requires more time to reach the extreme temperatures. This results in longer latencies, the time between temperature changes. It is paramount to use as small a range that can be detected to reduce time taken for the TECs to change temperature, and thereby reduce the time to communicate a temperature state. Limiting the number of thermal scale points and the temperature difference between them minimizes the total temperature range needed for a feedback system.

Wilson *et al.* used a temperature range of 22°C-38°C with 2°C as the smallest difference between two stimuli [40]. Within this range is a safe and comfortable zone of temperatures appropriate for thermal feedback. In contrast, we chose a narrower range of 29°C - 35°C and reduced the step between stimuli to 1°C. These two changes reduced the time to signal different temperature states. More importantly, smaller step changes make it more difficult to discern neighbouring states. This forms a better apparatus for testing fine stimuli discriminability with multiple TECs.

Table 2 shows how temperature was signalled in each test. Squares represent stimulators, where the left, middle, and right squares represent the wrist, middle, and elbow stimulators, respectively. Colours denote whether the stimulus was warm, cool, or neutral using red, blue, and white, respectively. Colour saturation indicates stimuli intensity. There are three intensities for warm and cool.

Single Test

This test used only the middle stimulator. The middle stimulator was chosen to prevent biasing effects from using either the elbow location, which would have made warm sensations stronger [36], or the wrist, which is the direction cold sensations spread better towards. Other stimulators were not worn as it eliminated the decision of whether to leave them on (at neutral) or off. Participants were asked to identify which of the seven stimuli was presented. Stimuli differed by 1°C increments with neutral at 32°C. Hence, warm was 33°C, warmer was 34°C, and warmest was 35°C. Cool was 31°C, cooler was 30°C, and coolest was 29°C.

Amplification Test

This method represents intensity by setting all stimulators to the same temperature. All three stimulators were worn, and the participants were asked to identify the combined stimulus. As with the single test, temperature states differed by 1°C increments with neutral at 32°C, applied to all three stimulators, using the temperatures from the Single test.

Quantification Test

Participants were asked to discriminate cues wearing all stimulators, however, this approach used only 29°C for cool stimuli and 35°C for warm stimuli. It is the number of active stimulators that determines the intensity rather than indicating intensity by temperature. Thus, warm set one stimulator to 35°C, warmer set two stimulators to 35°C, and warmest set all stimulators to 35°C. Cool set one stimulator to 29°C, cooler set two stimulators at 29°C, and coolest set all three stimulators to 29°C. Stimulators that are not set to either 29°C or 35°C were left at 32°C, neutral.

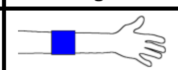
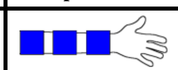
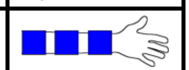
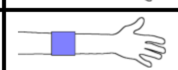
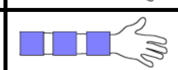
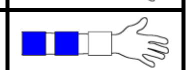
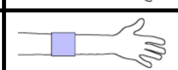
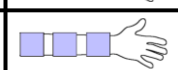
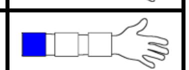
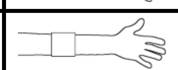
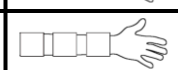
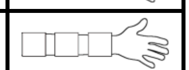
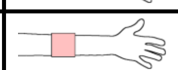
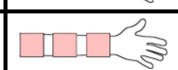
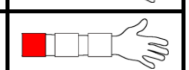
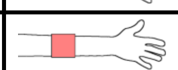
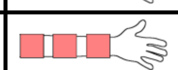
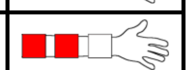
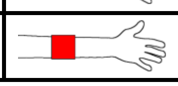
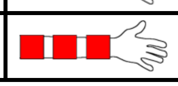
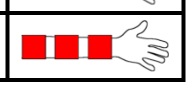
Name	Single	Amplification	Quantification
Coolest			
Cooler			
Cool			
Neutral			
Warm			
Warmer			
Warmest			

Table 2: Experiment 1 Stimuli

Procedure

Twelve participants, ten males and two females, were recruited from the engineering school of a UK university. While gender differences are a debatable subject in thermal perception studies, the most recent paper by Wilson *et al.* [41] showed no differences in perceiving temperature. Each participant received £10 for their time, in line with standard practices at the institution, and the experiment was approved by the school ethics board in advance.

To ensure both wellbeing of participants and efficacy of the study, exclusions were made. Individuals could not participate if they had medical problems that could impede temperature perception, such as over-sensitive skin, or where exposure to temperature causes discomfort or harm.

Participants wore the TAD on their non-dominant arm, following the practice of previous studies [40]. Each participant took approximately one hour to complete the experiment, including induction and completion of all tests. There was no time limit imposed on participants, thus the duration lasted until they submitted their selections for each trial. Participants, however, were instructed not to dwell on answers and to move on as quickly as they could.

The entire experiment was automated. Tests were separated by five-minute breaks to allow participants to relax their arms. Participants were told to read the instructions on screen and complete the tests by recording their perception of the signalled temperature on a 7-point Likert scale, shown in Figure 4. Each point denotes one of the states, colour coded from ‘Coolest’ to ‘Warmest’, with ‘Neutral’ in the middle. The seven stimuli were presented three times, in random order for each test. The order of the three tests was also randomized by counterbalancing beforehand.

Preceding each test was a calibration session to familiarize participants with the stimuli presented and the user interface. This session was nearly identical to the real tests that followed, but the Likert scale was pre-selected with the correct response. Additional color-coded graphics depicted the position of stimulators on the arm, with instructions on navigating the interface, and the displayed name of the selected stimulus, e.g. ‘Warmest’ or ‘Neutral’.

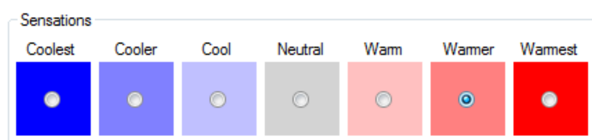


Figure 4: User Interface

Between each stimulus was a short delay to allow the skin temperature to re-adapt back to neutral. This process, discussed in the Stimuli Design section, ensured participants could discern the next trial without bias from the proceeding stimulus. It also serves to establish the reference temperature for judging subsequent stimuli. Previous studies used delays between ten seconds [40] to two minutes [15] for re-adaptation. We chose the shortest time of ten seconds due to time constraints of the study. Our temperature range was even smaller than the range used in [40], so this time was deemed acceptable. After re-adapting, the next stimulus was presented for three seconds and then the scale was displayed on screen for selection.

Results

We first tested the error rate (frequency) for all three presentations, using a chi-squared test. This produced $\chi^2 = 10.89$, df=2, p=0.004. The Single method provided the worst outcome, with 34.9% correct judgments, while Amplification and Quantification produced 49.2% and 44.4% correct ratings, respectively.

We also tested the degree of error, the absolute difference between the target and actual values. The degree of error was measured separately from error rate as non-significance in either test would lead to rejecting the alternate hypothesis. A Kruskall-Wallis test on the degree of error produced H=22.59, df=2, $p < 0.001$. Again, the multi-stimulator approaches both proved superior to the single stimulator. The alternative test for the population distribution of errors using chi-squared also proved significant (from errors of 1 to 5, calculated from the error formula above) and produced χ^2=20.55, df=8, p=0.001. The multi-stimulator methods gave more accurate detections, and resulted in lower degrees of error. As the data was not normally distributed, ANOVA was not used.

Subsequent testing for the precision of the two methods produced a clear advantage for the amplification method in terms of exact ratings (χ^2= 4.51, df=1, p=0.036), but there was no difference in the relative degree of error. This suggests that Amplification is the most promising method for signalling thermal states, but as the advantage over Quantification was low-power, both multi-stimulator approaches are more accurate alternatives to the traditional single stimulator method and merit further study.

EXPERIMENT 2

We examined how temperature could be used as an augmenting modality for Facebook post messages. The experiment consisted of two studies: a pilot study that selected appropriate media from an existing corpus of Facebook messages and thermal stimuli; and a main study which combined the messages and thermal stimuli in pairs to investigate whether temperature could augment the emotion communicated by the Facebook posts.

For both studies, twelve participants were selected from the engineering school of a UK university. Like the previous experiment, each participant received £10 for his or her time, and the same exclusions rules were applied. Nine males and three females were used in the pilot, which took about 40 minutes to complete. For the main study, which took about an hour to complete, twelve new participants comprised of four males and eight females were used.

Pilot Study

A two-part pilot was conducted to verify messages and thermal stimuli appropriate for the main study. First, participants evaluated valance and arousal of messages from a previous study [28]. Next, participants rated valance and arousal of the thermal stimuli from Experiment 1.

- In Part 1, participants rated twenty-five messages, each repeated three times.
- In Part 2, participants rated seven temperatures using Amplification, repeated three times each.
- Participants were given written instructions for both parts and a five-minute break in between.
- Participants reported valance and arousal selections on two 5-point SAM scales.

Stimuli Selection

Augmentation of text messages using temperature could be studied by examining impact of valence and arousal. Research investigating text messages and emotion such as [9] have demonstrated agreement between expert trained users and naïve (non-emotion expert) users when rating emotions from the Russell circumplex model [29]. Though databases of such messages exist [34], early pilots revealed difficulty of obtaining suitable messages that our non-expert participants agreed were happy or unhappy and excited or calm. Instead, we utilized results of a recent study [28] that rated Facebook posts by psychological trained annotators based on valence and arousal traits.

Similar to Halvey *et al.* [12] we selected messages for each emotional state: high valance/high arousal, high valence/low arousal, low valence/high arousal, low valence/low arousal, and neutral valence/neutral arousal. As the study in [28] rated messages on 9-point scales, any message rated 1-3 by both experts in the study was selected as a candidate for either low arousal or low valance. Messages rated 7-9 were candidates for high arousal or high valance. Messages that were rated 5 for both valance and arousal were candidates for the neutral stimulus. We used these criteria as there were only few instances of messages that had either 1 or 9 ratings for valence and arousal that were consistent across the reviewers. Neutral messages with ratings of 5 were abundant, and we did not have to extend their score range to 4-6 for inclusion. Along with the text messages, the thermal stimuli described in the Amplification section were also evaluated emotionally.

A 5-point Self-Assessment Manikin (SAM) technique [2] was employed to capture participants' valence and arousal reactions to both the temperature and message stimuli. In light of the experience of participants in the first study we aimed to simplify the effort required to rate signals. For this reason, we did not use the 9-point SAM scale used in the Facebook study, nor did we use the 7-point scale from Experiment 1 as we were not measuring discrimination of the seven thermal stimuli.

Procedure

To ensure consistency across participants, stimulator positions were marked on the arms before the study. Elbow distance to the wrist was measured; the midpoint was marked for placement of the middle stimulator to compensate for differing forearm lengths. Furthermore, participants were given a brief 'calibration' session where they were presented the warmest and coolest stimuli to ensure they could detect these temperatures and to allow themselves to become familiarized with the TAD.

After the setup, participants completed the two parts of the study. In Part 1, they rated the Facebook messages. They were instructed to read the message that appeared at the top of the screen and were given the context to imagine it was sent from a close friend on Facebook. Participants rated valence and arousal using the SAM as shown in Figure 5.

After completion, the TAD device was then attached to their non-dominant arm and they proceeded to rate the thermal stimuli. Unlike the messages, the temperatures were not given a context in the instructions, and participants were instructed to just rate how the temperatures made them feel while perceiving them. Like Experiment 1, ten seconds was used to re-adapt the skin to return to a baseline temperature in between trials. All stimuli for both parts were repeated three times in a random, counter-balanced order unknown to either the participant or the lab monitor until after the test. Like before, there was no time limit to making selections.

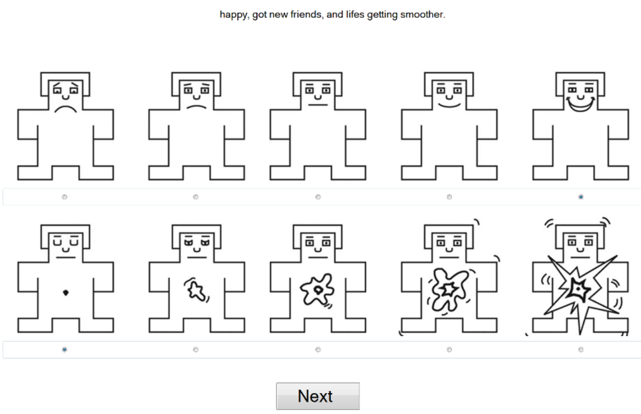


Figure 5: SAM Interface. The small text at the top is the Facebook message post.

Results – rating message valence and arousal

Participants could differentiate messages per valance and arousal. Table 3 shows the five messages selected for the main study, with mean valance and arousal scores. As a 5-point scale was used, neutral scores are 3. Message 1 was selected as the high valence/high arousal text, Message 2 as high valence/low arousal, Message 3 as low valence/low arousal, Message 4 as low valence/high arousal, and Message 5 as the neutral message.

ID	Message	V	A
1	Blessed with a baby boy today	3.6	3.5
2	life is beautiful	3.7	2.3
3	SICK AGAIN !!!! HATE IT !!!!!	2.3	2.4
4	At least 15 dead as israeli forces attack Gaza aid ahips!!!!!!! i hhhhhhate israil	1.4	3.8
5	And one careless match can start a forest fire but it takes a whole damn box to get a campfire going!	3.1	2.8

Table 3: Selected Messages

Figure 6 shows the valence and arousal means from Table 3 in a scatterplot, with the horizontal axis denoting the valence scale and the vertical axis denoting the arousal scale. Quadrants above the horizontal axis denote messages with high arousal and the bottom two quadrants denote messages with low arousal. Messages to the right of the vertical axis are high valence (happy), and messages to the left of the vertical axis are low valence (unhappy). The selected messages fall within their respective quadrants showing appropriateness for their valence and arousal traits.

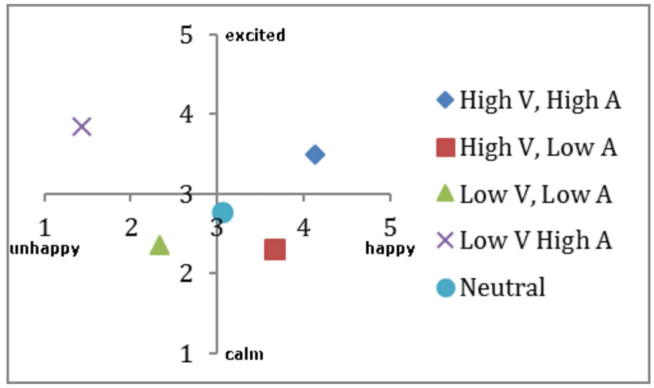


Figure 6: Selected message mean valence and arousal scores

Results – rating temperature valence and arousal

Participants disagreed which temperatures had a high or low valence. Six participants interpreted cool stimuli as high valence and warm as low valence. Two did the opposite: rating warm stimuli as high valence and cool stimuli as low valence. The remainder rated either all stimuli as low valence or only certain scales of warmth or cool as high valence. This was surprising, as [21] reported participants rating warm as high valence and cold as low valence. However, they only assessed this using qualitative data. Salminen *et al.* [30] on the other hand, concluded temperature did not affect pleasantness (valence) ratings and that it only affected arousal and dominance. Some research has been mixed. Halvey *et al.* [12, pp. 95] reported warm stimuli were given higher valence ratings than cool stimuli "with some exceptions", though they did not explain why neutral temperatures had higher valence ratings than warm stimuli.

On the other hand, there was general agreement amongst participants perceiving more intense stimuli as more arousing. Participants found scales of warm to be more arousing than cool scales. This may have depended on how intense they perceived the stimuli as some participants remarked warm stimuli felt more intense than the cool ones. Our findings here agree with prior literature.

The mean time to rate the messages was 6.82 sec (sd = 1.5 sec). The mean time to rate thermal cues was 6.84 sec (sd = 0.8 sec). This suggests that, despite latency of thermal cues, they require no more cognition than reading text messages.

Main Study

We proceeded to examine interaction between text messages and thermal stimuli. As discussed, research has examined emotions and thermal stimuli separately, as well as using temperature to augment images and music. However, it has yet looked at whether thermal cues can augment emotions communicated in text messages.

- The study consisted of 96 trials that were comprised of 48 unique stimuli that were each used twice.
- 12 trials were message-only stimuli. 72 were pairs of a message and temperature, 12 were temperature alone.

- The 12 message trials were tested together either before or after the other 84 trials.
- The 84 thermal trials were split into 3 blocks with 5 minute breaks between them.
- For all 96 trials, the participants reported valence and arousal on two 9-point SAM scales.

SAM scales were increased to nine points from five points. This was done as almost every participant in the pilot rated temperature using only the 2-, 3-, or 4-point selections and some participants remarked they would have preferred a wider range of choices. It should be emphasised that the stimuli chosen from the pilot were re-tested again in the manner they were presented alone in the pilot- results of the 5-point and 9-point scales were not 'mixed'.

The seven thermal stimuli were combined into pairs with one of the five message types or a blank message (for the temperature only condition) and displayed to the participant. Each pair was presented to the participant twice during the test, resulting in 84 trials. As before, there was a ten second re-adaption period between each trial. The order of all trials was randomized and divided into three blocks, with five-minute breaks between blocks to prevent fatigue.

Conditions where either the messages were displayed without temperature or thermal cues were displayed alone were tested again, due to the switch from 5-point SAM scales in the pilot to 9 points used in the main study. As it would have been difficult to detach the thermal device each time the message only stimulus was presented, they were tested separately from the rest of the thermal stimuli trials. To prevent ordering effects resulting from this, participants were split into two groups. The first group rated the messages and then proceeded to rate the other 84 thermal trials, and the second group rated the 84 thermal trials and then proceeded to rate the messages.

Results

We first tested the distribution of the participants' ratings of valence and arousal. Researchers have previously raised concerns on the validity of using ANOVA on Likert data, but when data is normally distributed, ANOVA is appropriate [4, p. 126] and can test for interaction effects.

To test for normality of the data, we used Shapiro-Wilkes tests for the data set as a whole, and then separated the data by message and thermal stimuli to ensure that all subsets were also normally distributed. All results produced $W>0.975$, and exceeded the critical values at $p<0.01$. This confirmed the normality of the data, and permitted the use of ANOVA.

The ratings for valence had a global mean of 4.8 and a standard deviation of 1.9; while arousal had a mean of 4.7 and standard deviation of 1.6. To again test for the validity of ANOVA on the data, we obtained standard deviations for the subsets of thermal and message stimuli, with valence ranging between 1.1 and 1.7, and arousal from 1.8 to 2.1. The level of variance in standard deviations was within the tolerances expected of a two-factor ANOVA.

Two tests allowed us to check for experimental effects from wearing the apparatus. First, we tested the temperature-only stimuli results against the trials that paired thermal signals with a neutral message. Second, the message-only responses were tested versus the same messages with a neutral thermal signal. Any positive result would indicate an undesirable substantial experimental effect. Using ANOVA, F values varied between 0.07 ($p>0.85$) and 1.5 ($p>0.20$). For the main effects, scores were at or above $F=8.5$ ($p<0.005$) Thus, we could discount the likelihood of a significant side effect from wearing the device.

The global descriptive data suggests that arousal responses were diffuse and inconsistent, whereas valence responses were more concentrated and consistent. As such, valence will be addressed first before proceeding to testing arousal.

We first tested valence using the message and thermal stimuli as the two variables. The ANOVA result was $F(2,385) = 118.45$ ($p < 0.001$) for the messages dimension, but the thermal dimension yielded $F = 0.43$, and interaction produced $F=0.29$, both very far from significant. While messages substantially influenced the perceived valence, thermal signals had no discernible effect.

For arousal, the ANOVA result was $F(2,385)=3.62$ ($p<0.05$) for message effect and 3.41 ($p<0.05$) for thermal effect, with the interaction producing $F=0.20$ ($p>0.80$). There is again no evidence of an interaction effect. Both the message and the thermal stimulus had a similar and reliable effect, but neither was as marked as the impact of the message on valence.

Thus, for valence and arousal, the message content had a reliable main effect. The effect was much more powerful in valence than arousal. In contrast, thermal stimulation had no reliable effect on the valence, but had a similar level of efficacy to the message for arousal levels.

Discussion

Figure 7 shows the plots of the mean valence and arousal scale responses (y-axis) as a function of temperature change (x-axis) for each category of message and thermal pairings. Plot (a) shows the pairing with a blank message for testing temperature only. The bottom of the y-axis denotes ratings of 1 on the valence and arousal scales (unhappy and calm), and the top of the y-axis denotes ratings of 9 on the scales (happy and excited). The far right of the x-axis denotes the coolest temperature setting and the far left denotes the warmest setting, with neutral at the position of the y-axis.

Arousal is marked by the red lines in each plot. As expected, as temperature increases, arousal ratings generally tend to move upward. Except for plot (c), arousal ratings tend to be negative for cooler temperatures and only cross the x-axis when warmer stimuli are applied. For all categories, temperature had a reliable main effect on arousal, including plot (f).

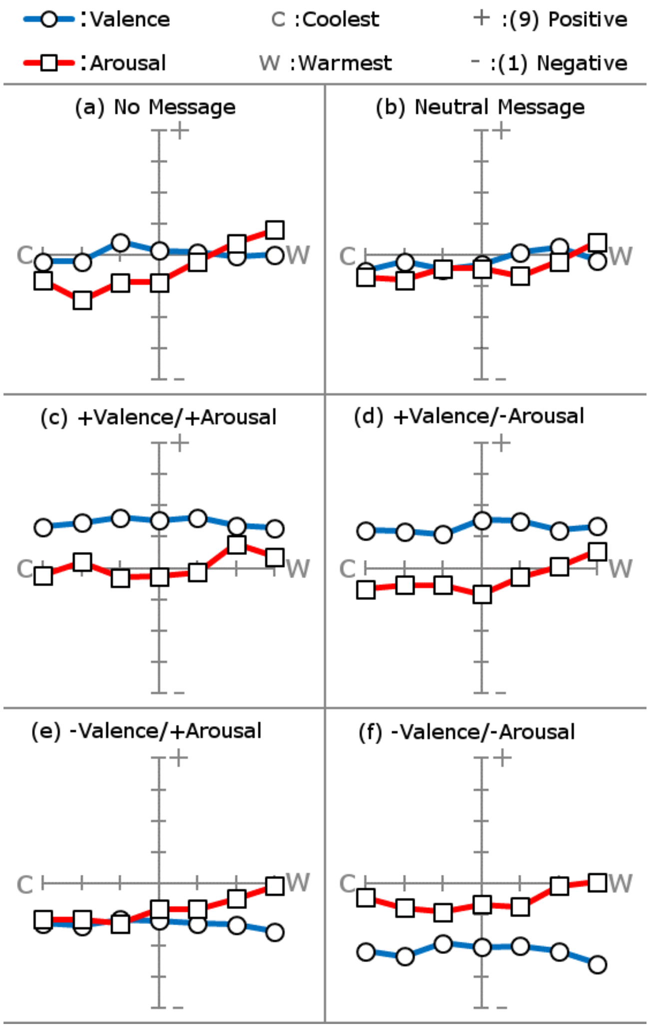


Figure 7: Message and temperature pairing mean plots for valence and arousal

Valance is marked with the blue line. As discussed in the Results section, temperature had no reliable effect. As plots (c), (d), (e), and (f) illustrate, the valance of the message clearly dominated, with the lines clearly above or below the x-axis. These lines remained relatively straight, regardless of thermal stimulus applied. For plot (a), where only temperature was displayed with no message and plot (b), where temperatures were paired with the neutral message, the means remained close to neutral. Plot (a) illustrates pilot test findings with no thermal valence effect.

Why did we not observe a thermal effect on valence? Lee and Lim offer some clues. They reported environmental factors could influence thermal expression, as humans tend to feel safe from factors that change body temperature [21]. We did not control this, and though thermal feedback recommendations still hold in varying ambient temperatures [13], it may influence thermal expression of valence. [21, p. 4235] also reports "heat seems to have hardly any meaning by alone without its context". As we instructed participants to "rate how the temperature made you feel" this context may have been ambiguous, as we did not ask them to interpret it in a context like with the messages. Future research should address the effect of context on the affective perception of thermal cues in different environments, including a control condition where temperature is sent ambiguously.

We can conclude that temperature itself consistently generates arousal responses. In a temperature-augmented message, strong textual valence will dominate the emotion communicated to the user. For all messages, but particularly if the message is neutral, temperature significantly influences the emotional arousal communicated.

CONCLUSION

Users find it hard to identify the physical position of TECs when they are placed in patterns. However, the TAD enabled more accurate discrimination with smaller temperature differences between thermal signals, reducing time for user identification of thermal state changes. In our test of single- versus multi-TEC methods, the single-TEC method had the worst error rate and degree of error. We deployed two multi-TEC methods: Amplification set all TECs to the same temperature, with the temperature indicating the system state; Quantification used the number of TECs set to hot or cold to indicate the state. The error rate and degree of error for Amplification were significantly lower than the Single method. Quantification was superior to the Single method but had higher error rates than Amplification. However, there was no significant difference in degree of error between the two multi-TEC methods.

Temperature without a message context gave arousal reactions but did not provide valence. Warm temperatures were perceived as more arousing than cool temperatures. For valence, message content was highly effective, and heat was ineffective. Temperature exerted a discernable and reliable effect on arousal when paired with neutral messages. This effect was also seen when paired with low and high arousal messages, providing a similar influence on arousal to text. No reliable interaction effect was found between temperature and message for arousal.

Thermal signals portrayed emotional arousal to participants as effectively as text. We suggest two areas where this feedback may be useful. Those with cognitive impairments, such as Autism, which impede their sense of emotional message content, could potentially benefit. Thermal cues could allow them to sense that a message is, for example, intended to excite them. Another possible application is education, where language learning could be reinforced by augmenting foreign sentences with temperature, which are mapped to intended emotional meanings of words.

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Heat-Nav: Using Temperature Changes as Navigational Cues

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ABSTRACT

HCI is increasingly exploring how temperature can be used as an interaction modality. One challenge is that temperature changes are perceived over the course of seconds. This can be attributed to both the slow response time of skin thermoreceptors and the latency of the technology used to heat and cool the skin. For this reason, thermal cues are typically used to communicate single states, such as an emotion, and then there is a pause of tens of seconds to allow the skin to re-adapt to a neutral temperature before sending another signal. In contrast, this paper presents the first experimental demonstration that continuous temperature changes can guide behaviour: significantly improving performance in a 2D maze navigation task, without having to return to a neutral state before a new signal is sent. We discuss how continuous thermal feedback may be used for real world navigational tasks.

Author Keywords

Thermal feedback; thermal haptics; navigation

ACM Classification Keywords

H.5.2. User Interfaces – Haptic IO.

INTRODUCTION

HCI research has primarily investigated whether or not thermal cues can communicate single states, for example, an emotion, activity level or social distance [4][15][9]. In these studies, the temperature is usually reset back to neutral for tens of seconds before sending a new thermal cue, a process referred to commonly as 're-adaptation'. This is necessary as the skin slowly habituates to temperature, which can undermine how strongly the participant can detect a new stimulus. There is an open question about the usefulness of thermal feedback for guiding behaviour if it is necessary to pause for tens of seconds before a new thermal cue is presented.

The limitations of human physiology and technology present other challenges for using thermal cues to guide behaviour. The cutaneous sense of temperature is carried on nerve endings that have slow response times [6]. Incorrect perception results in sensory illusions such as 'synthetic heat, as illustrated by placing a hand on interlaced warm and cool bars, which results in a burning sensation [2]. Furthermore, thermal signals need to be sufficiently intense, otherwise it can be difficult for users to perceive them correctly, if at all [16]. As well as these human factors, there are also the limitations of thermal electric coolers (TECs), the technology used to deliver thermal feedback in most research. TECs typically have high power consumption, slow rates of change, and large heat dissipation.

However, these limitations do not render thermal feedback useless. There remains an opportunity to use this channel of communication for tasks that require feedback only every few seconds. With their low resolution and slow refresh rate, a potential advantage of thermal displays is that they do not require significant focused attention from the user and can present information in an ambient manner [17]. This paper's contribution is to experimentally demonstrate that temperature feedback can effectively guide on-going behaviour. We developed a Thermal Array Display (TAD), consisting of three TECs worn on the arm, which can display patterns of warm, cool, and neutral temperatures. This paper presents a laboratory-based experiment that demonstrates how continuous thermal feedback provided by the TAD can improve user performance in a navigation task. Unlike previous research, we did not reset the TECs to a neutral temperature prior to sending the thermal signals.

BACKGROUND

User preferences for feedback modality can vary by location and situation. While vibrotactile feedback (VTF) is effective in many situations, it is not appropriate in noise-sensitive environments, such as libraries, and is also less effective in loud and bumpy environments, like trains [3]. Thermal feedback can be silent, depending on the technology used [14], and does not require users' full attention. An in-situ evaluation of PocketNavigator [10] further identified a number of issues using VTF for navigation. Participants often found VTF irritating and they had to learn how to interpret the VTF cues. Although distraction was reduced, participants still looked frequently at their mobile displays: "our results confirm that distraction is a challenge" (pp. 7-8).

Researchers have proposed that temperature cues could also be used to guide navigation. Wettach *et al.* argued that temperature could be a good interaction modality for 'calm technologies' that provide ambient signals, particularly in the domain of navigation, as thermal cues can provide "a rough clue about the intensity of a certain signal or entity" [13 p.2]. However, no outcomes were reported from their study other than "the user was able to find her way to the destination…" [p.2]. No controlled studies have been carried out on other thermal navigation prototypes that have been developed. Lécuyer *et al*. [5] proposed a device indicating sun direction to visually impaired users, but did not evaluate the potential of using both heat and cool cues to guide navigation. Quido [1] used both thermal and VTF to guide participants towards a goal in a 2D maze. While their results showed that performance improved over time, they did not investigate the relative contribution of the two modalities to guide behaviour. Hiya-Atsu [8] investigated a spatial navigation task where users searched for an object on a computer display with a temperature augmented mouse. While all participants found the hidden objects, no details were reported about how the device was evaluated. Our aim was to address the limitations of previous research by investigating the efficacy of temperature changes to guide navigation in a controlled laboratory experiment.

HARDWARE OVERVIEW

The Thermal Array Display, or TAD, is shown in Fig. 1. It is worn on the arm and consists of three stimulators, each one comprising a TEC device (MCPE1-01708NCS, Multicomp), a thermistor (MC65F103A, Amphenol Sensors), a 6V DC fan, and a heatsink. The TECs are controlled by a Proportional-Integral-Derivative (PID) controller on an Arduino Mega 2560 micro-controller. The PID reads the thermistor and sets the output temperature by varying the voltage and direction. Voltage is powered from a 6V, 10A mains supply and is varied using a 490 Hz Pulse Width Modulated signal and smoothed using a choke inductor. A motor driver (MC33926, Pololu) controls the direction, allowing both sides of the TEC to warm up or cool down. This system enables reliable detection of smaller temperature differences than with a single TEC as it both improves error rate and degree of error significantly [11].

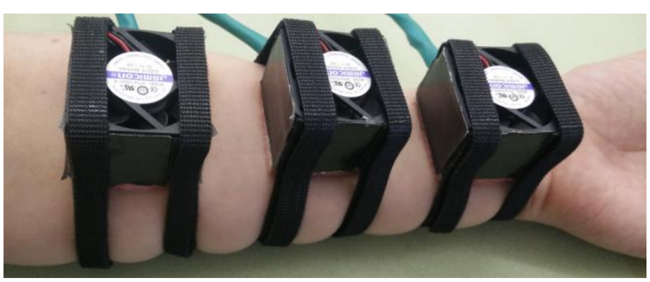

Figure 1. The Thermal Array Display consists of three stimulator units, one positioned on the wrist, one under the elbow and the other between them.

EXPERIMENT DESIGN

In the children's game 'Hot-and-Cold', a temperature metaphor is used to guide players towards the location of a hidden object. We hypothesised that actual temperature changes on the skin could provide similar proximity information in a navigation task: increasing heat could indicate getting closer to a goal; conversely, increasing cold could let a user know they are moving further away. To test this hypothesis, we developed a 2D maze navigation task and in a controlled experiment compared user navigation performance with and without thermal feedback.

A participant is represented by a red dot in a 2D maze displayed on a computer display (Fig. 2). They controlled their position by moving from one path block to an adjacent one, using the keyboard arrow keys. Participants were instructed to make as few moves as possible and to try and find the goal within a time limit of ten minutes. The goal, represented by a green dot on the screen, was hidden somewhere inside the maze, and only the local area around the player's current position was visible, the rest of the maze being blacked out. Fig. 2 shows a 3x3 block section of a maze visible to the user on screen, with the surrounding area left semi-transparent in the image—rather than blacked out—to show the maze.

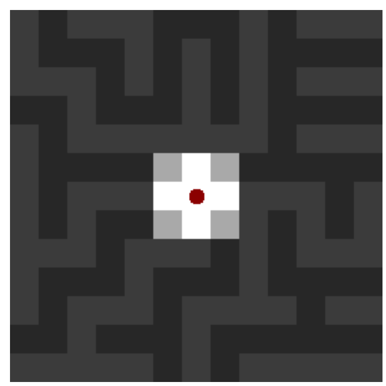

Figure 2. Participants (represented by a red dot) could only see the maze in the immediate area around their current position and the rest of the maze was blacked out (left semi-transparent in this image to show the underlying maze design).

Thermal Feedback Design

Wilson *et al.* used a temperature range of 22°C-38°C [15], a safe and comfortable zone of temperatures appropriate for thermal feedback. As our apparatus has a rate of change of about 1°C/sec, we chose feedback stimuli in the narrower range of 29°C - 35°C to minimize time taken for the TECs to reach the desired temperature.

To design effective thermal feedback for maze navigation, different techniques for correlating temperature changes with a participant's location relative to the goal were explored in pilot studies. We experimented with both *what* was being signalled and *how* it was mapped to temperature changes. We initially tried signalling the current distance from the *global* shortest path between the start and end goal. Pilot study participants found this hard to interpret and often got stuck in a region of the maze. Even if participants did get onto the globally shortest path, they would sometimes head towards the start rather than the goal.

It was more useful to signal distance from the *current* shortest path, recalculated each turn, based on the current position using breadth-first search. We experimented mapping distance from the path to a range of temperatures, with feedback getting colder the further they moved away. However, pilot study participants found these subtle temperature changes and slow rate of change confusing.

It was more effective to use only two temperatures: very warm (35°C) to indicate the participant was on the current shortest path, and very cool (29°C) for when they left the current shortest path. If the user remained on the path, feedback stayed very warm and a change in temperature only occurred if they left the path. The TAD took 6 seconds to cool from 35°C to 29°C given the latency of the TECs, but participants in the pilot usually noticed the cooling and reacted before the minimum temperature was reached. We were interested in determining whether, even with the high latency, lack of re-adaptation, and ambient style feedback, temperature changes would improve navigation in a controlled experiment using 2D mazes.

Maze Design

Several maze designs were explored to determine an appropriate size and complexity: the number of maze junctions that lead to different paths and number of moves needed to go direct from start to finish. We choose mazes of 40x40 blocks, where each block is a single move up, down, left or right. These dimensions were chosen based on the average length of time it took pilot participants to complete a maze without thermal feedback (317.8s, std. dev. 167.9s), meaning we could expect our participants to complete four mazes within an hour session. Four mazes were designed by hand, assisted by an on-line generator: http://www.billsgames.com/mazegenerator/. Each maze design consisted of the same number of junctions, contained no loops, and had a single path from the start point to the goal (global shortest path) of 245 moves.

PROCEDURE

The experiment used a within-subjects design and the order that participants experienced control and thermal feedback conditions was counterbalanced. 12 participants, 9 males and 3 females, all students in the engineering school of a UK university (mean age 31.7 years, std. dev. 6.3 years), were split into two groups. Group 1 wore the device for the first two mazes (feedback condition) and then removed it for the other two (the control condition). Group 2 did not wear the device for the first two mazes and wore it for the last two. In the control condition, a participant had to reach the goal location without any guidance; in the feedback condition, they were provided with thermal cues that informed them whether they were on (very warm) or off (very cool) the local shortest path. Mazes were completed in a pre-determined, randomized order, unique to each participant.

Before navigating any mazes, participants were given written and oral instructions to ensure they understood what the thermal feedback signified and how the controls worked. Participants wore earplugs due to audible sounds from the inductors, as confirmed in the pilots. Before each of the two mazes in the feedback condition started, their skin was re-adapted to a neutral temperature (32°C). However, re-adaptation only occurred before participants started each maze and not while they were navigating the maze.

The time taken to reach the goal and the number of moves made were recorded for each maze. If a participant did not complete the maze within the time limit, they were 'timed out' and a cap time of 10 minutes was used. Every move was logged so that we could generate heat maps of participants' behaviour with and without thermal feedback. After the four mazes were completed, each participant was interviewed about their experience with the thermal feedback.

RESULTS

The mean time to complete mazes with thermal feedback was 249.0s, (std. dev. 115.6s); in the control condition, it was 358.5s, (std. dev. 165.3s). The mean number of moves taken with feedback was 593.5 (std. dev. 321.4); the control condition mean was 1396.0 (std. dev. 577.7). Participants tended to slow down when using thermal cues: on average 2.4 moves per second (mps) were made in the feedback case, whereas 3.9 mps were made in the control condition.

As the data were non-normal, we used a Mann-Whitney non-parametric test to compare performance in the two conditions. This produced $U_a=413.5$, $z=-2.58$, $p=0.0049$ (one sided) when comparing times. Applying the same test to the number of turns taken produced $U_a=537$, $z=-5.12$, $p<0.0001$ (one-sided). Thermal feedback, while of relatively long latency, strongly reduced maze solution time. The low time-out rate across the two conditions did not permit a valid statistical comparison, but the relative counts of 5 (control) versus 1 (thermal) are consistent with the improved performance of using thermal feedback.

In interviews, every participant reported that they understood the thermal feedback and found it easier to find the target with temperature cues: "the temperature feedback helped me to predict where the target was" [P11]; "it's like a guide to the right path" [P6]. All participants reported that the temperatures were comfortable, P12 said "it was at a level that lets you just feel it". Participants used temperature changes, rather than the absence or presence of feedback to guide their navigation: P3 reporting "it's not too hot or cold but there's enough of a difference to tell them apart." Some participants emphasised it had taken time to learn the feedback, P5 saying "once I got used to it, I went a bit slower". There is statistical evidence of a learning effect between the first and second maze. Discarding all pairs that include an unsuccessful attempt (timed out), the average time using thermal feedback fell from 248.2s to 198.0s (std. dev. 75.0s); in the control condition, performance was 355.3s vs 337.3s. The latter was not significant. Improvement with thermal guidance was normally distributed and a pair-wise t-test proved significant (p=0.01, t=2.65, df=2).

Fig. 3 shows 'heat maps' for Maze #2: the start position is bottom right and the target is bottom left. The left image shows P6's moves without thermal feedback, using a strategy they described as, "just try all available paths – some of the paths, I visited them 3 or 4 times". Seven participants reported using this 'exploration' strategy in the control condition. Two reported that they did this systematically—e.g. always turning the same direction at a junction—while others admitted they were more random. Three users said they tried to memorise the maze, but P5 admitted, "I tried to remember the junctions but it was too difficult". Fig. 3 (middle) shows P4 navigating with thermal feedback and it can be compared to the global shortest path shown in blue (right). Thermal feedback reduced exploration of the maze, indicating when participants left the path and thereby reduced their exploration of blind alleys. However, some participants still turned in the wrong direction at some junctions and took some time to return to the correct path. P8 said "sometimes I couldn't distinguish the difference so I had to continue further to understand is it cold or warm". Participants had to learn to adapt to the latency of the feedback, by slowing movements and seeing how the temperature changed when they took a certain path. P10 expressed frustration that they "had to keep turning around" and expressed a preference for navigation cues that more actively guided them, rather than feedback after the path was left. P1 was more comfortable with the ambient feedback, saying "[you] can't always rely just on temperature – it's more of a complementary hint – I still need to trace the maze in my head".

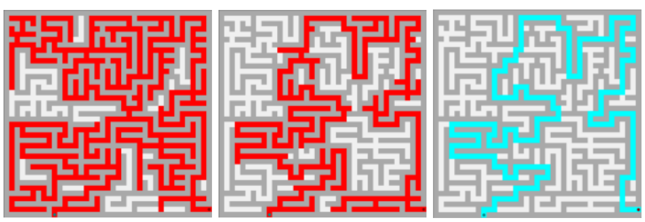

Figure 3: Heat Maps for Maze #2. Left: P6's moves without thermal feedback; Middle: P4's moves with thermal feedback; Right: the global shortest path from start to end.

We asked participants if they felt the thermal feedback could be useful for pedestrian navigation, and all agreed it could be. Two said the device would have to be smaller. The subtlety of the feedback gave rise to differing opinions on how useful it would be in a real-world environment, with three participants suggesting that VTF might be more effective and one stating that, "with this system you will be able to look around" [P3].

DISCUSSION

Given the high latency of the feedback provided to participants, how were they able to use temperature information to improve navigation? First, the feedback was simple to understand, using a warm temperature to inform participants that they were on the right path and a decrease in temperature only when they left the shortest local path. Second, though it took six seconds for the TAD to change between the warmest and the coolest temperature, most participants detected the temperature change before the extremes were reached. Participants all found the feedback useful, but they needed to initially learn how to interpret the temperature changes.

The feedback is similar to a method previously used to successfully guide a complex real-time behaviour using VTF, specifically the bowing action of children learning the violin, who were 'buzzed' when their bow left the desired trajectory [7]. A key difference is that participants reported using both the thermal cues to navigate, rather than relying on the absence or presence of feedback. Future work can explore how the TAD could provide more complex thermal signals to indicate direction as well as the distance from the optimal path.

Our results are particularly relevant for the design of mobile interfaces for pedestrian navigation. Continuous thermal feedback could provide ambient cues for pedestrian exploration of urban areas. It could indicate both a route to follow and the presence of points of interest while tourists can focus on their environment, rather than their mobiles, and make serendipitous discoveries [12]. Given the slower speed that people walk compared to the rate at which participants could move around the maze, the high latency of the feedback may be less of an issue for real-world pedestrian navigation. Temperature could also potentially provide anticipatory navigation cues for drivers, as some drivers' seats and steering wheels already have heating elements built in, although it's not immediately clear whether they would be suitable for communicating salient temperature cues. Future work will investigate whether our findings will transfer to noisy and challenging real world environments [16].

More generally, the interview data suggests the potential of using temperature to convey ambient information - a sensory channel that stays in the periphery of a users' attention and only shifts to the centre of attention when necessary. Whether thermal cues are less distracting than other feedback modalities needs verification, but our participants reported barely feeling them.

CONCLUSION

Our controlled study demonstrates the effectiveness of continuous thermal feedback for guiding behaviour, without having to pause between signals to re-adapt the skin. In contrast to previous work that only demonstrated the potential of temperature for guiding navigation, we provide the first experimental evaluation of simple thermal cues for guiding navigation in a 2D maze. Given the latency of the thermal feedback and lack of re-adaptation between signals, it was not clear whether it would be effective, but our results show thermal feedback enhances navigation performance in a 2D maze task, compared to when there is no feedback.

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