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Enhancing User Experience with Olfaction in Virtual Reality

Marius Hans Braun

A dissertation submitted in partial fulfilment

of the requirements for the degree of

Doctor of Philosophy

of

City, University of London

Centre for Human-Computer Interaction Design

Department of Computer Science

May 2019

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Acknowledgements

It is unlikely that this thesis would have been completed without the support of a number of people around during the time of writing. First of all I wish to thank, with my sincere gratitude, my unusually long list of supervisors, in chronological order rather than trying to rank them by influence on the work: Adrian Cheok, who did not see this thesis to its completion but without whom I would not have had a chance to begin it; George Buchanan, who was on my side whenever there were difficulties; Dympna O'Sullivan, who supported me through a period that saw fundamental changes to the direction of my PhD; Jon Bird, who was incredibly motivating and steered this ship onward until the finish line; and Simone Stumpf, who kindly agreed to take over the reins during the final stretch. While the repeated change in supervisors of course created challenges, it also gave me the opportunity to have my thesis considered, aided, and commented on by all of these insightful people, for which I am grateful. I wish to say thank you to my peers and colleagues who shared some of the PhD experiences with me, most of all Jordan and Gilang, for topical discussions as well as fun and comradery around the work. I am also thankful for the wonderful support and friendship from Stuart. To my friends, especially Robert and Mio, with whom I experienced PhD and start-up life to the fullest, which truly shaped my future work: thank you so much for all the help, the ideas, and of course the distractions also. An especially resounding thank you must go to Hannah, who read many drafts and versions of the 'stink-IT research study' and helped with brilliant ideas and critique but also created a supporting space both for work and at home which allowed me to experience the PhD more happily and less stressful than it would have been without her. To finish I thank my family: overall, nobody has done more in my life to get me to this point than Hans and Johanna but also Laura, for listening, for pushing, for steering me in the proper direction from afar. By extension this includes Ulrike, for the constant support and advise and the creation of a third home to go back to, and by historical extension my grandparents, too.

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Abstract

Human experiences in the physical world are inherently multi-modal, in that we rely on all our senses to perceive our environment, yet experiences within virtual reality (VR) are mainly restricted to our primary senses of vision and audition. The sense of smell (olfaction) has been shown to strongly affect human emotions, memories, and behaviour, but there have only been few attempts to integrate olfactory stimuli into virtual environments. This thesis investigates the addition of olfaction as a modality for VR to enhance user experiences through odour-emitting virtual objects and olfactory notifications. As part of this research, I introduce a systematic methodology for odour selection, and develop an off-the-shelf, affordable device for odour display (olfactory display) for VR head-mounted displays. My research begins with a preliminary study examining the effect of olfactory stimuli on participants' emotional perception of digital images, which was used as a test-bed for gaining insights into the use of olfactory displays and olfaction in a HCI setting. I then report on three empirical studies that examine how olfactory cues can enhance user experience in VR in terms of three key metrics: the quality of experience, task performance, and the sense of presence, which is the feeling of 'being there' in the virtual environment. The results from these three studies indicated that congruent, pleasant odours could significantly enhance quality of experience, improve task performance, and to varying degrees increase the sense of presence in VR. Incongruent, pleasant odours however often caused confusion among participants and appeared not to have a significant effect on the sense of presence but were able to improve task performance. The third of these studies also examined the use of odour notifications to enhance user experiences in VR. Participants were able to perceive and understand the olfaction-based notifications, which produced an increase in the sense of presence, quality of experience, as well as task performance. Overall, this thesis' findings support the notion that olfaction can enhance user experience in VR and it also draws attention to the importance of a systematic odour selection methodology.

Acronyms

ANS Autonomic Nervous System.

API Application Programming Interface.

GAPED Geneva Affective Picture Database.

HCI Human-Computer Interaction.

HCID Human-Computer Interaction Design.

HMD Head-Mounted Display.

IAPS International Affective Picture System.

IPQ Igroup Presence Questionnaire.

ITC-SOPI Independent Television Commission Sense of Presence Inventory.

ITU-T International Telecommunication Union.

JPQ Jennet et al. Presence Questionnaire.

Mulsemedia Multi-sensory-media.

OD Olfactory Display.

OSQ Odour Selection Questionnaire.

PGQ Post-Game Questionnaire.

Q-SIT Quick Smell Identification Test.

QoE Quality of Experience.

QoS Quality of Service.

QUALINET European Network on Quality of Experience in Multimedia Systems and Services.

VE Virtual Environment.

VR Virtual Reality.

WEIRD Western, Educated, Industrialized, Rich, and Democratic.

Chapter 1

Introduction

Every day, we rely on our sense of smell to tell us if our food has gone off, if someone has left the gas on in the kitchen or if the bakery around the corner has just taken a batch of croissants out of the oven. This sense of smell, called olfaction, also plays a major role in our emotional lives, whether it concerns recognition of a familiar person or place, the vivid recollection of a long-lost memory, or our aesthetic appreciation of the world (Herz, 2002; Jacob et al., 2002; Tafalla, 2014). Olfaction is an unusual sense in that its inputs are generally unobtrusive and can be perceived and understood without a shift of our attention to the olfactory stimulus (Sela and Sobel, 2010). In many cases, the effects of olfaction on behaviour can occur without conscious awareness (Arroyo et al., 2002; Stevenson and Attuquayefio, 2013). This stands in contrast to our more dominant senses of audition and vision, where most of our conscious attention lies. Auditory cues, for example, can be very disruptive when in public (such as from an ambulance), and to understand their meaning one must often concentrate; with visual cues, one is usually aware and actively processing an image. Odours have been shown to affect behaviour without the user always becoming actively aware of them (Arzi, Shedlesky, et al., 2012; Hatt and Dee, 2008; Rouby, 2002; Stevenson and Attuquayefio, 2013), and it has been proposed that contrary to common belief, humans have an acute sense of smell (Shepherd, 2004) and are able to distinguish more than 1 trillion olfactory stimuli (Bushdid et al., 2014).

These properties of olfaction bear great potential for Human-Computer Interaction (HCI): a keen sense of smell means that cues can be easily noted; the unobtrusiveness of the sense means it can be used in mentally demanding applications, such as those found in Virtual Reality (VR) , without distracting from a main task, while its properties as a powerful trigger for memories and its ability to modulate moods and emotions suggest that it may prove potent for affective computing. It is because of these traits that olfaction should be considered a valuable modality for HCI. Prior work has proposed smell as a sensory modality in HCI to reinforce or train behaviour, to alter moods or emotions, as a notification or reminder tool, to share or enhance experiences, as well as in combination with other technology (Garcia-Ruiz et al., 2008; Murray, Lee, et al., 2016a; Obrist et al., 2014). Given these opportunities of olfaction, in this thesis I explore the possibilities of using odours to enhance user experiences in a VR context.

Despite these properties, compared to other senses, such as vision and touch, there has been little research in HCI into the use of olfaction as a modality, although this has been increasing in recent years. Studies to date give a promising indication for the potential use of olfactory stimuli in digital applications such as VR (see Section 3.4.4), notification systems (see Section 3.4.6), and in enhancing user-perceived Quality of Experience (QoE) (see Section 3.4.1. An issue with previous work is that it remains difficult to judge how generalisable individual results are, due to the often-lacking description of odours used, missing descriptions of the odour selection process and due to the stark differences in the technology used to display the odours. The key areas of research on the use of olfaction as a modality in HCI are as follows: the effect of olfaction on QoE with a focus on odour-synchronised multimedia (Ghinea and Ademoye, 2010b; Murray, Lee, et al., 2014; Murray, Qiao, et al., 2013a); olfaction based notification systems (Arroyo et al., 2002; Bodnar et al., 2004; J. N. Kaye, 2001); the effects of odours on recall and memory (Ademoye and Ghinea, 2013; Brewster et al., 2006; Ghinea and Ademoye, 2009); and on the crossmodal effects of olfaction when used in conjunction with other interaction modalities (Brkic et al., 2009; Narumi, Nishizaka, et al., 2011; Richard et al., 2006). Due to a recent resurgence in research in the field of VR, brought on by maturing and more affordable technology, the effect of olfaction on the subjective perception of VR environments has become a topic of interest (Baus and Bouchard, 2017; Dinh et al., 1999; Egan et al., 2017; Jones et al., 2004). The properties of olfaction, specifically to be able to affect behaviour and perception without requiring direct user attention, seem very appropriate for VR in general but more specifically in enhancing the sense of presence in VR (Barfield and Danas, 1996). Presence is generally seen as the defining feature of VR (Steuer, 1992) and refers to the subjective sense of being in one place or environment, while physically being in another, or the sense of 'being there' (Witmer and Singer, 1998). Two of the main factors contributing to the perception of presence in VR are the sensory factor (the degree of sensory fidelity and accuracy in terms of the information presented to a person's senses) and the realism or believability factor of a Virtual Environment (VE) (Witmer and Singer, 1998). Both the sensory and realism factor should be directly affectable by the sense of olfaction, however research that demonstrates this relationship is sparse and results have been contradictory. As a matter of fact, only one study to date has been able to show that olfaction can enhance the sense of presence in VR (Baus and Bouchard, 2017). Baus and Bouchard (2017) showed that when participants were exposed to an unpleasant odour (urine) while exploring a virtual apartment, they perceived a significantly stronger sense of presence compared to those that were not exposed to the odour. However, other studies, where odours of an unspecified pleasantness were used, reported that the sense of presence was not significantly affected by olfaction (Dinh et al., 1999; Egan et al., 2017). The exact relationship between olfaction and the sense of presence remains undefined and these negative results seem counter intuitive as the addition of a new sensory modality to VR should, by all definitions, increase the sense of presence in VR. While this may seem like a testament against the suitability of olfaction in VR, this thesis argues that it is a manifestation of issues associated with the selection of odours as well as olfactory display technology. The latter is not only an issue in the field of VR, but is prevalent with the use of olfaction as an interaction medium in HCI.

One of the contributing issues to this problem is the lack of clearly defined terms used to describe olfactory stimuli and their perception. When we register, or experience smell, we experience a scent or odour, which is usually induced by an external odorant - a volatile chemical substance, which can evoke an odour experience. In HCI literature, the term scent is often used to describe both the experience as well as the chemical or substance that induces the experience, bringing with it a certain amount of ambiguity. However, neither term is precisely defined in HCI literature, their meaning being implied by the context alone, with scent often referring to both the odour and odorant. For the purpose of my thesis, I will mainly use the term odour, and at times, for quotations, the word scent - these two terms are used interchangeably in this work, based on the following definition:

An odour or scent is an individual's experience of a chemical substance called an odorant.

An odorant is a volatile chemical substance, a single or a mixed compound, which can evoke the experience of an odour.

In some of the earliest work on the use of olfaction in a HCI context, Kaye argues that there are a number of issues with olfaction research in HCI, namely "technical difficulties in emitting scent on demand, chemical difficulties in creating accurate and pleasant scents, and issues of research focus and direction" (J. J. Kaye, 2004, p. 50), issues which have not been adequately addressed to date (Murray, Lee, et al., 2016a). Accompanying these technical difficulties in displaying odours is a general lack of odour selection methodology. To date there is no systematic method that guides researchers in terms of how to select appropriate odours for research scenarios; instead researchers have developed a range of methods, not all of which are systematic in terms of selecting which odours to use. This has caused a wide array of issues across the board, such as the problem of odours that are not noticed by participants at all, odours that are difficult to identify, odours that are perceived as unpleasant, and odours that are perceived very differently by each participant (Arroyo et al., 2002; Bodnar et al., 2004; Brewster et al., 2006; J. N. Kaye, 2001). To tackle these general problems in odour selection, in my thesis I develop a systematic odour selection methodology, basing the selection process on the basic dimensions of olfactory perception, namely intensity, valence (pleasantness) and, familiarity, which define how we perceive odours. These dimensions are discussed in Section 3.3.1, while the selection methodology is discussed and described in Section 5.5.

In previous research, issues in odour selection were often paired with problems caused by the display of the odours through an Olfactory Display (OD). ODs are pieces of technology that essentially disperse volatile chemical substances, i.e. an odorant, in a user's vicinity so that they can perceive smell as part of a computer driven application. Issues associated with the use of ODs include prominent and recurring examples such as odours lingering in the room, the unwanted mixing of odours, and changing intensities of odours throughout the experiment (Brewster et al., 2006; J. N. Kaye, 2001; Nakamoto and Yoshikawa, 2006). Because of this, in recent years, a large focus of olfaction-based research has been on the development of novel ODs which exert far greater control over the amount and intensity of odour that is released. In addition, these technologies have become mobile (Emsenhuber, 2011) and can be integrated into other appliances, such as LCD screens (Hodson, 2013) or mobile gadgets (ChatPerf Inc., 2014). They also have become more affordable over time. However, especially for VR, olfactory displays are still lacking in various areas, are often associated with great cost, and are often based on dispersing ambient odours, which fill an entire room with an odour, causing odours to linger, which is not suitable for quick changes or multiple odours. Others try to circumvent this issue by requiring participants to wear a mask and flush out leftover odours with fresh air, effectively eliminating lingering odours (Ischer et al., 2014). This approach however is associated with high costs, requires specialised equipment to be installed in a large room, can be cumbersome for participants and may even be detrimental to the perception of presence as it potentially reminds participants of the real world. To date there is still no affordable, off-the-shelf OD for VR, which displays odours quickly, prevents lingering odours, and which is not cumbersome for participants or potentially intrudes on their experience. In order to deal with these issues, I develop and test a novel OD as part of this PhD project.

The focus on the development of novel technologies has however also been a limiting factor in olfaction research in HCI: with most researchers being more concerned with new technological developments, exploring the characteristics of odours and their effects on users has taken a secondary role. This is despite cues from other disciplines pointing towards promising research gaps, which are discussed in Section 3.2. As noted by Obrist et al. (2014), odours used in previous studies were often not directly connected to experiences but were chosen at random, and due to issues in odour selection these studies have often remained quite general. The authors suggest a shift in research direction, by designing specific experiences with olfaction and then linking them to technology. With maturing technology, it may be possible for this progress to occur, however, we need to understand much better the aspects of olfaction that have a decisive impact on user experience to be able to design for them effectively. A large portion of my thesis is dedicated to this purpose specifically, to add to our understanding of smell congruence, an issue which was identified as important in influencing user perception in previous works in other disciplines such as crossmodal perception (Laurienti et al., 2004; Seo and Hummel, 2011), but is not yet well understood in HCI, with a few exceptions (Covaci et al., 2018; Ranasinghe, Eason Wai Tung, et al., 2018) and has not been researched at all in a VR context and may at least partially answer why existing research in terms of the effect of olfaction on the perceived degree of presence in VR has been contradictory and inconclusive.

In my thesis, I add to the growing research on the potential of olfaction in enhancing user experience in VR. I do this by conducting four research studies. Based on the results and experiences gained from the exploratory Study One, I develop a method for odour selection, as well as a novel OD for VEs, both of which I use and evaluate in studies Two, Three and Four. I further explore how olfaction can enhance user experience in VR by conducting a study (Study Two) on the effect of pleasant, congruent odours on the sense of presence in VR, a study (Study Three) on the effect of pleasant, incongruent odours on the sense of presence in VR, and a fourth study (Study Four) in which I examine the effectiveness of odour notifications in VR towards enhancing user experience. In combination, my studies add to the growing body of research on the use of olfaction as a sensory modality in HCI by further narrowing down the olfactory factors influencing user behaviour and perception when utilising odours as a tool to improve user experience.

The research objectives of this PhD thesis are thus:

OBJ1. To develop and test a method for odour selection.

OBJ2. To develop an olfactory display for virtual environments.

OBJ3. To investigate how olfaction can affect the user experience in virtual reality.

1.1 Research Questions

To examine the effect of olfactory stimuli on participants' user experience in VR, this thesis aimed to address the following research questions:

RQ_0 - Main RQ *In what ways can odours be used to enhance user experience in virtual reality?*

RQ_1 *How does congruence of odour affect presence in virtual reality?*

RQ_2 *How do odours affect task performance in virtual reality?*

RQ_3 *Are olfactory notifications effective in virtual reality?*

1.2 PhD Journey and Direction

While the focus of this PhD is on the effect of olfaction on the user experience in VR, it was initially set out with the motivation to explore the use of olfaction for affective computing. Because of this, a first exploratory study was conducted that examined the effect of olfaction on the emotional perception of digital images on a mobile device. The study is described in Chapter 4 and answers the following exploratory research question:

$RQ_{exploratory}$ *Do odours affect the emotional perception of digital images?*

Following the completion and during the write up of this first study, I changed direction in my PhD due to a variety of factors. Gaining likely evidence that odours could affect emotion and perception, and by reading up on the existing literature in this field for the background chapter of this first study, I became interested in other potential applications of odours, namely, to enhance user experiences. Around the same time, two external factors changed for my PhD:

for one, my supervisory team and research conditions changed as my original main supervisors Prof Cheok and Dr Buchanan left City, University of London and with them went a variety of equipment that I had used and intended to use in future studies, as well as their expertise on the subject. Secondly, recent developments in VR at the time, had brought with it a new generation of Head-Mounted Display (HMD)s, with high-resolution, high fidelity displays as well as highly accurate head- and hand-tracking. As discussed in this introduction, the field of olfaction in VR is very underexplored, making it an enticing area of study. This coincided with the City Interaction Laboratory purchasing a set of said new VR HMDs, therefore VR experiments became possible for me.

1.3 Contributions

The below list of contributions is given in order of their relative importance, with the first being most important.

OBJ_3 To investigate how olfaction can affect the user experience in VR. The most important contributions of this thesis were a result of this objective.

1. **Congruent pleasant odours increase a sense of presence in VR:**
   One of the main contributions of this thesis is novel empirical evidence which adds support to the argument that congruent pleasant odours can increase the sense of presence in VR. The addition of odours to VR should theoretically enhance the sense of presence by increasing the spectrum of sensory stimulation, thereby providing a more realistic experience that is more consistent with our real-world experiences. In two studies that examine the congruence of odours and VR content, the results indicate that congruent, pleasant odours appear to increase the sense of presence in VR. Whereas a second study on incongruent, pleasant odours produced results indicating that these would not affect the sense of presence in VR.

2. **Pleasant odours can increase interactions with virtual objects:**
   In my studies, pleasant odours emitted by virtual objects were seen to increase interaction with the object, regardless of congruence with the object. My studies showed that when virtual objects were associated with the release of pleasant odours, regardless of whether this odour was perceived as congruent or incongruent with the object, then participants interacted with them significantly more than they did with non-odour emitting virtual objects.

3. **Odours can be effective VR notifications:**

   A further contribution of the thesis is the finding that within the framework of my experiment set-up, odours proved to be effective as VR notification tools and did not divert attention from the main task. Odour perception mostly occurs on a subconscious level, meaning that we do not have to shift our attention to process the perception of an odour. In a VR-based study I demonstrated that odours could be used as notifications in two ways. First, as a direct notification - users were notified of the presence of an object in their vicinity. Second, to reinforce a primary notification delivered in a different sensory modality - to reinforce a visual notification on a person's virtual wrist that they had to perform a certain sequence of movements. Both types of odour notification were effective and resulted in a change of behaviour that increased task performance in the user experiment, indicating that the odour notifications were noticed, correctly identified and understood by the users.

4. **Odours can affect the emotional perception of digital images:** This thesis also makes a contribution of knowledge about the effect of odours on emotional responses, namely that they appear capable of altering them. Odours have the ability to affect a person's emotions, for example, to change a person's judgement of the attractiveness of human faces (Dematte et al., 2007). In a study on the effects of valence of odour on the emotional perception of digital images, I demonstrated that negative odours affect a person's perception of an image, changing how they rate the valence and arousal of the images. These results emerged during an exploratory study on the use of odours in a broader HCI context, and were not related to VR specifically. The importance of this contribution is therefore minor when compared to the other contributions of this thesis, including those from the remaining objectives.

OBJ$_1$ To develop and test a method for odour selection.

1. A contribution of this thesis is the development of a method for odour selection for HCI studies. This is the first systematic method for odour selection in HCI and takes into consideration the basic factors of odour perception, such as valence, intensity, and familiarity, to ensure consistency and reproducibility of the odours. Up until

now, no concrete selection methodology has existed which means that it is difficult, if not impossible, to reproduce odour-based studies, as the properties of the odorants are not systematically recorded.

OBJ$_2$ To develop an olfactory display for VEs.

1. Currently, commercially available ODs for VR systems are both expensive and limited in their delivery of odorants. The system developed in this thesis tackles current shortcomings and is based on an off-the shelf piezoelectric atomizer. The atomizer can vaporise liquid based odorants in minute quantities; <0.01 ml of odorant is vaporised in a single puff. This mostly prevents the odours from lingering in the environment. The OD delivers odorants directly to a person's nose, even with swift head-motions. Finally, the OD costs less than £20, reducing the cost barrier and providing an easy solution to add odours to any headset-based VR system. The OD was assembled using a combination of readily available technology.

1.4 Thesis Outline

Following this introductory chapter, the thesis starts out with a literature review in Chapter 3: *Literature Review*. The chapter is divided into three major sections, covering the psychology and physiology of the sense of smell (Section 3.2), uses of the sense of smell in Human-Computer Interaction (HCI) (Section 3.4), in which I discuss the concepts of Quality of Experience (QoE) (Section 3.4.1), presence (Section 3.4.4.1), and congruence (Section 3.4.4.1), as well as olfactory display (OD) technologies (Section 3.5).

The literature review is followed by Chapter 4: *Study One*, which reports on an exploratory study on the effect of odours on the emotional perception of digital images. The study was conducted with the aim of examining the effect of odours on the emotional perception of digital images and the procedural aim of gaining an understanding of how to better approach odour selection and to trial a novel type of OD. The chapter first describes a pilot study (Section 4.2), and then reports the details of a user-based study which answers the research question. The chapter concludes with a discussion of the insights gained in regard to the OD and odour selection methodology.

Chapter 5: *Instrumentation*, describes the common instruments and methods used in the main study of this thesis. The chapter describes the VR setup, including VR headset, sensors and controllers (Section 5.3) and the virtual environment (VE) based on game *The Climb* (Section 5.2). The chapter then describes a novel OD for VR headsets (Section 5.4), followed by a systematic method of odour selection (Section 5.5). The chapter concludes with the details of the questionnaires used to assess user experience of the VE, in terms of QoE and sense of presence (Section 5.6.1).

The Instrumentation chapter is followed by the Main Study, which examines how odours can enhance user experience in VR. The study has three separate parts, which are reported on in Chapters 6 (Main Study, Part One), 7 (Main Study, Part Two), and 8 (Main Study, Part Three). The parts each evaluate the effect of olfactory cues on the sense of presence, QoE and task performance, but under a different condition. The conditions are the exposure to congruent, pleasant odours as emitted by virtual objects for Part One (Chapter 6), the exposure to incongruent, pleasant odours as emitted by virtual objects for Part Two (Chapter 7), and the exposure to congruent, pleasant odours, emitted as olfactory notifications for Part Three (Chapter 8). For ease of distinction and to avoid confusion with the exploratory Study One, from now on these parts will be labelled Study Two (Main Study, Part One), Study Three (Main Study, Part Two), and Study Four (Main Study, Part Three).

Chapter 6: *Study Two*, examines how congruent, pleasant odours affect the sense of presence, QoE, and task performance in VR. The chapter describes an odour selection task (Section 6.2), which implements the methods of the odour selection method described in the previous chapter (Section 5.5). The odours from the selection task are used in a user-based study, where participants are given the task to find and interact with as many flowers in the mountain-climbing VR game *The Climb* (Section 6.4). The results of this study are given in Section 6.5, which is followed by a discussion of these results in Section 6.6.

Chapter 7: *Study Three*, replicated Study Two closely but instead of using congruent, pleasant odours it explored the effect of incongruent, pleasant odours on the sense of presence, QoE and task performance in VR. The chapter first describes an odour selection task (Section 7.2), which is followed by the details of a user based study (Section 7.3). The results of this study are given in Section 7.4, which is followed by a discussion of these results in Section 7.5. The chapter concludes reports the results of a statistical analysis between the results of Study Two and Study Three, which are reported in Section 7.6.

Chapter 8: *Study Four*, replicated Study Two and Three in its methodology, but assessed how the exposure to congruent, pleasant odours delivered as olfactory notifications affects the sense of presence, QoE and task performance in VR. The chapter first reports on an odour selection task (Section 8.3), followed by the details of a user based study (Section 8.4). The detailed results of the study are presented in Section 8.5, which is followed by a discussion of these results in terms of the research questions and hypotheses of the study (Section 8.6).

Chapter 9: *Discussion*, summarises the research contributions of this thesis by reviewing the findings from the empirical studies conducted as part of this PhD research project. The chapter then discusses the limitations to the work, and concludes this thesis with future research in this area of olfaction enhanced VR.

Chapter 2

Research Methods

2.1 Introduction

In this short chapter I discuss my methodological approach and which schools of thought my research falls into. I briefly consider positivism and social constructionism and then elaborate how my own work draws on these large theoretical schools of thought (or does not) and more specifically which aspects and approaches from the different methods I have used.

2.2 Research Methods

Broadly, both positivism and social constructionism engage with quantitative and qualitative research quantitative research is most common in positivism, and social constructionism often uses qualitative research, but there are exceptions (Alvesson and Sköldberg, 2018b).

Positivism states that specific types of knowledge (positive knowledge) are based on observable natural facts or phenomena, and information from experience only can form the source of knowledge. Another way to express this is by gathering evidence - positivism is therefore based on empirical evidence, or empiricism. K. A. Goodwin and C. J. Goodwin (2016) define empirical research as approaches that try to produce understanding and further knowledge by directly or indirectly observing a subject matter. Common methods of positivist research deal with the comparison of data, often in a statistical manner. It is wrong to assume that positivism is only 'about facts', or only concerned with facts - in fact Nietzsche once argued that facts are "precisely what there is not, only interpretations" (Alvesson and Sköldberg, 2018a, p. 16) in brief, positivism is an interpretation of theory or science based on data collection or observation in the real-world but interpreted through logical reason. In positivism, knowledge is created through data, and theories are just connections and systems created by us between data points and to order them.

Most HCI research that examined olfaction has been conducted with a positivist, quantitative approach, with studies focusing largely on collecting questionnaire data that is then analysed statistically to determine whether odours significantly affect various metrics. My research mainly follows in this path as I based both my literature review and hypotheses on these previous studies and chose to follow a positive, empirical approach with several quantitative data with my own experiments. I do however, deviate from a purely classical positivist approach and incorporate lessons from social constructionism, which I will discuss within the following few paragraphs.

In social constructionism, any reality or factual situation is socially constructed, implying that there is no ground truth to be discovered as is the case with positivism (Berger and Luckmann, 1966). This theory or philosophy acknowledges and tries to examine the creation of (jointly not individually) constructed views or understandings of our reality which are underlying any assumption one can make about how the world works. All knowledge is linked entirely to human interpretation and social constructions of understanding and should not surpass these. It is important to the theory that this is a shared human activity and not individualistic, it is only by interaction with other humans or human institutions that such assumptions become strong enough to become constructionist understandings underlying our observations and interpretations. Simply put, many things are only real to us because we collectively assume them to be so. For example, one standard example of this is money - the only reason why dirty slips of paper or previously shells and more recently long numbers typed out on a screen hold such immense value to humans is because we all agree them to be important and enshrined such importance in laws and institutions.

My work in observing the effect of olfaction on VR experiences is empirical, rather than critical, since I do not question the very foundations of either field. However, I do allow for the notion and elaborate (see Section 3.3) that there is no direct generalisable correlation between a human's experience of an odour and a reaction e.g. a memory or a change to the sense presence; because olfaction is highly subjective and also because there is no universally agreed classification of odours in the first place. In this sense, I am allowing for a diversion from a strict empirical, positivist and quantitative approach and acknowledging that human responses and emotions around odours are constructed. However, I am not closely linked to constructionism in that I expressly do not consider exclusively a shared construction of olfaction, although these do exist, large groups of people have been found to react positively to the smell or fresh bread in supermarkets for example, but that I also allow for very individual construction of connections between odours and experiences. In this regard my approach can also be called 'interpretivist' because it relies on observations as well as interviews to really understand the participants' experiences within the context of their experiment setting, which is the definition of interpretivism, "qualitative research concerned with understanding experiences of the person in context" (Braun and Clarke, 2013, p. 332).

My decision to incorporate this view is also based on several HCI studies on olfaction which supplement their quantitative data with qualitative results from observations. This was usually done as an addendum and not as part of the original research design or key research results. These few additions have highlighted important factors for the use of odours in HCI, such as the high degree of variability between participants in terms of their interpretation of what an odour means when they perceive it (Arroyo et al., 2002; Brewster et al., 2006), which is usually not explicitly considered a factor in these studies. In order to gain a better understanding, I therefore felt that it was necessary to expand on a purely positivist approach and to include elements from interpretivism, namely that these interpretations of an odour's meaning are constructed and that any results have to be examined in terms of the context in which they were gathered.

In my research, I therefore employ a mixed-methods approach that uses both quantitative and qualitative research methods. As I did not wish to miss out on insights due to over-reliance on a small toolset that may not have been the most suitable for a novel and underexplored area of research, such as the field of olfaction enhanced VR. Therefore, I moved towards a more open research design that included qualitative elements and allows for the formulation of new hypotheses whilst still including mostly quantitative and measurable elements designed to increase the potential for comparison and inductive generalisation.

In my thesis I use mixed methods as a form of triangulation (Denzin, 2015) to gain a fuller understanding of the relationship of odours and user experience. Whilst triangulation can strengthen analytic claims (Smith, 1996), it can also provide context to other results, providing a richer or fuller story (Braun and Clarke, 2013). My research is therefore mixed, both quantitative and qualitative: it is qualitative in that it seeks to gather and evaluate the reactions and statements of individual study participants, which I felt was especially important in a field as novel as olfaction enhanced VR. It is also quantitative in that I construct and use questionnaires with measurable answers that can be accumulated and evaluated against one another and further collect quantifiable performance data from participants during game play.

There is a further distinction in research methodology to be made between induction and deduction (King et al., 1994). Inductive approaches go from the bottom up, assuming that evidence from a number of individual cases can also be valid for a general population. Deduction is the opposite in this sense: starting from the general and aiming to verify claims or existing theories by applying them to a single case or single cases currently interesting to the research. Induction is somewhat risky, as it includes a presumptuous leap, but deduction carries that drawback that is basically already seems to know in advance the truth that it is meant to explain, and therefore does not leave much room for actually explaining a case. Despite its horrible name, abduction is a co-joint method often used in research: single cases are interpreted first from a general rule or theory like in deduction, but then this is supported by adding more cases with similar observations to strengthen and confirm the theory (such as with induction if a theory already existed). It allows for more interpretation and understanding than the other two methods and is often used to diagnose medial issue or also technical system errors (Alvesson and Sköldberg, 2018b, p. 4).

Again, with my mixed method approach I use a mixture of the above I base my hypotheses on prior results and theories, such as that odours can affect emotion, and added several experiments. These new cases at points strengthen and confirm the theory (or more the axioms as I would say there is no fully developed theory of olfaction yet) and at other points challenge it, thereby adding to our understanding of how odours affect user experience in VR.

Chapter 3

Literature Review

3.1 Introduction

In this chapter, I first cover the fundamental concepts of olfactory perception from a physiological and psychological perspective 3.2, then put my work into the context of theories and practices of the use of olfaction as a modality in HCI (Section 3.4). As part of this literature review, the concepts of Quality of Experience (QoE) (Section 3.4.1), congruence (Section 3.4.3) and presence (Section 3.4.4.1) are introduced. This is followed by a review of olfactory display (OD) technologies (Section 3.5), giving a brief history of their development and highlighting recurring issues with current systems.

3.2 How We Experience Smell

This section covers the perception of smell and its underlying physiology, to provide insights into the complexity of the sense and for a comparison with the other senses. It also serves the purpose of introducing challenges with the use of odours that have been identified in non-HCI fields, such as in psychology and neuroscience, which are also applicable to the use of odours with technology. This section further establishes how humans perceive odours, how the exposure to odours can affect our behaviour and to draw attention to any difficulties that may arise with the use of odours in an HCI setting.

3.2.1 Defining Scents and Odours

To give an impression of what is special about the sense of smell, or also called olfaction, it is necessary to provide the reader with a certain terminology. When we register, or experience smell, we experience a scent or odour, which is usually induced by an external odorant. In literature, the term scent is often used to describe both the experience as well as the chemical or substance that induces the experience, bringing with it a certain amount of ambiguity. Because of this, I will use the term scent as synonymous with odour and not with odorant. This distinction will become clearer with the below definitions of the terms. Before it is possible to discuss the application of odours and their use in HCI it is important to define what an odour is, and what it is not. In my work, I follow the definitions used by Smeets and Dijksterhuis (2014). According to them, an odour only refers to an individual's experience of a chemical substance called an odorant. An odorant is a volatile chemical substance, a single or a mixed compound, which can evoke an odour experience. An odour can therefore originate from a single type of molecule, such as benzaldehyde, which produces a cherry odour, or from a multitude of mixed chemicals, such as that of a flavourful meal. During such an experience, the odour is most likely evoked by a type of odorant, but it can also be experienced in its absence, for example through heavy suggestions or an active imagination, or both (Knasko et al., 1990; Stevenson and Wilson, 2007). The experience of an odour can also vary from person to person. An odorant can be experienced as a different odour based on a person's environment or their prior experiences and may not be experienced at all, for example through partial or complete anosmia (loss of the sense of smell). Furthermore, there is no essential relationship between the chemicals a person perceives and the odour experience that is evoked. While an odorant may consist of a plethora of compounds, we perceive this mixture as a single odour (Smeets and Dijksterhuis, 2014). While this description uses the term 'odour', the word is only rarely used in the field of HCI (J. N. Kaye, 2001; Obrist et al., 2014), where the term scent is more prevalent (Brewster et al., 2006; Ghinea and Ademoye, 2010a; Murray, Lee, et al., 2016a) As described in Section 1.1, the following definitions for the terms odour and odorant will be used throughout this thesis:

An odour or scent is an individual's experience of a chemical substance called an odorant.

An odorant is a volatile chemical substance, a single or a mixed compound, which can evoke the experience of an odour.

3.2.2 Being Aware of Odours

Humans are thought to have around one thousand different smell receptors in their nose. Each one of these receptors is able to detect the exposure to a single specific bond in a molecule (Lawless, 1997; Turin, 1996). This number is much larger than the five (or six receptors) for gustatory (taste) perception or the four (red, green, blue cones and rods) of vision. Recently, it has been found that through combination of the different smell receptors, humans can distinguish more than one trillion olfactory stimuli, demonstrating the discriminatory power and complexity of our olfactory system (Bushdid et al., 2014).

Olfaction is also unique when compared to our other senses in that it is difficult, if not impossible, to ignore on a behavioural as well as perceptual level (Smeets and Dijksterhuis, 2014). On a behavioural level for example, the odour of gas will make many check if their stove is turned off. On a perceptual level, while we may instinctively close our eyelids to shut out visual perception, the nostrils cannot be closed as easily or for long periods of time. It is possible that this is the reason why the olfactory system displays faster habituation than any other sense, acting as a protective system to escape aversive odours (Engen and Pfaffmann, 1959). It is not possible to successfully shut out the sense of smell for long periods of time, such as we may with vision during sleep, and recently the properties of smell have been proven to carry on into our subconscious during sleep, such as when researchers found that smell is able to induce or reduce a state of fear in humans while sleeping (Hatt and Dee, 2008). Nevertheless, our sense of vision is often at the forefront of our attention and many researchers consider it to be dominant; similarly, hearing is considered second in our attention, followed by the sense of touch. The sense of smell is rarely at the centre of our attention and mostly plays a subconscious rule (Köster, 2002). Because of this, the sense of smell has also been called the 'hidden sense' (Köster, 2002). As a general tendency, people are not as aware of odorants as they are of sounds or sights. This is partly due to the fact that we only perceive a physiological response to the exposure to an odorant when it is at such a high intensity that it triggers the trigeminal nerve, which innervates the nose, mouth, throat and eyes and causes sensations that range from tingling to burning. This sensation is often accompanied by a reflex backward motion of the head, such as when smelling a bad odour (Doty et al., 2004). And clearly, humans are sensitive to odours to varying degrees (Smeets, Schifferstein, et al., 2008) - some hardly notice the smoke from their own kitchen catching on fire, others cannot wear items of clothing that were washed with the wrong detergent due to over-sensitivity to its odour. For completeness, it is worth mentioning that the level of sensitivity not only varies between different humans but within the same individual. For example, pregnancy is known to cause different and sometimes violent reactions to odorants previously considered inoffensive (Leslie Cameron, 2007); bad reactions to a certain food or drink can create sensitivity to its odour that was previously non-existent. Most odorants, however, are not consciously perceived. Exceptions are few and can generally be categorised as unusually strong, pleasant or unpleasant odours. An explanation for this phenomenon is that it is due to evolutionary selection as certain odorants can alert us of dangerous situations e.g. smoke and fire (Stevenson, 2010). Smeets and Dijksterhuis (2014) define this relationship between conscious and subconscious perception of odours in terms of three levels of awareness.

1. Attentively, that means they are called out, i.e. mentioned verbally and possibly also labelled, either pinpointing the source - “I smell fish” or just noticing its odour “I can smell this thing, but I am not sure what I am smelling”.

2. Semi-attentively, that means a person notices that something is different or special but not the fact that this is due to an odour. For example, one might notice that something about a person has changed (Did they get a new haircut?) but might not be able to pinpoint exactly what has changed (They are wearing a new perfume).

3. Inattentively: the individual shows no indication that they are aware of anything but perceives the odour on a subconscious level.

While we may perceive an odorant attentively and odours may be at the centre of our attention, they do not remain there for longer periods of time due to the speed at which we adapt to odorants in our surroundings. Adaptation refers to a reduction in the response to a stimulus that occurs with repetition or continuous exposure to the stimulus (Dalton, 2000). Such peripheral adaptation is more common and much stronger for smell receptors and the sense of olfaction than that of some other senses, and it happens quickly enough to be noticeable (Dalton, 2000). For example, you may be in a classroom that you, upon entering, thought smelled somewhat stuffy but have, after some time has passed, stopped noticing. This adaption is often noticed as a decrease in perceived odour intensity and causes the odours to fade into the background of perception. However, the swiftness of adaptation and the associated decrease in conscious awareness of the odorant does not preclude the odorant from continuing to effect information processing (de Groot et al., 2012). Whilst odorants may affect our sense of smell, and humans are rarely fully aware of the odorants in their environment, this in fact is very promising for the use of odours as part of affective technology. For example, odours have been used in sleep studies to change smoking behaviour and the odours are considered to have had an impact because of the subconscious nature of the method (Arzi, Holtzman, et al., 2014). It is therefore possible to develop olfactory technology that can facilitate behavioural change. A passionate smoker who is aware that he or she is being manipulated into disliking smoking may put up resistance despite their resolution to quit smoking - if this aversion, however, is induced subconsciously, this urge to resist will likely not kick in. The olfactory sense and its unobtrusive properties could potentially be used in HCI as a notification tool that does not distract from the current task, which is challenging to accomplish with sound or vision (Bodnar et al., 2004). The very properties of olfaction that make it promising for work in HCI, specifically its aptitude at influencing behaviour, also increase the need for ethical considerations and the potential for ethical dilemma. Many previous studies exist into the benefits and drawbacks of trying to subconsciously influence human behaviour - among them the book *Nudge* by Sunstein and Thaler (2009), which treats subconscious influencing as a force for the positive. The book inspired a litany of further articles but also actual governmental committees exploring the possibilities of 'nudging' citizen behaviour to make healthier choices through restructuring the existing choice architecture, for example by the Behavioural Insights Team of the UK Government (Behavioural Insights Team, 2019). Examples of choice architecture include rearranging school cafeteria shops to make healthier options likelier to be picked than sweets, or creating work insurances that require new employees to opt out rather than to opt in. Sales tactics already exist that use odours such as the smell of fresh bread to try and alter customers' mood into a happier, hungrier or other state to increase consumption (Emsenhuber, 2009), without the shopper being consciously aware of this influence. While this may be beneficial from a sales perspective, ethical issues arise as consumers are not given the choice of whether they want to be influenced in this manner or not. A researcher therefore cannot simply assume that participants may be aware of potential influences but should ensure that they are aware of them, such as by using comprehensive consent forms. As the above examples have shown, there can be positive outcomes of using olfaction to change behaviour, such as by beating a smoking addiction, however the risks of such a technology must always be considered. Participants must therefore always give their clear consent to take part in any study, and must be aware of the purpose of any research being undertaken. Therefore, in planning my thesis, I became very aware of the ethical implications of such work and decided that best practice included following all of City, University of London's ethical clearance guidelines as detailed by the Computer Science Research Ethics Committee. Part of this included what I considered most necessary in order to forego negative issues, requiring the test participants to read through and sign a comprehensive information sheet before the experiments so that they were fully informed of the tests about to take place and the fact that odours would be administered that had the potential to affect their behaviour during the VR experience.

3.3 The Relationship of Olfaction, Memory and Emotions

Odours are known to have strong potential for triggering memories and emotions, which is sometimes called 'the Proust effect', after Marcel Proust's experience in In Search of Lost Time. Inspired by Proust and other prominent examples, researchers have since been speculating that odours may in fact be more powerful than other forms of perception in accessing emotional memory- however, since this effect often escapes awareness, it is a difficult thing to notice (Gilbert, 2008; Jellinek, 2004; Toffolo et al., 2012).

> *No sooner had the warm liquid mixed with the crumbs touched my palate than a shudder ran through me and I stopped, intent upon the extraordinary thing that was happening to me. An exquisite pleasure had invaded my senses, something isolated, detached, with no suggestion of its origin. And at once the vicissitudes of life had become indifferent to me, its disasters innocuous, its brevity illusory - this new sensation having had on me the effect which love has of filling me with a precious essence; or rather this essence was not in me it was me. ... Whence did it come? What did it mean? How could I seize and apprehend it? ... And suddenly the memory revealed itself. The taste was that of the little piece of madeleine which on Sunday mornings at Combray (because on those mornings I did not go out before mass), when I went to say good morning to her in her bedroom, my aunt Léonie used to give me, dipping it first in her own cup of tea or tisane. The sight of the little madeleine had recalled nothing to my mind before I tasted it. And all from my cup of tea.*
>
> (Proust, 1928, pp. 61-62)

Unbeknownst to Proust at the time, the effect of 'tasting' the madeleines that evoked this powerful memory was actually largely based on the odour of the pastries that was transported towards his olfactory bulb as he swallowed (J. N. Kaye, 2001). While there is an active discussion about whether the above is an example of voluntary or involuntary memory recall, the point that the memory itself was emotional and powerful cannot be contended. Olfaction has proven able to conjure powerful emotions through memories, but its capabilities as a trigger for emotions appear not simply to be bound to memories (Herz and Cupchik, 1995). Aversive smells can activate the amygdala, a portion of our brain related to emotion, even without prior exposure to the odorant. Smell outperforms visual and auditory stimuli both in terms of being able to evoke emotions and memories (Royet et al., 2000; Zald and Pardo, 1997). A study by

Alaoui-Ismaïli et al. (1997) showed that particular odours can induce emotions on both a conscious (verbal) and unconscious (physiological) level. Unconscious emotions were recorded in terms of physiological expressions of the Autonomic Nervous System (ANS) by measuring skin potential, skin temperature, skin blood flow, instantaneous respiratory frequency, and instantaneous heart rate. A clear correlation between verbal and physiological responses was found. The valence (also referred to as perceived pleasantness) of an odour allowed the authors to make predictions about the induced emotions, with a negative valence resulting in basic emotions such as disgust and anger, while positive valences produced positive emotions such as surprise and happiness. The authors were able to distinguish different autonomic patterns induced by pleasant and unpleasant odorants (Royet et al., 2000; Zald and Pardo, 1997).

While odours have a very direct connection to our memory and emotion centres, conscious processing of odours is more challenging. For example, describing odours very specifically, or translating odours into language at all, can be very difficult (Auffarth, 2013; Cain, 1979; Lawless, 1977; Wise et al., 2000). There are no comparable ways of 'showing' an odour to another person the way you might a photograph, unless the source can be identified and brought to them. Many people hence have trouble describing odours accurately. Furthermore, the vocabulary for describing odours is also less rich and less regulated and precise than images are for most people.

A potential reason for the difficulty of describing odours with words might be the poor connection between the piriform cortex, where our brain encodes how we perceive odours, and our language network (Olofsson et al., 2013). Smeets and Dijksterhuis (2014) hypothesise that this might be due to our evolutionary history. While an immediate behavioural response to odours was necessary for survival, e.g. spitting out a toxic piece of food or running away from the smell of smoke, it might not have been important to be able to name that odour. However, while humans are generally bad at naming odours, we do have immediate reactions to odorants, depending on how the odour is perceived.

3.3.1 Dimensions of Odour Perception

Humans perceive odours in terms of several dimensions. First and foremost, the primary dimension is valence, which can vary on a scale between pleasant and unpleasant and defines how much we like or dislike an odour. The determination of odour boundaries - how we perceive where one odour ends and the other begins - is tied to judgements of valence (Yeshurun and Sobel, 2010). It is considered the most important characteristic of an odour (Engen, 1982; Kaeppler and Mueller, 2013). Although there are also the dimensions of familiarity, intensity and edibility, there is no universally agreed set of dimensions of odours (Kaeppler and Mueller, 2013; Kermen et al., 2011; Wise et al., 2000). All of the above dimensions appear to fit with Stevenson's classification of major functions for the evolution of olfaction: digestion and appetite - valence and edibility, fear of environmental dangers - valence and intensity (fire, or poisonous items such as bad eggs or dead animals) and social communication - familiarity (recognising your parent's or your partner's odour) (Stevenson, 2010). Knowing your kin, avoiding rotten meat and detecting a wildfire could all boost survival from an evolutionary point of view. It should be noted that none of the above dimensions of odour perception, namely valence, intensity, familiarity and edibility, have been specifically researched in an HCI setting. Their interplay and properties remain unknown variables and further research is necessary to establish their effects on user experience. If these are established, they could be used to guide odour selection to make precise choices for intended outcomes with odour-based research in HCI.

3.3.2 Affecting Behaviour with Odours

Recent research has confirmed that odours might prove equally or even more powerful than visual stimuli at affecting behaviour (Gaillet et al., 2013; Miller and Maner, 2011). This is due to the automatic responses that occur to the exposure to certain odorants. For example, whilst the link between an odour and not drinking rotten milk may be a conscious one, the response (repulsion) is nonetheless an automatic one.

Olfaction can also be used successfully to change user goals - for example the odour of freshly baked biscuits may likely divert you from your original goal when coming to the kitchen, seeking help with homework or the like. In fact, supermarkets and shopping centres have built a business around assumptions about which odours (e.g. freshly baked bread), not only which music (e.g. pop music) tends to keep shoppers present, happy and spending (Emsenhuber, 2009). This connection between an odour and a behavioural response has also been tested and confirmed in experimental studies, for example Gaillet et al. (2013), Miller and Maner (2011).

However, drawing these kinds of semantic connections, such as between the odour of fresh bread and increased consumer behaviour, through odours is challenging. Since odours are so hard to categorise it is difficult to predict a person's exact response and even more difficult, if not impossible, to choose an odour that will always produce the intended reaction. For example, seeing an image of a big wheel of old Gouda cheese may evoke mental images of other food, other cheese, and maybe other Dutch objects, such as clogs, as soon as it has been identified and named, through conceptual links with Gouda. But it is not possible to simply expect the strong odour of old Gouda to have the same effect. Difficulties arise on various levels. Firstly, there is the level of identification. One might identify the odour as a food, and as a cheese; and hence one may be able to elicit thoughts of other cheese, or foods related to cheese. But individuals could not be counted on to recognise the odour of cheese as Gouda, or as specifically Dutch. Secondly, due to the ambiguity of the human sense of olfaction, and to the large role played by individual interpretation of an odour, the exposure to an odorant might lead to entirely unforeseen and unaccounted-for outcomes due to a person's individual memories and experiences.[1] For example, while one might recognise the odour as that of a cheese, one might remember a cheese one had in France, and think of that. One might recognise cheese, think of a cheese platter they once shared on a dinner date (this may of course have a positive or negative connotation depending on how said date went) and think of that. Variances in the perception of the cheese odour may also occur due to a person's preference for or against cheese, or Gouda, or whether they dislike it or happen to have any other preposition that may affect their perception of cheese. A person might relate a food they love or hate to other foods they love or hate, rather than the category a researcher may have intended the odour to represent. When using odours as an affective tool, these individual variances pose a clear challenge. Often, the effect of odours cannot be generalised but must be person-specific; furthermore, without additional interviews or commentary, it may become hard to draw causal inferences from participant behaviour and choices. However, what is clear is that odours must be selected carefully, taking into consideration the intended population, and this process must involve participant feedback, capturing any associations and preconceptions that they may have.

The property that we draw associations between memories and odours can also have a positive effect. For instance, it is possible to create these associations artificially by first creating a memory in a learning phase that is paired with an odour, and which can then be evoked by stimulation with that same odour (Degel and Köster, 1999). Another aspect where odour can pose as an effective tool for HCI technology is by modulating a person's mood. Previous literature has shown that judgments and decision can be influenced by a person's mood at the time they are making the decision (Schwarz and Clore, 1983, 2003). Altering a person's

[1] This example is based on de Araujo et al. (2005), and is considered by Smeets and Dijksterhuis (2014).

mood through odours they strongly like has proven effective in creating the feeling of wellbeing, such as through aromatherapy (Herz, 2009; Stevenson and Boakes, 2003). The assumption is that pleasant odours do not cause physiological changes that curb stress or promote calm, but rather that those feelings are influenced just as they would be by a good mood, which is evoked by the odour. Hence if a person likes roses, their odour might enhance their mood. In his famous research Baron (1997) showed that ambient odorant (it was baked goods, not cheese) could induce people to behave more helpfully. As the relationship between the odour of baked bread and behaving helpfully are not in a conceptual relationship that is logically sequential - why should the perception of the odour of baked bread lead to an increase in helpfulness - it is clear that a secondary affective change took place, most likely by enhancing a person's mood, i.e. a person perceives the odour of baked bread; the person enjoys the odour of baked bread and her mood improves; being in a better mood, she is more likely to behave helpfully.

The above discussion shows that there are likely strong barriers to drawing direct semantic connections with odours, but that it may serve to be a more successful tool than others when it comes to emotions and mood. Olfactory stimuli that are intended as semantic information could have unintentional secondary effects such as affecting one's mood or perception of valence, i.e. I do not like this odour, hence I do not like this person's face that I am being shown. Substantially divergent reactions from individuals are likely with this kind of stimulation, as people attach different values to memories. It is necessary to find out more about what affects the use of odours in technology: intensity, accuracy of odorant, and subjectivity. In my thesis, I add to our understanding of which factors influence the potential of olfaction in odour-enhanced technology.

3.3.3 Summary

The above section gave a concise view of current physiological and psychological research concerning the sense of smell. Beginning by giving a definition for the relevant terms of odour - an individual's experience of a chemical substance called an odorant, and odorant - a volatile chemical substance, a single or a mixed compound, which can evoke the experience of an odour, the section showed the degrees of awareness we exert to odours in our vicinity (Section 3.2.2). It also shows that our perception of odours is closely interlinked with our memories and emotions (Section 3.3), dissected the dimensions of odour perception (Section 3.3.1) and demonstrated that odours can affect our behaviour (Section 3.3.2).

3.4 Augmenting Digital Systems with Olfaction

In this section I review related research from within the field of HCI that deals with olfaction, highlighting gaps in research that need to be addressed to successfully integrate the sense of smell into HCI applications, some of which this thesis aims to resolve. A particularly challenging aspect of the use of olfaction as a sensory modality in HCI research is the fact that there is no complete understanding of human perception of olfactory cues (Murray, Lee, et al., 2016a). For a review of the findings and limitations identified in the fields of neuroscience and psychology, see Section 3.2 above. While Section 3.2 has highlighted findings on olfaction from the fields of psychology and neuroscience, the field of computing has conducted a separate research strand into the properties of olfaction. More specifically, researchers in the fields of multimedia and Multi-sensory-media (Mulsemedia), HCI and virtual reality have conducted studies on olfaction (Jones et al., 2004). The research is often based on the development of new olfactory technologies designed to fit a specific scenario or purpose (Choi, Cheok, et al., 2011; Nakamoto, Ishida, et al., 2012). Compared to other senses, such as vision and touch, there has been relatively little research into the use of olfaction as a modality for HCI. Studies to date however give a promising indication for the potential use of olfactory stimuli in digital applications such as VR (Section 3.4.4) and notification systems (Section 3.4.6), and show positive results in a variety of areas, however it is difficult to judge how generalisable individual results are, due to the often-lacking description of the odorants used, missing descriptions of the odour selection process and due to the stark differences in odour delivery. The key areas of research are as follows: the effect of olfaction on Quality of Experience (QoE) (see Section 3.4.1) with a focus on odour-synchronised multimedia (Ghinea and Ademoye, 2010b; Murray, Lee, et al., 2014; Murray, Qiao, et al., 2013a); the effects of odour on the subjective perception of VR environments (see Section 3.4.4) (Baus and Bouchard, 2017; Dinh et al., 1999; Egan et al., 2017; Jones et al., 2004); the effects of odours on recall and memory (see Section 3.4.5) (Ademoye and Ghinea, 2013; Brewster et al., 2006; Ghinea and Ademoye, 2009); olfaction based notification systems (see Section 3.4.6) (Bodnar et al., 2004; J. N. Kaye, 2001); and on the crossmodal effects of olfaction when used in conjunction with other interaction modalities (see Section 3.4.7) (Brkic et al., 2009; Narumi, Nishizaka, et al., 2011; Richard et al., 2006).

3.4.1 Odour-Enhanced Quality of Experience

There are various definitions of QoE. Its most basic definition is given by the International Telecommunication Union (ITU-T). They define QoE as "[t]he overall acceptability of an application or service, as perceived subjectively by the end-user" (ITU-T, 2007a,b). A more detailed description is offered by the European Network on Quality of Experience in Multimedia Systems and Services (QUALINET):

> ***Quality of Experience (QoE)*** *is the degree of delight or annoyance of the user of an application or service. It results from the fulfillment [sic] of his or her expectations with respect to the utility and / or enjoyment of the application or service in the light of the user's personality and current state.*
>
> (Qualinet, 2013, p. 6)

Throughout this thesis the term quality of experience (QoE) will refer to this second and more detailed description by Qualinet (2013). The aim of QoE researchers is to model human perception of multimedia experiences beyond Quality of Service (QoS) approaches (Stankiewicz et al., 2011). QoS-based research to date has focused on network and multimedia system characteristics, such as delay, loss, jitter, codecs and display capability. Although the key focus in multimedia networking research has been on maintaining network QoS control, an improvement in QoS does not necessarily translate to proportionate QoE increases (Kilkki, 2008). To capture user QoE therefore involves subjective ratings and is influenced by user behaviour and past experience, appropriateness, context, usability, and human factors, as discussed by Möller and Raake (2014). As discussed in Section 3.2 above, many of these aspects, specifically those of past experience (memory), appropriateness and context can be affected through odours, making QoE an appropriate measure to quantify and understand the influence that the addition of olfaction to multimedia can have on user experience. QoE for systems that display odours is generally measured using questionnaires that capture subjective ratings of perceived relevance of odour, sense of realism, distractions caused by the odour, annoyance caused by the odour and general enjoyment of the displayed media. Only one questionnaire has been published to date, by Ademoye and Ghinea (2009) which can be seen in Table 3.1.

The olfaction research focused on QoE has investigated a variety of factors, including the temporal synchronisation of odour and multimedia (Ghinea and Ademoye, 2010b; Murray, Lee, et al., 2014; Murray, Qiao, et al., 2013a); the congruence of audiovisual media with associated odours (Ghinea and Ademoye, 2012b); and odorants as part of multi-sensorial delivery (Yuan et al., 2015). This varied research has shown that odours may affect QoE in a variety of ways. In the following sections I will discuss the literature from each of the above areas, beginning with

Questionnaire Statement
The smell was relevant to what I was watching
The smell heightened the sense of reality whilst watching the video clip
The smell was distracting
The smell was annoying
I enjoyed watching the video clip

Table 3.1: Quality of experience questionnaire (Ademoye and Ghinea, 2009, p. 563)

the temporal synchronisation of odours and multimedia.

3.4.2 The Effect of Temporal Offsets of Odour and Audiovisual Media on Quality of Experience

In this section, there is an overview of studies that primarily investigate the effect of temporal offset and synchronisation of odours and audiovisual media on QoE. As a brief example, Huang et al. (2012a) conducted a study to evaluate changes in odour cue timing, by changing the point at which an odorant is released when a person moves their head close to a virtual odour-emitting object. Their results show that when the odorant is delivered too late or too early in comparison to the movement of the virtual object, QoE decreases. The study is based on the previously introduced concept of smell space, a term the authors defined as the area surrounding the olfactory source in which the object's odour can be detected (Huang et al., 2012b). It is a way to assign odours to a virtual object that are only perceivable when the user moves close enough to the odour emitting object. The authors developed a system through which a radius can be defined around a virtual object, in the case of the study a virtual flower, in which odour is displayed. By allowing participants to manipulate the virtual object's position in virtual space, using a haptic interface device that can translate movements of the user's arm into on-screen movements in the virtual space, the smell space could be moved. When the virtual object was moved close enough towards the screen and hence user, the user was said to be in the smell space, and an odorant was released from an olfactory display. Participants were asked to move the virtual flower towards or away from themselves at a constant speed. The authors used this setup to study the ability of olfaction to improve QoE in VEs in terms of perceived quality (Huang et al., 2012a). Quality was assessed by asking participants to report their perception of the system's quality using a five-point Likert scale ranging from bad to excellent as shown in Table 3.2. The exact statement to which participants gave this response was not given.

Score	Description
5	Excellent
4	Good
3	Fair
2	Poor
1	Bad

Table 3.2: Five-Grade Quality Scale (Huang et al., 2012b, p. 4)

In terms of results, unfortunately, the authors do not disclose the units of measurement and only state the raw values of the optimal radius. The results show that the size of the radius was dependent on the mean speed at which the flower was moved towards or away from the participant, however it appears that no linear correlation could be observed, and faster movement speeds did not necessarily require a larger radius. The optimal radius for a mean movement of 1.46 [units]/s was 10 [units], while the optimal radius for 1.50 [units]/s was 6 units. For 0.68 [units]/s and 0.51 [units]/s the optimal radius was 8 [units]. The results did however show that when odorants were delivered too slow or too late, i.e. the radius was too small or too large, QoE decreased.

The most extensive work on olfaction-enhanced technology in general and QoE specifically has been carried out by Ademoye and Ghinea, who conducted a multitude of studies on the effect of olfaction on user-perceived QoE of mulsemedia. In 2009, the authors conducted a study into the synchronisation of olfactory and multimedia content, which was reported in two separate publications (Ademoye and Ghinea, 2009; Ghinea and Ademoye, 2010b). In these studies, they developed a multimedia presentation display program which displays videos with a synchronised release of odours using the Dale Air *Vortex Active* Olfactory Display (OD). ODs are computer controlled devices used to deliver olfactory cues by means of odorants. To work effectively, ODs need to present odours with the right intensity, realism and duration. See Section 3.5 for an overview of past and current technology. A set of six odours was chosen from the Henning (1915) smell prism classification scheme, which defines odours as based on six primary types: spicy, resinous, burnt, floral, fruity and foul. The authors noted that no standard odour categorisation schemes exist and that they therefore selected odours on the basis of their familiarity to participants and wide use in research. The prism can be seen in Figure 3.1.

A set of six audiovisual video clips, each of approximately 90 seconds in length, were selected to match the six odour categories (burnt, flowery, fruity, foul, resinous, spicy). In the

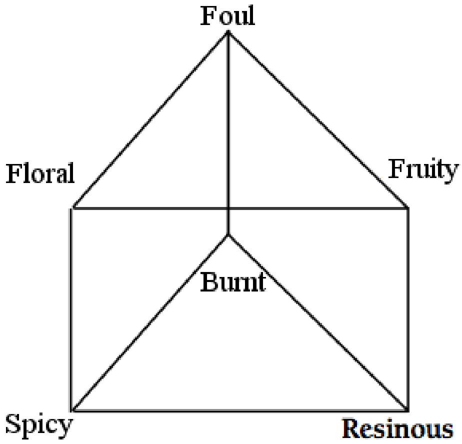


Figure 3.1: Henning's smell prism.

middle of every video clip was 30 seconds of content that matched the odour category. For example, in clip 2 (Figure 3.2), the video was about the launch of a perfume and a flowery odour was used. Brief descriptions and preview images of the video clips can be seen in Figure 3.2.

Smell Category	Burnt	Flowery	Fruity	Foul	Resinous	Spicy
Video Clip #	**Clip1**	**Clip2**	**Clip3**	**Clip4**	**Clip5**	**Clip6**
Video Description	Documentary on bush fires in Oklahoma	News broadcast featuring perfume launch	Documentary about rotting fruits	Cookery show on how to make a fruit cocktail	Documentary on Spring allergies & cedar wood	Cookery show on how to make chicken curry
Smell Used	Burning Wood	Wallflower	Strawberry	Rancid Acrid	Cedar Wood	Curry

Figure 3.2: Video category and smell used (Ghinea and Ademoye, 2010b, p. 3)

The study was conducted with 42 participants, 14 females and 28 males between 18 and 40 years of age (Ademoye and Ghinea, 2009; Ghinea and Ademoye, 2010b). Participants were shown the video clips, during which the associated odorant was delivered for a period of 30 seconds. Odours were delivered before, during and after the 30 second 'in sync' section in the middle of video clips, delivery being varied in 10 second increments from -30s to +30 seconds. Participants were asked a series of questions pertaining to QoE. The questions can be seen in Table 3.1.

Results showed that participants perceived the odours and audiovisual content as being in-sync when the odours were delivered up to 30 seconds before (-30s) and up to 20 seconds after (+20s) the in-sync period. Besides the results in terms of odour-media synchronisation, the study raises several points concerning difficulties regarding the selection of odours for user-based studies. These difficulties are examples for a wider range of studies in the field of HCI. The authors note a general lack of odour selection methodology, which could have guided them towards a suitable set of odours. Due to a general lack of odour selection method , and to gain a wide spread of distinct odours, the authors state that they based their selection on those odours that are widely used in research, namely based on the Henning Smell Prism classification scheme (Henning, 1915), which attempts to map the entire breadth of the olfactory space into a set of six primary odours. Research however indicates that there is a declining importance of the classification, as evidence for primary odours could not be found and that "the olfactory space, as defined by a set of notes, should [instead] be seen as a continuum" (Chastrette, 2002, p. 106). This is especially important when aiming to select a broad spectrum of odours as it has been shown that odour boundaries mainly depend on valence (see Section 3.3.1 and Yeshurun and Sobel (2010)). It is therefore advisable to conduct pre-trials to establish that chosen odours have the desired effect on a person's perception. It seems plausible that any kind of odour-based study should capture a set of metrics concerning the odours used, so that they can be reproduced. Ideally, this should include both the molecular properties, i.e. a chromatographic analysis of the odorant and the subjective sensory or perceptual properties of its odour. However, as a chromatographic analysis of an odorant is vastly out of scope of most studies due to restrictions of expertise, cost, and time, perceptual parameters must be recorded. Ideally, these should be based on the main dimensions of odour perception. The most widely agreed upon dimensions are valence, intensity, and familiarity (see Section 3.3.1 for details). By recording how odours are perceived in terms of these three dimensions, it would be possible to make inferences about the relationship between the properties of odours and study outcomes. For a complete odour selection method that takes into consideration the basic dimensions of odour perception, see Section 5.5.

Ademoye and Ghinea's experimental setup consisting of a multimedia presentation display with odours and video sequences has been used in other olfaction based research (Murray, Lee, et al., 2016b; Murray, Qiao, et al., 2013a,b) and it is the only methodical approach that has seen a more widespread use in the field of QoE. In a series of similar studies, using the same experimental setup as Ademoye and Ghinea (2009), including odours and video clips, Murray, Qiao, et al. showed that a temporal offset between video viewing and olfactory cues has a negative impact on QoE (Murray, Lee, et al., 2014; Murray, Qiao, et al., 2013a,b).

In one 2013 study, Murray, Qiao, et al. examined the effects of age and gender on the perception of temporal offsets between odorant delivery and visual-only video content (Murray, Qiao, et al., 2013a). 15 participants took part in the study, with 9 males and 6 females. While the age of the participants is not specified, the study grouped results in terms of the age groups 20-30 years and 30-40 years split by gender. Similarly, to Ademoye and Ghinea (2009), Murray, Qiao, et al. (2013a) report on a degradation of QoE with increased temporal offset of odorant and video. However, the effect appears to be stronger with a reduced window where participants felt that video and odour were in-sync: up to 10 seconds before and up to 15 seconds after the in-sync period, compared to 30 seconds before and 20 seconds after the in-sync period as reported by Ademoye and Ghinea (2009). Murray, Qiao, et al. (2013a) conclude that this is due to the removal of contextual audio. QoE was measured in terms of the sense of relevance, reality and enjoyment. Participant responses were recorded in the form of answers on a five-point Likert scale ranging from strongly agree to strongly disagree in regard to three statements, one for each QoE category of sense of relevance, reality and enjoyment. The statements have not been published, however, the authors say that a psychologist reviewed the statements and that reliability assessment was carried out with a "subset" of assessors. Participants indicated their response to a set of statements. It was found that temporal offsets negatively impacted these factors in comparison to conditions with no offset. Due to the small sample size, with at best three female participants per group, the effect size of these results in terms of gender and age group remains in question. No p-values for statistical significance are reported. Nevertheless, the authors report that younger females are more sensitive to temporal offset of odorant and video than older females and males, older males being the least sensitive.

In a similar study, Murray, Qiao, et al. further investigated the impact of a temporal offset between odorants and visual-only video content on QoE (Murray, Qiao, et al., 2013b). This study followed the same method as in Murray, Qiao, et al. (2013a), however, more participants completed the experiment (20 females and 23 males) between the age of 19 and 56. Results largely follow those of their earlier study on temporal offset between odorant and video, where an in-sync period of -10s to +15s was found and a reduction of QoE in terms of perceived relevance, reality and enjoyment were observed when odorants were displayed outside of the in-sync period. The in-sync region was found to be further reduced to -7.5s to +10s, indicating a sweet spot far narrower than the one reported by Ghinea and Ademoye (2010b). As the main difference between the two studies was the removal of the audio stream Murray, Qiao, et al. (2013b) conclude that this was the reason why participants were less accepting of out of sync odour. In terms of QoE, relevance, reality, and enjoyment were negatively impacted by temporal offsets between the odorant and video, with odorants displayed before the video generally producing worse responses.

While Murray, Qiao, et al. (2013b) carefully replicated many aspects of Ademoye and Ghinea (2009) and Ghinea and Ademoye (2010b), namely the olfactory display, video sequences, and experimental procedure, to compare results, they used odorants provided by a different manufacturer. As the chemical make as well as participants' odour perception of the odorants is not known, this could indeed be one reason for the starkly different results, reducing the in-sync window of odour and video presentation from -30s to +20s (Ademoye and Ghinea, 2009) to -7.5s to +10s (Murray, Qiao, et al., 2013b). Odorants of the same category or description may produce completely different odour experiences can hence have different effects on user perception (Van Toller and Dodd, 1988). A further factor that was not controlled for in either of Murray, Qiao, et al.'s studies is that of odour intensity. As the intensities are not known it is possible that users were simply more aware of odorants before or after the in-sync sweet spot in the video due to an increased intensity in odour in Murray, Qiao, et al. (2013b) compared to those in Ademoye and Ghinea (2009).

In a further study, Murray, Lee, et al. (2014) investigated the effect of a temporal offset between multi-odour delivery and audiovisual video clips. This study introduced the delivery of multiple odours, investigating whether delivering two odours simultaneously or one after the other affected the perceived QoE. While the experimental equipment remained the same as in previous studies by Murray, Qiao, et al. (2013a,b), a new set of odours was selected. The selection criteria was once again based on Ademoye and Ghinea (2009) and the aim was for the set to contain an equal number of unpleasant and pleasant odours. What constitutes a pleasant or an unpleasant odour is not defined, nor was there any verification that the odorants were perceived by participants as pleasant or unpleasant. The intensities of the odours were once more not verified or reported on, making it difficult to compare the results to those from other studies.

100 participants took part in this study, aged between 19 years and 60 years with an equal distribution of age and gender. Building on previous studies by Murray, Qiao, et al. (2013a,b) the effect of temporal offsets of odorant and video clips ion QoE was examined. Two scenarios were tested. In the first scenario, two odorants were delivered at the same time. In the second scenario, the time difference between the first and second odorant delivery was varied between

0 seconds (both odorants delivered simultaneously) and +/-20 seconds before or after the first odorant. This meant that in some cases there was an overlap between the first and second odorant, while in other cases there was a gap between the odorants. For the first scenario, results were once again in line with their previous findings, namely that odorant delivered before the related video content was less acceptable to participants compared to a higher acceptability of odorants delivered after the related video content, and an acceptable temporal offset of -5 seconds to +10 seconds was reported and that QoE in terms of the perceived factors of reality, relevance and enjoyment was negatively impacted by temporal offsets of odorant and video. Conversely, this is in contrast to (Ademoye and Ghinea, 2009), who reported a higher degree of acceptance of odours delivered before the in-sync period. Interestingly, when two odours were delivered simultaneously, participants did not report an improvement to the QoE factors of enjoyment, relevance or sense of reality. In line with this result, the second scenario, with changes in the temporal offset between the first and second odour, showed that a gap of 20 seconds between consecutive odours is needed to improve QoE factors of enjoyment, relevance and sense of reality. This is in contrast with a study by Nakamoto and Yoshikawa (2006) who also investigated the effect of time delays of olfactory cues on audiovisual media enjoyment and claimed that there should be a gap of five seconds between consecutive odour cues. One reason for this difference in results may be due to the qualities of the odours used. Neither study quantified the perceived intensities of the odours and it is possible that a difference in intensities of the odours was responsible for the difference in the reported timings. As neither study recorded odour intensities however, it is not possible to compare the results. This once again is a manifestation of the lack of an odour selection methodology. For such a methodology, see Section 5.5.

3.4.3 Odour-Media Congruence and Quality of Experience

In a 2012 study, using the setup from their 2009 study on synchronisation of odorant display and audiovisual video clips (Ademoye and Ghinea, 2009), Ghinea and Ademoye (2012b) explored how semantic differences between odours and the video content (e.g. a burning odour with the video of a perfume launch, or the odour of gasoline with the video of a cookery show) affect user perceived QoE. In this study 50 participants aged between 18 and 38 took part, of which 21 were male and 29 were female. Participants were shown a series of 90 second video clips, which were accompanied by the display six odours. For a list of used odorants and videos see the description of Ademoye and Ghinea (2009) in Section 3.4.1, and Figure 3.2. The results show that QoE scores for enjoyment, sense of relevance and sense of reality are significantly higher for odour-video combinations that are semantically congruent. The authors use the term semantic congruence as a synonym for 'relevance' between olfactory and multimedia content. The metric was measured using responses to a questionnaire item, that asked participants to rate their response to the statement 'The smell was relevant to what I was watching'. What must be noted with the choice of the odorants in this study is that the authors do not state how the odours were verified in terms of their semantic content. As noted by Brewster et al. (2006), the choice of odour cannot simply be made on the basis of the name given by its producer or by a broad category that an odour falls under. A sea odour may, for example, smell like a fresh breeze or like rotting fish, which will certainly influence QoE. However, the results of Ghinea and Ademoye's study demonstrate that congruence of odour significantly affects QoE and thereby show that congruence of odour must be considered in terms of an odour selection methodology. The results also raise the question of how congruence of odour could affect other metrics in a context beyond mulsemedia. For example, the sense of presence, which is considered as one of the defining features of VR (see Section 3.4.4.1) is affected by the degree to which users are presented with a consistent set of sensory stimuli. The concept of congruence of odour has not yet been explored in the context of VR and presents a gap in research. In order to gain a better understanding of the concept of presence and to better define any research opportunities how presence could be affected by olfactory stimuli and their congruence, I conducted a literature review into presence related research (Section 3.4.4) and looked into existing studies on the the use of olfaction in VR (Section 3.4.4.2).

3.4.4 The Use of Odours in Virtual Reality

Given the challenges of the use of olfaction as a modality, with a lack of method for odorant selection, limited understanding of how we perceive odours (Section 3.2.2), and potentially unforeseen interactions through subjective perceptions of odours due to linked memories and emotions (Section 3.3 and Section 3.3.2), and due to difficulties and lack of existing ODs (see Section 3.5), it is perhaps not surprising that only a few studies have investigated the use of odours in VR. The largest area of research, where three studies have been carried out, have investigated how olfaction affects the sense of presence in VEs.

Before examining these studies, it is important to define the terms presence and immersion in relation to VR as these terms are used in a number of different ways in the literature.

3.4.4.1 Presence and Immersion in Virtual Reality

The aim of a large body of Virtual Reality (VR) research to date has been to create Virtual Environments (VEs) that provide experiences that are as believable and engaging as possible for users. The defining feature of VR and perhaps the primary goal of VR is to create a sense of presence (Slater and Wilbur, 1997; Steuer, 1992). In its essence, presence in VR refers to the subjective sense of being in one place or environment, while physically being in another, or the sense of 'being there' (Witmer and Singer, 1998). With it comes a secondary concept, that of immersion, which precedes the achievement of presence in VR and is defined as the technical specifications of a VE.

From reviewing the existing literature, it is clear that while the concepts of presence and immersion are regularly used to describe users' experience of VR (Barfield and Hendrix, 1995; Held and Durlach, 1992; Regenbrecht, Schubert, and Friedmann, 1998; Schubert, Friedmann, et al., 1999; Sheridan, 1992; Slater, Lotto, et al., 2009; Slater, Usoh, and Steed, 1994; Slater and Wilbur, 1997; Steuer, 1992), there appears to be considerable disagreement as to their exact definitions. These differences are further exemplified by relevant but contrasting definitions of the terms from related fields, such as computer gaming, which VR is an extension of. For example, one line of research (Brown et al., 2003; Jennett et al., 2008) uses the concept of immersion to describe the "degree of involvement" with a computer game, that has the features of "loss of awareness of the real world" and "involvement and a sense of being in the task environment" (Jennett et al., 2008, p. 5) whereas presence is only achieved in a state of "total immersion" and is defined as "being cut off from reality to such an extent that the game was all that mattered" (Jennett et al., 2008, p. 5). Interestingly, this definition of immersion, largely matches what several other researchers (Schubert, 2003; Schubert, Friedmann, et al., 1999; Slater, Usoh, and Steed, 1994) call presence, not immersion. It has previously been noted in research, for example by Steuer (1992) and by Schubert, Friedmann, et al. (1999) that the terms are often badly defined or used synonymously which creates confusion. I will now give a short overview on the concepts of presence and immersion, show how there is disagreement about what these terms mean and how they are measured and make clear how the terms are defined in this thesis.

Immersion is a property of the virtual reality environment that can create or enhance the sense of presence, which is the experience that user has of a VR environment. This is well described by Schubert, Friedmann, et al. (1999, p. 270) "Immersion and the content which is presented by it on the one side and presence on the other side describe a dichotomy between presentation of stimuli and psychological experience." Therefore, immersion is objective and relates to technical features of a VR environment, such as the screen refresh rate, the number of frames per second that can be displayed, the field of view, but also the number of sensory modalities that are being stimulated, such as through tactile feedback, odorant display and temperature. Immersion is distinct from presence which is a subjective experience and is measured by capturing participants' subjective impressions of their sense of "being there" in the VE (Schubert, Friedmann, et al., 1999, p. 270), as well as through objective observations of the degree to which a participant's behaviour in the VE matches how she would behave in a similar real-life situation (Slater and Wilbur, 1997). One can alter the immersive characteristics of a VE; for example, by increasing the resolution of the display screen, by adding odours to a virtual experience, by adding noise-cancelling headphones to reduce distraction of real-world sounds, or by adding tactile feedback. The concept of immersion is sometimes defined in terms of the specific equipment that generates properties of the VR environment: "the term immersion is reserved to describe all hardware and software elements that are needed to present stimuli to the user's senses" (Regenbrecht, Schubert, and Friedmann, 1998, p. 234). Similarly, Slater and Wilbur state how "immersion is a description of a technology" describing the "extent to which the computer displays are capable of delivering an [...] illusion of reality to the senses of a human participant" (Slater and Wilbur, 1997, p. 3).

In contrast, some authors, such as Witmer and Singer (1998), consider immersion to be a state of inclusion in the VE that provides stimuli and experiences, yet they also find that immersion "is necessary for experiencing presence" (Witmer and Singer, 1998, p. 227). Similarly, Schubert, Friedmann, et al. note that "in current theoretical models, the sense of presence is seen as the outcome or a direct function of immersion" (Schubert, Friedmann, et al., 2001, p. 267). Schubert, Friedmann, et al. (1999) further argue that while it is tempting to combine these two models in a single direction causal relationship, they caution against this conclusion as too clear cut considering the experience of presence combines both subjective cognitive and subjective bodily factors. However, it does seem that immersion is necessary, but not sufficient for the experience of presence. What remains uncontested however is that immersion is an objective property that can be altered by a research design in order to affect presence. Presence however is subjective.

Presence is widely understood as a defining element of virtual reality (Steuer, 1992) and even as a measure of the usefulness of virtual reality, e.g. for training simulations (Regenbrecht, Schubert, and Friedmann, 1998): in effect, "the effectiveness of virtual environments [...] has often been linked to the sense of presence reported by users of those VEs" (Witmer and Singer, 1998, p. 225). Slater (2004, p. 492) further stipulates that the subject of presence is "about verifying the "success" of replacing real sense data with virtually generated sense data". A collection of definitions which best summarise the concept of presence that I will utilize for my experiments includes the following: "To experience presence in a VE means to feel as if you existed inside this environment" (Schubert, 2003, p. 1), therefore it can be defined as "the subjective sense of being in the virtual place" (Schubert, Friedmann, et al., 1999, p. 269), "the participant's sense of 'being there' in the virtual environment" (Slater, Usoh, and Steed, 1994, p. 131). "Presence is defined as the subjective experience of being in one place or environment, even when one is physically situated in another" (Witmer and Singer, 1998, p. 225).

The experience of presence can be observed or self-reported when people start interacting within a virtual reality environment as if they exist in it without or with less regard for the real world in which they may find themselves at the time. For example, presence may be observed when those inside a VE begin to naturally reach out for objects inside that world or if they experience a fear of heights while standing at the ledge of a virtual skyscraper inside a virtual environment, ignoring or forgetting the fact that they are safely sat in an immobile armchair inside a lab or living room. Biocca (1997, sect. 5.1.1) equally describes that "users experiencing presence report having a compelling sense of being in a mediated space other than where their physical body is located", giving an example of a subjective experience of presence that can only be measured by self-report. This dichotomy of subjective and objective measures of presence are echoed by (Slater, Lotto, et al., 2009; Slater and Wilbur, 1997), who claim that presence can be described both subjectively and objectively: subjectively by a person's own evaluation of 'being' inside a VE and their judgement of its realness, and objectively by a third person observer in more extreme cases such as inducing fear of heights in test persons or having them genuinely react to objects within the VE such as a scary dinosaur.

Slater, Usoh, and Steed (1994) and Slater and Usoh (1993) distinguish between different external and internal factors which can contribute to the experience of presence. External factors are from the Virtual Environment (VE) itself: the visual quality, extent of the view and field of vision, auditory cues, how one can interact with objects in VR, how interactive the VE is, and many more (Held and Durlach, 1992; Slater, Usoh, and Steed, 1994; Steuer, 1992) - smell and odours as well as other sensory modalities would be part of this category. In this sense, these factors form part of the immersion of the VE. Slater and Usoh make references to Steuer's 1992 notion of vividness and how it can increase sense of presence: information needs to be high quality, high resolution, consistent, interactive and unobtrusive. Internal factors are subjective, and they decide the potentially different reactions and responses of different participants to the same stimuli. It is these internal factors that can be measured via self-reports while some of the reactions and responses can be observed. Slater and Wilbur (1997) further suggest that the degree of presence depends on four factors; how extensive it is, its vividness, how surrounding it is and its inclusiveness. The extensiveness of a VE is the degree of inclusion of sensory modalities, therefore the addition of olfactory data should increase the extensiveness of a VE. Vividness means the fidelity of technical modalities, e.g. the screen resolution. How surrounding a VE is depends on the extent of a user's field of vision dictated by the display technology used, e.g. a small screen vs a head mounted display (HMD) with wide field of view. Lastly, inclusiveness refers to the degree that a VE shuts out the real world, e.g. by blocking out all sounds with noise-cancelling headphones. These factors define the immersive properties of a VE, and they define the relationship between immersion and presence. Any change to these objective, immersive factors should hence manifest in a change of subjectively perceived presence.

The factors that constitute to presence have been up for much debate and while several recurring factors exist, consensus on their definition is scarce. The two main recurring factors that affect presence are realness or reality, and involvement or focus. Schubert, Friedmann, et al. (1999) state spatial presence in the VE, realness, as well as involvement as aspects of a subjective experience of presence, which can be measured by self-evaluation. They define spatial presence as the feeling that one's body is inside the VE as opposed to the real world; realness as the degree to which a person accepts a VE as their current environment of existence; and involvement as the level of attention a person exerts toward a VE. Witmer and Singer (1998) define a set of overarching factors that define the experience of presence, which they base on theoretical work by Held and Durlach (1992), Sheridan (1992), and McGreevy (1992). The factors they define are sensory, control, distraction and realism. The Sensory factor is defined as the degree of sensory fidelity and accuracy in terms of the information presented to a person's senses via a VE. Control refers to the degree that a person is able to influence the environment via the available interaction modalities. Distraction factors are those which make a person aware of the real world surrounding the VE and are generally seen to reduce perceived presence. Lastly, realism, which largely matches the Schubert, Friedmann, et al. (1999) definition of realness, i.e. the believability of a VE, dependent on the consistency of information portrayed in relation to our real-world expectations. Witmer and Singer however also see the level of disorientation or anxiety a person experiences while exiting a VE as an indicator for the realism factor. The authors assume that the more anxious or disoriented a person feels while exiting the VE, the higher the degree of presence that was felt. Witmer and Singer further describe the concept of 'involvement', similar to focus levels, which is necessary for presence but is not seen as a contributing factor but rather as a determinant for presence.

Involvement or focus towards a coherent and meaningful set of stimuli, is a recurring factor that is discussed in a wider array of research. Fontaine (1992), connects the concept of presence with focus, claiming that presence is the direction of attention, i.e. focus, often easily obtained in a novel, unique, and immediate environment such as VR, that allows for the experience of presence. A different view is that presence in a VE is connected to the idea of selective attention, and that focus is based on how meaningful presented information is (Treisman and Riley, 1969; Witmer and Singer, 1998). (Witmer and Singer, 1998, p. 226) argue that "experiencing presence" depends upon the ability "to focus on one meaningfully coherent set of stimuli (in the VE) and the exclusion of unrelated stimuli", similarly to McGreevy's 1992 claim of that experiencing presence depends on coherence, continuity and connectedness of the stimuli.

3.4.4.2 The Effect of Olfaction on the Sense of Presence in Virtual Reality

Having defined the terms presence - a subjective experience of a sense of being in a place, while physically being located in another, and immersion - an objective description of the technical properties of a VR system that affects presence, it is now possible to look at the existing literature concerned with the effects of olfaction (an immersive property) on presence in virtual reality. A study by Jones et al., examined the impact of olfaction on a user's subjective sense of presence in a VE (Jones et al., 2004). The motivation was to enhance military training environments with odours to increase military personnel's performance in the field. 30 students were split into three groups in a between subjects design, and were given five minutes to play a video game, which was displayed via a Head-Mounted Display (HMD) while depending on the condition, odours were dispensed using a hidden olfactory display attached to a user-worn headset. The students were exposed to no odours, a congruent odour that matched the environment or a non-congruent odour, depending on which conditional group they were in. The authors do not state how presence was measured, but report that while there were differences between the three groups in terms of their perceived presence, the odours did not lead to statistically significant differences in the participants' experiences. Interestingly, males reported a significantly higher degree of presence than females, however this difference was not related to the use of odours.

Dinh et al. (1999), conducted a study that aimed to establish the effects of multi-sensory inputs in the form of heat, olfactory, audio, and visual cues on users perceived sense of presence and memory in virtual reality. 322 participants took part in a between subjects design study with 16 conditions, which were determined by sensory stimulation: heat, olfaction. audio, visual detail. There were two conditions for each sensory modality. For heat, olfaction and audio, sensory modality actuation was either on or off, while the visual detail condition was either at a high or low fidelity setting, determined by the lighting technology used (ambient only for low fidelity), and the rendering quality of textures (25% texture resolution for low fidelity). Participants were only able to control their head-movements in the VE and were moved between the rooms by the experimenters. In terms of sensory stimulation, one of the rooms in the VE contained a coffee machine and while participants were inside of this room, they were exposed to a coffee odorant. The olfactory display was composed of an oxygen mask attached to two air pumps. The first pump was connected to a canister containing ground coffee, while the other supplied fresh air to ensure that the coffee odorant was only present in the vicinity of the coffee machine. The authors do not state whether the coffee was exchanged for each of the 322 participants and do not mention the perceived intensity of the coffee odour or if this remained the same throughout the experiment. Heat and wind cues (the authors called these tactile cues) were present when participants entered the balcony area to simulate the shining sun (both a fan and a heat lamp were turned on) and when passing by a fan in the reception area (only a fan was turned on). Auditory cues were included in the form of stereo sounds that grew louder as participants came closer certain objects spread across the VE. The sounds were noises from a copy machine, wind blowing from a fan, flushing noises from a toilet, and city noises from the balcony.

Participants were asked to evaluate the effectiveness of VR environment consisting of an office building, which they were told was designed for real estate brokers. The effectiveness was determined using two questionnaires that measured (1) perceived presence and realism, and (2) participant ability to recall spatial layout and object location in the VE. Questionnaire 1 on perceived presence and realism was a 14 item questionnaire based on a mix of questions from questionnaires by Fontaine (1992), and Hendrix and Barfield (1996). The questionnaire contained a question about rating one's perception of presence on a scale from 1 to 100: "If your level of presence in the real world is "100" and your level of presence is "1" if you lack presence, rate your level of presence in this virtual world (presence is a "feeling of being there"). Enter a number 1-100." The remaining 13 questionnaire items can be found in Table 3.3.

1	How strong was your sense of presence in the virtual environment?
2	How strong was your sense of "being there" in the virtual environment?
3	How strong was your sense of inclusion in the virtual environment?
4	How aware were you of the real world surroundings while moving through the virtual world (i.e., sounds, room temperature, other people, etc.)?
5	In general, how realistic did the virtual world appear to you?
6	How realistically were you moved through the virtual world?
7	With what degree of ease were you able to look around the virtual environment?
8	Do you feel that you could have reached into the virtual world and grasped an object?
9	What was your overall comfort level in this environment?
10	What was your overall enjoyment level in the virtual environment?
11	Please rate your sense of being there in the computer generated world.
12	To what extent were there times during the experience when the computer-generated world became the reality for you, and you almost forgot about the "real world" outside?
13	What was the quality of the visual display?

Table 3.3: Presence and realism questionnaire (Dinh et al., 1999, p. 7):
Subjects were asked to rate each question on scale of 1-5 where 1=poor, 2=fair, 3=good, 4=very good, and 5=excellent.

The special layout and object location questionnaire contained questions concerning the office layout in general and the location of items in the office. For each question, participants answered by selecting one of the rooms of the VE, 'Nowhere' or 'Do not remember'.

In terms of the results, only a rudimentary analysis is provided. The authors combine the mean scores of each sensory modality, giving an overall score of how each modality performed in terms of presence/realism, and memory. They reported that the auditory and tactile cues significantly increased the sense of presence, both in terms of the 1-item 100-point rating scale as well as compound scores from the 13-item presence/realism questionnaire, while olfactory cues were only able to increase the mean scores for presence in the VE but did not significantly increase the reported sense of presence. The reduction in visual fidelity did not affect presence significantly, and mean responses for the 100-point presence rating were actually higher for the visual-low condition (66.2 for visual-high compared to 66.4 for the visual low) while scores for the 13-item presence/realism questionnaire were equal for both conditions. The authors state that this is possibly due to the fact that the test on the other sensory modalities was stronger due to being removed completely from half of the conditions, while the visual-low condition only provided a reduction in quality. Furthermore, both of the visual conditions were on the lower end of the spectrum of visual quality when one compares a real-world experience compared to what was offered in the VE., possibly further reducing the impact of the reduction in visual quality. The authors state that increasing the number of sensory modalities overall increased presence additively, however, unfortunately no data is given to disseminate this information. The authors do not give any indications as to why the olfactory cues provided less of an effect when compared to their auditory and temperature counterparts. However, taking into consideration the statement that the sensory modalities worked additively, it is possible that the temperature condition was given an unfair advantage as it stimulated temperature (heat lamp and fan) and provided tactile feedback via the wind from the fan. Furthermore, the olfactory sense was only stimulated once during the experience, via an ambient odour, while the other sensory modalities were stimulated at a higher frequency and with a wider spectrum, such as through the different auditory and temperature cues. While the results are promising in terms of the addition of olfaction to VR (the mean results were increased with olfactory display), many questions remain unanswered. For example, was the odour noticed by all of the participants and if not, would an increase in intensity have provided stronger results? Was the odour of coffee simply not interesting enough to affect presence significantly? As discussed in Section 3.4.4.1, a major aspect of presence is involvement, perhaps demonstrating that the coffee odour simply was not very interesting or relevant to participants, and that the other sensory cues, such as the flushing of a toilet or the breeze and heat under a summer sun were able to involve participants to a higher degree.

In a 2017 study by Baus and Bouchard, the effects of unpleasant odours on perceived presence in a VR environment were examined (Baus and Bouchard, 2017). The primary objective was to quantify the potential effect of odours on the sense of presence in a VE. 20 participants took part in a between subjects design study, with three independent variables. The IV were tied to the odorant, one pleasant odour, one unpleasant odour and one neutral odour. Participants were told that they were part of a security team that was called to an apartment where they were to look for a knife that was used in a murder, and that the location of the murderer was still unknown, seemingly suggesting that he could still be in the apartment. The VE consisted of an apartment with kitchen, bathroom, living room, office and bedroom. To heighten participant's stress levels, participants were exposed to suspense-type soundtracks in each room. Two types of odours were displayed while participants were in the virtual kitchen area, a pleasant odour (apple pie/cinnamon like "Grand-Ma's Kitchen" by Enviroscent) or an unpleasant odour (urine "Urine" by Enviroscent). The odours were selected on a consensus basis for their hedonic properties (pleasantness) during a pilot study. Unfortunately, no further details are given and the test protocol, including any information concerning participants, as well as results are unknown. The authors state that the odours were not related to the environment (i.e. they were semantically incongruent (see Section 3.4.3) and that there were no immediate visual cues in the kitchen area that would warrant the odours. This semantic incongruence was however only measured post experimental session, once participants had exited the VE and the odours were considered moderately congruent with the environment (apple/cinnamon odour median = 3.00, urine odour median = 2.00 - scores were on a scale from 1 to 6, 1 being incongruent, 6 being most congruent). However, it should be noted that the kitchen contained both a refrigerator as well as an oven, which could potentially be associated with the pleasant apple pie/cinnamon-like odour, the name of which being "Grand-Ma's Kitchen" even implies an intended semantic connection. In each room, while inside the VE, participants were asked two questions via pre-recorded audio messages, one each for the perceived sense of presence ("On a scale from 0 to 100%, to what point do you feel present, here in the ________?"), and sense of reality ("On a scale from 0 to 100%, to what point does your experience here, in the ________, seem real?"). The practice of questioning participants during a VE experience has been shown to create a break in perceived presence (Slater, 2004), negatively affecting reported levels of presence, a fact which the authors acknowledge, but which was deemed necessary to prevent post-experimental biases. Participants may rate their experience differently after having exited the VE and having acclimatised to the real world again, however post-VE experience questionnaires have been deemed as the only way for participants to respond to their experiences in the context of a study without breaking presence (Slater, 2004, p. 492). After exploring the VE, participants answered the Independent Television Commission Sense of Presence Inventory (ITC-SOPI) questionnaire. As the questionnaire is under copyright, questions cannot be reproduced, however the questionnaire contains a total of 44 items, that ask participants to respond to their thoughts and feelings during and after the virtual reality experience. Baus and Bouchard were specifically interested in "spatial presence" (a sense of being physically inside the VE and degree to which one feels to be able to interact with the VE) and "ecological validity/naturalness" (degree to which participants feel that the VE is real - Baus and Bouchard refer to this subscale as the "sense of realism") subscales.

In terms of the results, the authors' report that only 15% of participants that received the pleasant odour (3 out of 20 participants) were able to detect it and that 60% (12 out of 20 participants) of the participants that were exposed to the unpleasant odorant were able to detect it. The authors suggest that the pleasant odour, due to its pleasantness, low intensity and high familiarity, was not consciously perceived by the participants, however, no reason is given for the low detection rate of the unpleasant odour. However, when examining the mean intensity scores for the pleasant and unpleasant odours, the difference is minimal (pleasant odour median = 5.00, unpleasant odour median = 6.00). Returning to the main measure of this study, the effect of odours on the perceived sense of presence, the results showed that the unpleasant odour was able to significantly increase the user perceived sense of presence in the VR environment, determined by both the spatial presence and ecological validity/naturalness subscales of the ITC-SOPI. No significant differences between the control condition (ambient air) and the pleasant odour (apple pie / cinnamon) were found. The authors state that this may have been due to the lower intensity of the pleasant odour, which the authors hypothesise, may have caused the low detection rates. To determine how participants had perceived the odour in terms of intensity, pleasantness and familiarity, the authors re-exposed participants post VE experience, to the odour they had previously experienced while in the VE. This time, 100% of participants stated that they had perceived the pleasant odour, and as stated previously, rated the odour's intensity on average at 5 out of 6, with 6 being the most intense. Therefore, the conclusion that a lower intensity caused participants to miss the odour seems inappropriate. An explanation may be given by the source of the odour as presumed by the participants. 66.67% of participants that perceived the pleasant odour while in the VE stated that they believed the source to be an element of the physical world (compared to 16.67% of participants that experienced the unpleasant odour). It is therefore possible that other participants ignored the stimulus as it was deemed to be incompatible with their current experience. Interestingly, 41.67% of the participants that were exposed to the urine odour attributed it to an imaginary source (rather than an object in the VE or in the real world). Perhaps, the odour of urine was more relevant to the scenario provided to participants at the beginning of the experimental sessions. In this context one might interpret the odour of urine as the reek of the killer or possibly as an ammonia-based cleaning fluid used to scrub the murder weapon (or perhaps murder scene) of any prints and DNA. This interpretation of the results assumes that the congruence of the unpleasant odour and the virtual experience as a whole was high, even though its reported congruence to the "visual scene" of the kitchen itself was low. This is further underscored by the high number of participants which reported having an association of the unpleasant odour with a memory (58.33%), indicating that regardless of whether this interpretation holds truth, the effect of the congruence of odour and VE on the sense of presence poses a gap in research and is as of yet not known.

In a recent study by Ranasinghe, Eason Wai Tung, et al. (2018) the authors introduce a novel type of VR HMD that is able to stimulate haptic (wind + thermal) and olfactory feedback. In their study, they examined the effect of these sensory modalities on the sense of presence in a VR game based on the four seasons. Each season had an associated sensory profile for each sensory modality e.g. summer: low wind + high temperature + lemon odour. The odours were determined in a trial with 12 participants, where subjects were asked to associate each of 12 odours with one of the four seasons. The authors selected the odours with the highest number of associations for each season. In the main study, participants experienced the VE in each of the seasons in five conditions, once only with audiovisual feedback, once with each sensory modality on its own, and once with a combination of all three modalities. Participants were given 120 seconds to experience the VE in each condition. Movement was restricted to head movement, limiting the degree of interaction with the VE. The sense of presence was recorded using an adapted version of the Witmer and Singer Presence Questionnaire. The results showed that olfactory stimulation was able to significantly increase the olfactory involvement subscale of the sensory factor of the questionnaire. This subscale includes questions such as "How much did the visual aspects of the environment involve you?" or "How well could you identify sounds?", which were adapted by Ranasinghe, Eason Wai Tung, et al. for the different sensory modalities. When comparing a condition with a sensory modality against a condition without this sensory modality, it should therefore not be surprising that significant differences are found. There were no significant differences for the distraction factor or the realism factor. It is possible that the short exposure to the sensory modalities in each of the conditions was not sufficient to fully assess the effect of the sensory modalities beyond noticing them. In terms of olfaction, several statements by the participants also indicate that selection of odours may have negatively affected results. Participants stated that the odours were sometimes too strong and sometimes not relevant to the visual aspects of the VE.

3.4.5 Information Recall and Processing

A further strand of research has been into the impact of odours on information recall and processing (Ademoye and Ghinea, 2013; Brewster et al., 2006; Covaci et al., 2018; Ghinea and Ademoye, 2009). Brewster et al. (2006) studied the effect of odours on recall and memory. Specifically, they analysed the potential of olfactory cues for facilitating multimedia content searching, browsing, and retrieval, specifically, searching digital photo collections using an olfactory photo browsing and searching tool, called *Olfoto* and is shown in Figure 3.3.

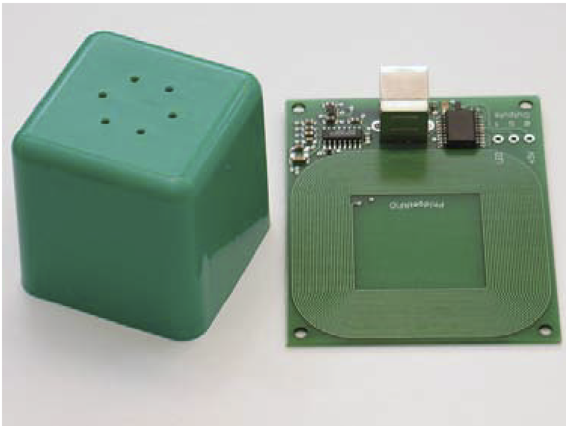


Figure 3.3: *Olfoto* smell cube and RFID tag reader (Brewster et al., 2006, p. 656)

Users could tag images with odours in a simple photo browsing and searching application using odour cubes. To scent-tag an image, odour cubes had to be held over an RFID reader while an image was selected. To search, the user could hold a cube over the reader and all the images tagged with that odour would be shown. The study consisted of three parts, categorisation, tagging, and recall.

In the categorisation part of the study, three study participants and the three authors of the paper collated a list of odour labels, which they used to describe and tag images in their personal photo libraries. The chosen labels were alcohol, pine, food, fresh, beach, smoke, garden, musty, grass, floral, sea, sweat, river, perfume, petrol and chocolate. This list was to used to purchase representative odours for each label from odorant manufacturer Aroma Prime (formerly Dale Air) (AromaPrime, 2018). The authors report on difficulties with matching odours to labels based on the Dale Air catalogue description alone as there is no standard classification system for odours. A rose odour from one manufacturer may smell completely different to another manufacturer's and neither of these odours may smell like a real rose. It is therefore virtually impossible to tell if an odour matches a chosen category before purchasing it and conducting a trial study to verify the chosen odorants.

The purchased odorants were called brewery, alpine, bread, ozone, sea shore, smoke, farmyard, dusty, grass, floral, sea breeze, sweaty feet, riverbank, unisex perfume, machine oil, dark chocolate and correspond to the above labels from the categorisation study.

In the subsequent tagging study, 12 new participants were asked to use the purchased odorant cubes to tag their personal photo libraries. As part of this task, participants labelled the odorants according to how they perceived them. The results of this task can be seen in Table 3.4; they show the large discrepancy between the different perceptions of the participants and exemplify one of the difficulties with odour selection. As described in Section 3.2, users will perceive odours differently and will make their own associations with the odours, which has to be taken into consideration when choosing odours. For example, while one participant perceived the floral odour like lavender, the floral odour was often perceived as smelling like soap by other participants.

In the recall study 6 of the original 12 participants returned two weeks after the categorisation study. Participants completed three tasks, identifying one image amongst a set using an odour or text tag; identifying the odour or text tag a photo was associated with from a set of 4 odour tags or text tags; and lastly, searching for photos using odour or text tags given certain key features of the photo. Participants performed better using text tags than with odour tags in both the first and second tasks of the categorisation study. However, for the searching task, using odour and text tags performed equally well. Brewster et al. note that the intensity of the odour cubes had changed in the two-week break between the categorisation and recall studies. This has made the recall task much more difficult for participants as the odour cubes did not reflect their odour memories due to a reduction in the intensity of the odour. Overall this study identifies some of the key difficulties when working with odours in HCI, namely, there is no established odour categorisation framework, users make their own personal associations with odours, and the effects of varying odorant intensity remains unknown.

In a 2013 study, Ademoye and Ghinea investigated the impact of odour cues on an information recall task (Ademoye and Ghinea, 2013). Returning to the methods used in their 2009 study, as described above in Section 3.4.1, including the use of the Vortex Air and associated odours and 90 second audiovisual video clips, Ademoye and Ghinea compared information recall performance for video clips viewed with odour content compared to video clips viewed

Smell Name	Floral	Ozone	Riverbank	Dusty	Alpine
Participant Labels	Sweet Sawdust	Tree Bark	Musk	Engine	Perfume
	Soap	Deodorant	Olbas Oil	Sport Shop	Talcum
	Bleach	Toothpaste	Vicks	-	Perfume
	Lavender	Menthol	Menthol	Painted Wood	Talcum Powder
	Talcum Powder	Soap	Herb (Oregano)	Dust	Air Freshener
	Trees	Water	Menthol	Smoke	Perfume
	Bathroom Spray	Flowers	Vicks	Toilet Cleaner	-
	Soap	Mint	Vicks	Campfire	Soap
	Talcum Powder	-	Sweet Pepper	Wet Wood	Strong Flowers
	Culicura	Vicks 2	Vicks	Bad Smell	Powder

Smell Name	Unisex Perfume	Grass	Sweaty Feet	Dark Chocolate	Farmyard
Participant Labels	Mild Fume	Sickly	Pale oil	Chocolate	Horse
	Orange	Grass	Sweat	Chocolate	Sh*te
	Orange	Wood	Cider	Chocolate	Rubber
	-	Flower	Cheese	Caramel	-
	Shampoo	Cut Grass	Trash Can	Coffee Chocolate	Wet Board Cleaner
	-	-	Sweaty Feet	Chocolate	Sh*te
	Orange	Grass	Sweaty Feet	Chocolate	Sh*te
	Perfume	Pepper	Feet	Chocolate	Incense
	Bathroom Cleaner	Grass	Cheesy Feet	Chocolate	Poo
	Sports Building	Leaves	Compost	Cake	Bad Smelling Compost
	-	Fruit	Pajhem	Raspberry	Bad Smell

Table 3.4: Names used by participants to describe smells in the tagging study (Brewster et al., 2006, p. 658), edited

without the addition of odour. The authors developed a set of questions for each of the video clips, quizzing participants about specific details that were presented either in the form of audio commentary or as part of the visual content, e.g. for the audio commentary of the burnt video clip: "What is the name of the tree invading the prairie?" or for the visual content "How many vehicles were shown in the clip?". Odorants were delivered for 30 seconds in the middle of each video clip, where audiovisual content, congruent to the odours, was displayed. This congruence was however not measured or verified with participants. Results show that the addition of odour did not have a significant effect on information recall performance. The authors however also measured the perceived QoE for each of the video clips that was accompanied by an odorant, using their previously developed QoE questionnaire (Table 3.1). In accordance to their previous studies (Ademoye and Ghinea, 2009; Ghinea and Ademoye, 2010b) the addition of odours showed positive results for perceived QoE.

3.4.6 Olfactory Notification Systems

The earliest research into olfactory notification systems was undertaken by Kaye (J. J. Kaye, 2004; J. N. Kaye, 2001). Kaye developed several olfactory ambient notification systems. One of them, *inStink* used two spice racks located in different places but connected via the internet so that the odorant of a spice at one rack was released as it is being picked up from the other rack. *inStink* notified users at one location when a spice was picked up at the other, with the goal of communicating a sense of connectedness from one place to the other. The system used a set of connected and computer-controlled airbrushes, filled with liquid odorants, that were attached to the underside of the spice rack. No evaluation of the system was carried out, although Kaye notes a disappointment with the quality of the odours, caused partially by the limited control over their intensity, and when certain odours were mixed. *Dollars and Scents* was another system developed by Kaye that used olfactory notifications to alert users when the NASDAQ stock exchange market value was rising or falling. When the stock market was rising, a mint odour was delivered and falling stock prices were indicated by the release of a lemon odour. While Kaye reported that the odours were quickly incorporated into the culture of the workplace, where the prototype was located, and were easily understood, no formal evaluation of *Dollars and Scents* was carried out. Kaye does not report how the odours were chosen, for example, why the choice for lemon and mint was made and if the intensity was controlled. Furthermore, no information is given as to how often the system became active in terms of odour delivery i.e. how large the changes had to be in stock market value to trigger the release of an odour. The hardware for both systems was custom made. The systems were developed as a proof of concept and were thus not evaluated in detail, limiting their generalisability but nevertheless highlighting some of the potential that the addition of smell to digital interfaces poses and that ambient olfactory notifications.

In a 2004 study, Bodnar et al. compared olfactory notifications to visual and auditory notifications for users working on a cognitively engaging task (Bodnar et al., 2004). Users were asked to answer a set of arithmetic questions, during which they were interrupted by olfactory, visual and auditory notifications. Each sensory modality had two types of notifications. For type 1 notifications participants were instructed to stop their current task to immediately respond to the notification, while participants were instructed to ignore type 2 notifications. Auditory notifications were two bell-like sounds, how these were delivered, is not reported. Visual notifications were delivered using two differently coloured squares, one red, the other blue. It is not certain how these were displayed to participants. Olfactory notifications were displayed using two *Spa Centre Aromatherapy* diffusers that were modified with directional cones to drive the odorants towards the participants, and the odorants used were clove extract and *VitalPlus Active*, which the authors state has a distinct artificial eucalyptus odour. The odorants were chosen from a set of ten odorants and were selected by the researchers for being easily differentiated. The selection criteria for the ten initial odorants is not specified, neither is what odorants were part of this selection. The authors do not mention the intensity or valence of the odours, which is unfortunate, seeing that these are two critical perceptual factors in terms of odour perception and directly influences a person's awareness of an odour (see Section 3.3.1 and Section 3.2.2). To assess the performance of the notification modalities, error rates were calculated for incorrectly identified type 1 and type 2 notifications i.e. if a participant ignored a type 1 notification, this was an error. Results showed that there were no significant differences in terms of response error rates for any of the modalities. However, olfactory notifications produced a higher number of errors, with one participant mis-interpreting two type 1 notifications (and ignoring them). Due to the nature of the task to ignore type 2 notifications, it is not certain whether the participant did not notice the notification or whether he/she simply misunderstood the odour notification. In post-experimental interviews, participants did however state that they had difficulties in differentiating between the two odours, and that this was partially due to the lingering of odorants from the previous notifications and a lack of training regarding differentiation between the odours.

At the end of the experimental sessions, participants were asked to rank the sensory modalities in terms of their non-disruptiveness. Olfactory notifications were found to be significantly less disruptive when compared to auditory notifications, but no significant difference was found between olfactory and visual notifications. Bodnar et al. state that the olfactory notifications therefore have a strong potential use in any situation in which a non-disruptive notification was required. While these results are promising for olfactory notifications as a non-disruptive notification, the validity of the results must be questioned due to the limitations in odorant selection and the implications of lingering odorants as well as odours that are hard to differentiate. The study therefore once again exemplifies difficulties with the use of olfaction in an HCI setting. It is yet not certain how well olfactory notifications perform even though there is an indication for their use as a secondary or non-disruptive notification.

These results do not match the findings of Arroyo et al. (2002) who compared odour to heat, sound, light and vibration for disruption by measuring test subjects' performance at a reading task while they were interrupted by different sensory notification modalities, and also their ability to recall what they read later. Sensory notifications were delivered as follows: olfactory stimulation was provided using an unspecific "atomizer and air absorber" (Arroyo et al., 2002, p. 3) while Elmer's glue and soy sauce were chosen as odorants. No information was given concerning properties of the odorants or a selection methodology. Heat notifications were actuated via a ceramic infrared heat lamp, sound was actuated using computer speakers, light notifications were delivered using three spotlights pointed at the screen, and vibration notifications were actuated using a vibrating device placed under the participant's chair. Participants were given the task to read a text passage on a computer screen and were told that their reading performance was the subject of the experiment to ensure that participants focused on the task. While reading, participants were interrupted once with each of the sensory notifications, in a randomised order and were asked to acknowledge the interruption by clicking on an icon on the screen. It is not certain whether the icon was displayed continuously or as a prompt when a sensory notification was triggered. The authors found that olfactory notifications proved the most disruptive of the different sensory modalities, followed by vibration, then sound, heat and finally light, which was deemed least responsive. The authors do not state whether there were significant interactions between the sensory modalities but report that a strong determinant of how interruptive a notification was seen, was regarding prior experience with the sensory modality. For example, a participant who was involved in "homemaking and kitchens" (Arroyo et al., 2002, p. 4) was acutely aware of the odours, while another participant did not perceive the odorants at all. Similarly, a participant with experience in tv broadcasting was more aware of visual notifications and rated these as more disruptive. When comparing the odour related results to Bodnar et al.'s 2004 study on notification modalities, where olfactory notifications were shown to be non-disruptive, the difference in results can perhaps be drawn to the choice of odorants. Though the intensities of the odorants are not recorded by Arroyo et al., Elmer's glue and soy sauce both would appear to produce very intense odours, especially if undiluted, that perhaps trigger the trigeminal nerve, producing a physical response to the odorants (see Section 3.2.2) and would therefore be highly disruptive. Once again, it is clear that there is a gap in research regarding the methodology of odorant selection criteria. First of all, by omitting to record how the odorants were perceived in regards to the basic dimensions of odour perception (see Section 3.3.1) it is not possible to determine why these odours were perceived as disruptive. Second, because these basic perceptive properties of the used odorants are not know, it is not possible to correctly interpret the results and to draw appropriate conclusions about the use of olfaction as a notification modality in general.

In two studies, reported on in one research paper by Dmitrenko et al. (2017), the authors aimed to answer the question of whether participants could correctly understand and differentiate between different olfactory notifications for in-car interactions. In contrast to the previous studies detailed in this section (Arroyo et al., 2002; Bodnar et al., 2004; J. N. Kaye, 2001), Dmitrenko et al. aimed to determine the congruence of an odour and a notification to determine whether participants could draw semantic connections between the odours and the notification. The authors however do not evaluate the effectiveness of the olfactory notifications.

In the first study, the authors examined if a set of 30 participants could draw semantic connections between 5 odours (lemon, lavender, rose, peppermint, and water) and 3 driving related notification messages ("Fill gas", "Passing by point of interest", and "Slow down"). The authors state that these odours were chose as they are widely used in research, where the odours have been shown to exhibit specific alerting and relaxing qualities. The lemon and peppermint odours were chosen as they were previously used to increase alertness (Ilmberger et al., 2001), while rose and lavender have been shown to have a relaxing effect on participants (Hongratanaworakit, 2009). The notifications were selected to fit into a two-dimensional framework of perceived urgency, that ranked the notifications according to their alertness and reaction time, and which can be seen in Figure 3.4.

The authors report having had difficulties with an OD during a pilot study, due to lingering and mixing odours. They therefore decided to present the odours to the participants using five different jars, each containing one of the odours, according to literature (Velasco, Balboa, et al., 2014). In a first step participants were asked to rate the notification messages in terms of how alerting, relaxing, and urgent they were perceived, using 7-point Likert scales for item 1, 2, 3 as shown in Table 3.5.

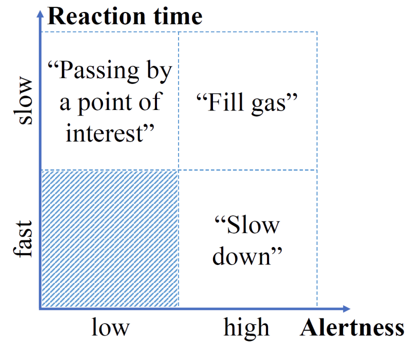


Figure 3.4: 2D framework of message urgency along two axes: alertness (i.e. salience: low-high) and reaction time (range estimation considering the time required to detect an odour: fast(≤10s)-slow(<10s)) (Dmitrenko et al., 2017, p. 3)

	Question	Left Anchor	Right Anchor
1	How alerting do you consider the message presented in this storyline?	1 Not alerting at all	7 Very alerting
2	How relaxing do you consider the message presented in this storyline?	1 Not relaxing at all	7 Very relaxing
3	How urgently would you react to the message presented in this storyline?	1 Not urgently at all	7 Very urgently
4	How much do you think this scent represents the message from this storyline?	1 Very little	7 Very much
5	If you think of smell as a medium to convey information, which message (“Fill gas”, “Slow down”, or “Passing by a point of interest”) would you assign this smell to?	1 is the best to convey this message	3 is the worst to convey this message
6	How alerting is this scent for you?	1 Not alerting at all	7 Very alerting
7	How relaxing is this scent for you?	1 Not relaxing at all	7 Very relaxing
8	How much do you like this scent?	1 I don’t like it at all	7 I like it very much

Table 3.5: Likert scales used in Study One of Dmitrenko et al. (2017) to assess olfactory stimuli. Labels are only given for minimum and maximum.

The results showed that the “Slow down” notification was seen as the most alerting, “Passing by a point of interest” was seen as the most relaxing, while “Slow down” and “Fill gas” were seen as significantly more urgent than the “Passing by a point of interest” message.

In a second step, participants were asked to rate the perceived degree of congruence between a notification message and an odour by using a 7-point Likert scale (item 4 of Table 3.5). The results of a statistical analysis showed that the “Fill gas” notification was represented best by the lemon, lavender and peppermint odours, which were rated significantly more congruent with the notification than the rose and water odours. The "Slow down" message was best represented by the lemon, lavender, and peppermint odours, which were all perceived significantly more congruent with the notification than the rose and water odours. However, the lavender odour was also perceived as significantly more congruent with the notification than the lemon odour. Finally, for "Passing by a point of interest" the water odour was rated as significantly less congruent than the other odours.

In a third step, participants were asked to rank which notification an odour best represented, using item 5 of Table 3.5. While participants were asked to rank their all three notifications for each odour, the authors only considered the first ranked notification for each odour, i.e. the best notification to convey an odour. The authors report that the rose odour was associated significantly more often with the "Passing by a point of interest" notification than with the other notifications. The other odours did not show significant differences between their associations with the notifications.

In a fourth step, participants were asked to rate each of the 5 odours in terms of how alerting, relaxing and pleasant they were perceived using items 6, 7, and 8 of Table 3.5 respectively. Rose and water were perceived as significantly less alerting than the other odours. Rose was rated significantly more relaxing than lavender and water, and finally, water was perceived as significantly less pleasant than the other odours. Results from this step show that while the odours were selected due to their apparent relaxing and alerting properties, these were not always reflected in how the participants perceived them. For example, the lavender odour was perceived with a low relaxation and a high alertness, which was similar to the lemon and peppermint odours, once again demonstrating that while generalisations about the qualities and properties of an odour can give an initial indication of if an odour could potentially work in the context of a study, it is vital to assess how participants perceive the odour in an experimental setting.

There are several important results for my work in Dmitrenko et al.'s first study, which are worth pointing out. While participants perceived the rose odour as congruent with the low alertness and low urgency notification "Passing by a point of interest", there were no such preferences for the other odours. The authors unfortunately do not answer the question of why only the rose odour was perceived as significantly congruent with one of the notifications, but this nevertheless shows that at least for the rose odour, participants displayed significant preferences in terms of which notification they felt that it represented and that this may have occurred due to the perceived congruence of the odour and the notification in terms of a match in terms of (high) perceived relaxation and (low) alertness. Finally, while the authors report that they found associations between the (arousing) odours of lemon and peppermint and alerting urgent notifications, participants associated the odours equally with the relaxing 'Passing by a Point of Interest' notification, showing that there were no clear preferences for these odours and that participants therefore must have felt that the notifications and odours were congruent due to other (unknown) factors besides of alertness and relaxation.

In their second study, in which 17 participants took part, Dmitrenko et al. aimed to determine whether participants could associate odours (lemon essential oil, peppermint essential oil, and rose essential oil) with the notifications from their first study, while in a driving simulator. Participants were seated in a driving simulator, consisting of a 55' curved screen, a steering wheel, noise-cancelling headphones and a self-made OD, which was integrated into the back of the steering wheel. The OD functioned by pumping compressed air through one of three jars, which were filled with one odour each (lemon, peppermint, rose) after which the odours were output towards the participant via a tube facing the participant. The study was conducted in two steps. In the first step, participants were seated in the driving simulator where they were presented with item 1 of Table 3.6, which shows the questions used during the second study, to assess perceived alertness of the notifications. This was followed by an assessment of the perceived alertness levels of the odours using item 2 of Table 3.6. The question was displayed on the screen in front of participants. Odours were displayed for the first 5 seconds that the question was displayed. The authors do not report the results of this step.

	Question	**Left Anchor**	**Right Anchor**
1	How alerting do you consider the "[Slow Down / Fill Gas / Passing by a Point of Interest]" message?	1 Not alerting at all	7 Very alerting
2	How alerting do you consider this scent?	1 Not alerting at all	7 Very alerting

Table 3.6: Likert scales used in Study Two of Dmitrenko et al. (2017) to assess olfactory stimuli. Labels are only given for minimum and maximum.

Participants were then instructed to start driving. After 5 minutes, one of the three odours was displayed for 10 seconds, after which the message "Which message could this scent convey? (1-"Slow Down", 2-"Fill Gas", 3-"Passing by a Point of Interest")" was displayed on the screen. Participants were told that the odours were not in sync with the current driving situation. The results of this second step show that the rose odour was associated with the "Passing by a Point of Interest" significantly more often than with the other notifications. The peppermint odour was associated with the "Slow Down" and "Fill Gas" notifications significantly more than with the "Passing by a Point of Interest" notification, while the lemon odour could not be associated with any notification. While these results confirm those of the first study, they leave several unanswered questions. Dmitrenko et al., for example do not determine whether participants would actually understand the meaning of an olfactory notification while driving, which seems to be a vital point. While the results indicate that it would be possible to form an olfactory notification between the peppermint odour and the "Slow Down" notification, would participants understand it as such or would they interpret it as the "Fill Gas" notification, which was also perceived as congruent with the odour? Furthermore, would these olfactory notifications, based on congruent odours and notifications, outperform incongruent odour notifications, where the odour is not perceived to match the notification? This opened a promising research gap into the effectiveness of congruent olfactory notifications, which I explore in Study Four (Chapter 8) in the context of a VR game, where I answer the research question *Are congruent olfactory notifications effective in virtual reality?*.

3.4.7 Crossmodal Effects of Olfaction

While the fact that our sensory modalities can influence each other has been known for centuries, the exact interplay between olfaction and our other senses remains poorly specified (Calvert et al., 2004; J. N. Kaye, 2001). The field of psychology has recently brought forward a series of studies concerning crossmodal interactions between the olfactory sense and our other senses (Blackwell, 1995; Castiello, 2006; McGlone et al., 2013; Seigneuric et al., 2010; Spence, 2002). In a similar vein, studies in the field of HCI have also begun to explore not only how olfaction can be used in conjunction with other sensory modalities. One such application of smell was discovered by two studies which established that in several tested situations, visual quality could be significantly reduced without changing user perception of visual quality, if an odour was added (Brkic et al., 2009; Ramic et al., 2007). This provides support for the hypothesis that "spreading contextual information across the senses is a viable approach" (Murray, Lee, et al., 2016a, 56:21).

Narumi, Kajinami, et al. (2011) and Narumi, Nishizaka, et al. (2011) investigated the crossmodal effects between visual, gustatory, and olfactory stimuli via a pseudo-gustatory augmented reality display that presented the visual appearance and odour of a plain cookie. The researchers evaluated the effectiveness of their system for inducing/encouraging people to experience various flavours. Participants were presented with a plain cookie enhanced with olfaction and a visual overlay. Following this, they experienced only a plain cookie without any augmentation. In more than 79% of the trials, a positive change in taste was reported when the cookie was augmented with odours.

This overview of studies on olfaction in the different areas of HCI helps to inform the experimental design of the following main study.

3.5 Olfactory Display Technologies

While olfactory technology has been used since the late 1950s, devices based on the sense of smell have taken a back seat to the more established senses of vision and audition. Only recently have researchers begun to develop a wider array of applications, which are increasingly becoming available. A variety of Olfactory Display (OD) devices exist currently, each used to present olfactory cues using scented air. In order to work effectively, ODs need to present odour with the right intensity, realism and duration. As discussed in Section 3.2.2, an odour's intensity is correlated with its perceived valence and has a direct impact on our ability to perceive an odorant. If an odour is too intense, it may overpower an experience, while an odour with a low intensity may be missed entirely. Equally, an odour's realism factors in to our experience. An odours realism refers to the degree to which its occurrence matches our real-world experiences. If odours are perceived as being too chemical for example, they may be rejected by participants (Brewster et al., 2006; J. N. Kaye, 2001). Lastly, a control over the duration of odorant display is necessary to ensure that odours are only perceived during appropriate times when the odour stimulus matches those of other sensory modalities. A control over the duration of odorant display is also necessary to prevent lingering odours, which have shown to reduce QoE (see Section 3.4.1). The development of such devices is in their infancy (Kortum, 2008), especially compared to similar audio or visual tools.

The earliest attempts to use the sense of smell in technology have seen it used to augment other media, often in conjunction with films and as part of VR systems. The first commercial systems invented were *Smell-O-Vision* developed by Laube (1959), which used an array of tubes to deliver up to 30 odorants to the seats of cinemagoers, and *Aromarama* developed by Chuck Weiss, which used a cinema's air-conditioning system to deliver over 100 different odorants to customers, in the late 1950s and early 1960s, which aimed to bring smell to the cinema, although with minimal success, mostly due to early problems of lingering smells and an oversaturation of the olfactory system. Inspired by these early systems, two years later, Heilig

(1962) developed *Sensorama*, the first virtual reality system to incorporate smell. The device was meant for single-person operation and was able to display sensory information via a 3D screen, fans, OD, stereo-sound system, and a vibrating chair. As with its predecessors in film, *Sensorama* had little financial success and was not able to survive commercially.

Since the 1980s, further commercial systems for virtual reality have been developed, most prominently those by Digital Tech Frontier (J. J. Kaye, 2004), who offer odour as part of their virtual reality assemblies for trade fairs and other demonstrations but have remained a niche technology. Other commercial applications have been developed with the aim of ambience creation and as notification systems, such as in amusement parks and museums. Interestingly, museum visitors displayed an improved memory recollection for exhibit specific information when being exposed to these smells again at a later period (Aggleton and Waskett, 1999).

Olfaction-enhanced technology has also been developed in the domain of wearable technology to modulate interpersonal communication. Choi, Cheok, et al. (2011) and Choi, Parsani, et al. (2012) describe two prototype systems, *Sound Perfume* and *Light Perfume*, that aim to augment and strengthen emotional human relationships. With *Sound Perfume*, they describe the development of a prototype consisting of a pair of wirelessly connected glasses that are able to release odorants as well as play sounds. Each set of glasses has an ID which represents one unique odour and sound combination. This combination is played and released during conversations with other persons wearing the Sound Perfume system, with the aim of building odour-based memories of these encounters. Unfortunately, the authors report on technical difficulties with the exchange of IDs that plagued the prototype and while a technical evaluation of the device was performed, the effects of odour on the user interaction was not studied.

Choi, Parsani, et al. further explored odour as a medium for augmentation interpersonal communication with *Light Perfume*, an arm-worn device that was able to emit odours and light. Devices were able to sync during a conversation and emit the same light and odour to generate a sense of mimicry between the persons wearing the device. Results showed that perceived sociability could be modulated using the device. Unfortunately, the researchers did not determine whether this modulation occurred due to the presence of light and odour or if it was indeed the process of mimicry.

3.6 Summary

This chapter aimed to explore the current state of olfactory research in HCI while also giving an overview of the physiological and psychological research into olfaction. The chapter was split into three sections, focusing on the perception of olfaction in the first section (Section 3.2), on how odours can be used to augment digital systems in the second section (Section 3.4), and on olfactory display technologies in the third section (Section 3.5).

Amongst the key findings on the perception of olfaction was that we perceive odours based on a set of basic dimensions, the most important (and agreed upon) of which are valence and intensity. Odour perception is rarely at the front of our attention and the sense of smell often plays a subconscious role, affecting our moods and emotions, where it outperforms both vision and sound. Smell and memories are closely interlinked, and memories can be triggered by the perception of an odour. Because of this deeply subjective link between odours and memories, great care must be taken with the selection of odours, as unwanted side effects may arise when participants perceive odours starkly different to what is intended.

Amongst the key findings is the realisation that there is no common classification system for odours at all (J. N. Kaye, 2001). In lieu of this, several studies have relied on the Henning smell prism (see Section 3.4.2), which describes all odours to be based on the six primary odours: spicy, resinous, burnt, floral, fruity and foul (Henning, 1915). However, research has found that smell should be regarded as a continuum rather than as a subset of primary odours as no evidence could be found for the latter (Chastrette, 2002; J. N. Kaye, 2001). As no other common classification system for odours exists, the only logical conclusion for my own research is to verify odours (see Section 5.5) for each study until such a classification system emerges. The choice of odours throughout the field of HCI has only seen superficial attention from researchers and could hence be considered a rather neglected topic. The reason is that we simply do not yet know what makes an odour appropriate for our research. Throughout the reviewed literature several factors could however be identified that affect our perception of digital media in terms of choice of odours: congruence of odour and digital content, intensity of odour, and odour valence (Baus and Bouchard, 2017; Brewster et al., 2006; Ghinea and Ademoye, 2012a; J. N. Kaye, 2001). The finding of intensity and valence are perhaps not surprising, seeing that they have been defined as basic dimensions of odour perception (Kaeppler and Mueller, 2013; Kermen et al., 2011; Wise et al., 2000) (see Section 3.3.1. It is therefore necessary for my study purposes to record the intensities of the odours used by asking participants to rate how they perceive the odours.

Measuring how odour affects our perception of digital media has primarily focused on measuring user perceived QoE. It has been measured in terms of three factors: enjoyment, sense of relevance, and sense of reality. These factors are measured using five-point Likert scale responses to statements about each factor. An example set of questions can be found in Table 3.1. However, while the measurement is quite widespread, the factors of enjoyment, sense of relevance and reality have not been verified for use with odours. QoE has been used to assess the congruence of odour and media content. This is another factor that has been identified as affecting our perception of digital media (Ghinea and Ademoye, 2012b). While this is not a changeable factor in naturally occurring objects in the real world - grass smells like grass - objects in the digital world have no natural odour and hence understanding how we perceive congruence between odours and objects is a necessary path of research. This is especially pertinent for the use of odours in virtual reality environments, where we perceive entirely artificial environments, the success of which is closely tied to the fidelity and range of sensory modalities that are stimulated and importantly the consistency of the displayed sensory information (Sanchez-Vives and Slater, 2005). So far, the concept of congruence is little understood in the field of HCI and is based only on the semantic congruence of odour labels and video content (Ghinea and Ademoye, 2012b). However, further factors are likely to be relevant and research will be necessary to determine what these factors are. While the effect has generally been assessed with the use of QoE questionnaires, the current iteration of these questionnaires is only able to measure if a change in perception has taken place (i.e. 'The smell was relevant to what I was watching'), and would have to be modified to quantify the effect of odours. Hence it may be preferable to also consider other forms of measures to assess the effects of odours on our perception of digital media. In the field of virtual reality, presence has been established as the de-facto measure for how engaging an experience is and several robust assessment techniques exist, mainly through questionnaires (Schubert, Friedmann, et al., 2001; Witmer and Singer, 1998). Presence itself may be a good measure for the use of olfaction, as both have a strong relationship with emotions (Riva et al., 2007). The measure has been used with a variety of other sensory modalities, such as heat and wind (Ranasinghe, Jain, et al., 2017) and has been used previously with the sense of olfaction (Baus and Bouchard, 2017; Dinh et al., 1999). I therefore choose to study the effects of congruence on the perception of presence and QoE in a VR environment.

Lastly, the choice of odours in HCI research so far has often been based on categories and labels given to odours by producers or manufacturers (Bodnar et al., 2004; Brewster et al., 2006; Ghinea and Ademoye, 2009; J. N. Kaye, 2001; Murray, Lee, et al., 2016b). However, odour labels do not tell us how an odour smells and odours with the same name may smell completely different. Furthermore, they may be quite artificial and not smell like the real object they aim to portray at all (Brewster et al., 2006). Currently, there is no framework or method for selecting odours for HCI based studies has to be noted. I therefore propose to conduct an exploratory study to determine which factors of odour perception should be taken into consideration for an effective and robust odour selection process.

Chapter 4

Study One

4.1 Introduction

As became clear from conducting the literature review, the two main aspects that have been hindering the use of olfaction as a modality in HCI are a lack of a systematic method for odour selection (see Section 3.4), and issues associated with the use of Olfactory Displays (ODs) (see Section 3.5). This first exploratory Study One, therefore was conducted to gain an understanding of how to better approach odour selection and to trial a novel type of OD, which only disperses minute amounts of liquid odorant in the vicinity of the user.

In the study, I assessed olfaction as a medium for emotional stimulation in the context of HCI and explored the effects of smell on the emotional perception of digital images. Besides allowing me to gain insights into the selection of odours and their use with a novel type of OD, the aim of the study was to determine the effect of odours on users' emotional perception of digital images. Accordingly, this study addressed the following research question.

RQ$_{\textbf{exploratory}}$ *Do odours affect the emotional perception of digital images?*

This can be an important factor for user experience and could therefore potentially offer benefits by enhancing digital communication and digital media. If user perception can be altered through odours on top of viewing images, this could offer a new sensory modality for gaming, television and other media applications intending to create emotional responses.

Study One also addressed the congruence of image and odour valence. Congruence has previously been explored in a study by Ghinea and Ademoye (2012b), who examined how congruence of odour and media content, e.g. a burnt odour and a video of a fire, affects user perceived QoE. Results showed that incongruent video and odour combinations were detrimental to QoE. Congruence was defined as a match in media content, which refers to a connection on a semantic level between odour category and media content category. In contrast to the study by Ghinea and Ademoye, this study examines congruence in terms of odour and media (in this case digital image) valence. For Study One, congruence was defined as a match in the direction of valence (negative or positive) between images and odours, i.e. an odour with perceived positive valence and an image with perceived positive valence are considered congruent; an odour with perceived negative valence and an image with perceived positive valence are considered incongruent. Thus, research question $RQ_{exploratory}$ was addressed at this stage through an early hypothesis:

H_1 *The congruence of image and odour valence affects the emotional response to a digital image.*

This exploratory study further served specifically as a way to test the new OD as well as to establish a method of odour selection to be used in the main studies.

4.2 Pilot Study

A pilot study was conducted to gain base levels for emotion and arousal responses of the images to be used. Several standardised affective stimulus image databases currently exist that are used for emotional research (Dan-Glauser and Scherer, 2011; Lang et al., 1999). These databases contain selections of images that are sorted per their affective content. While numerous categories exist, the most basic and unilaterally recurring categories are valence and arousal, which have been established as the main components of emotional categorisation (Lang et al., 1999; Russell, 1980; Watson and Tellegen, 1985). Valence in this sense refers to the inherent attractiveness (positive valence) or aversiveness (negative valence) of an image, while arousal refers to a sense of activity, ranging from calm to excited and from stimulated to relaxed (Frijda, 1986).

At the time of conducting this study, two established affective image databases were available, the International Affective Picture System (IAPS) and the Geneva Affective Picture Database (GAPED) (Dan-Glauser and Scherer, 2011; Lang et al., 1999). Both databases include pictures rated for valence as well as arousal levels, while the IAPS also includes dominance ratings, the GAPED includes ratings that represent congruence of the represented scene with internal (moral) and external (legal) norms. As for their suitability to this study, certain limitations apply. Firstly, in terms of image resolution the IAPS uses images of a resolution of 300 x 400 pixels, while the GAPED uses a resolution of 640 x 480 pixels. Image resolution has been established as an important factor in terms of user perception of mobile content, with low resolutions not only having negative effects on acceptability but also causing perceptual strain (Knoche et al., 2005). It is therefore questionable whether a 300 x 400 pixel resolution is adequate for conducting a study on mobile devices. Furthermore, image categories are limited, especially in terms of the GAPED, where negative images are limited to spiders, snakes, and scenes that induce emotions related to the violation of moral and legal norms; and positive images mainly show human and animal babies as well as nature scenes (Dan-Glauser and Scherer, 2011). Aside from possible ethical concerns with the negative images, the GAPED does not cover a wide range of images as one might expect to encounter in a mobile setting and would therefore limit results to certain image types. It is because of these reasons that the GAPED was not chosen as a base for the images of this study. The IAPS on the other hand improves upon several of these issues, by including everyday objects and scenes in their images. The image library does include images depicting scenes that might be considered ethically questionable for the purpose of this study, such as mutilated bodies or pornographic material, it is however, not entirely reliant on these kinds of extreme imagery. While this makes the database suitable for this study, certain limitations apply, specifically in terms of the image ratings. The ratings were obtained by a predominantly US-American group, consisting exclusively of college students (Lang et al., 1999) raising the possibility of a potential cultural bias that should be noted. While the IAPS image database fits the purpose of this study, access could not be attained within a three months' period, and due to a lack of other suitable image databases and time constraints, an image set had to be created for this study.

The aim of the image selection process was to produce a set of 12 images, four of each with a neutral, positive and negative valence, while also recording arousal levels. 60 images were initially selected by 5 members of the City University London Mixed Reality Laboratory. Each member selected 4 positive, 4 negative and 4 neutral images, free to use[1] and openly available on the Internet. Initial selection criterion for positive images was that they had to portray scenes containing positive emotional content, such as love, trust or joy. Neutral images were selected from inanimate objects. Negative images were selected from content that portrayed negative emotions, such as disgust, dread or anger. This initial selection was cut down to 12 images that were informally agreed upon by each of the members according to the general consensus on each image in terms of fitting into each of the categories. The selected images were validated in terms of their generally perceived emotional valence and arousal in

[1] Images had to have a license that allowed the use of the image for this study.

a trial with a new set of 6 participants, which had not taken part in the previous assessment, of which 3 were female and 3 were male and with a median age of 28.5 years. Participants were shown all images on an Apple iPod Touch mobile device, in randomised order and were asked to rate their response using an adapted version of Plutchik's emotion wheel (see Figure 4.1 for Plutchik's original emotion wheel and Figure 4.3 for the adapted version). This wheel comprises the eight primary emotions of joy, trust, fear, surprise, sadness, disgust, anger and anticipation. One emotion can be selected for a response and must be selected on an intensity scale ranging from zero (no emotional response) to seven (very high emotional response). The wheel is described in detail in the following section.

4.3 Plutchik's Emotion Wheel and the ActivationEvaluation Space

In order to record and classify the perceived emotions of participants, Plutchik's emotion wheel was used (Feldman Barrett and Russell, 1998; Plutchik, 1994). The emotion wheel places 4 pairs of primary opposing (bipolar) emotions on a wheel: joy versus sadness; anger versus fear; trust versus disgust; and surprise versus anticipation and a neutral point at the centre. The wheel of emotions can be seen in Figure 4.1.

An alternate version of the wheel of emotions has been suggested in literature, with the purpose of allowing participants to rate their emotional responses to a stimulus, named the activation-evaluation wheel (Cowie, Douglas-Cowie, Tsapatsoulis, et al., 2001). In this version, each emotion is categorised according to its degree of arousal (or activation) and valence (or evaluation). Cowie, Douglas-Cowie, Tsapatsoulis, et al. (2001) describe arousal as "the strength

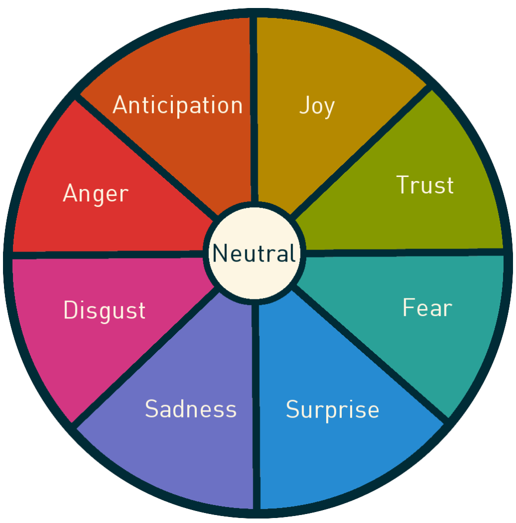


Figure 4.1: Plutchik wheel of emotions, showing primary emotions.

of the person's disposition to take some action rather than none" (Cowie, Douglas-Cowie, Tsapatsoulis, et al., 2001, p. 39) in response to people or things or events. Similarly valence refers to how negative or positive a person's response is.

The axes of the activation-evaluation wheel reflect these two dimensions, with the horizontal axis showing valence and the vertical axis showing arousal values (see also Figure 4.2). According to Cowie, Douglas-Cowie, Tsapatsoulis, et al. (2001), the depiction of these primary emotions as a wheel stems from data that shows that primary emotions are not evenly distributed in activation-evaluation space, but are spread out in a circular pattern. The centre of the wheel is considered the neutral point, or its natural origin. The distance from this neutral point indicates the strength of an emotion, with full blown emotions being the furthest away from the origin.

A benefit of the activation-evaluation wheel is that emotional states can be described numerically (in terms of the valence-arousal space), making them more manageable, and that emotional responses can be translated into and out of verbal descriptors (Cowie, Douglas-Cowie, Tsapatsoulis, et al., 2001). These properties have made the activation-evaluation wheel attractive to computational research (e.g. Cowie, Douglas-Cowie, Apolloni, et al., 1999; Cowie, Douglas-Cowie, and Romano, 1999) and more specifically HCI research, where it has been used to rate perception of emotion in speech (Makarova and Petrushin, 2002) or to study the effect of colour lighting- and tactile cues on the emotional perception of mobile text messages (Pradana et al., 2014).

Cowie, Douglas-Cowie, Tsapatsoulis, et al. (2001) suggested that the eight basic emotions that were defined by Plutchik (1994) are mapped onto the valence-arousal space, however they are thus no longer grouped into bipolar pairs. The resultant activation-evaluation wheel may therefore produce significantly different results to Plutchik's emotion wheel. This arrangement of emotions in the valence-arousal space was used by Pradana et al. (2014), and can be seen in Figure 4.2.

Emotional strength is measured as the distance from the origin to a given point on the valence-arousal space. Pradana et al. (2014) suggest limiting emotional strength to 7 values (from 1 to 7), with the origin serving as a neutral point with a strength of 0. When selecting an emotion response using this wheel, each emotion has a strength, indicated by its distance from the origin (i.e. a value from 1 to 7), a valence value, and an arousal value. The exact means of how numerical values were derived from this wheel are detailed in Section 4.4.

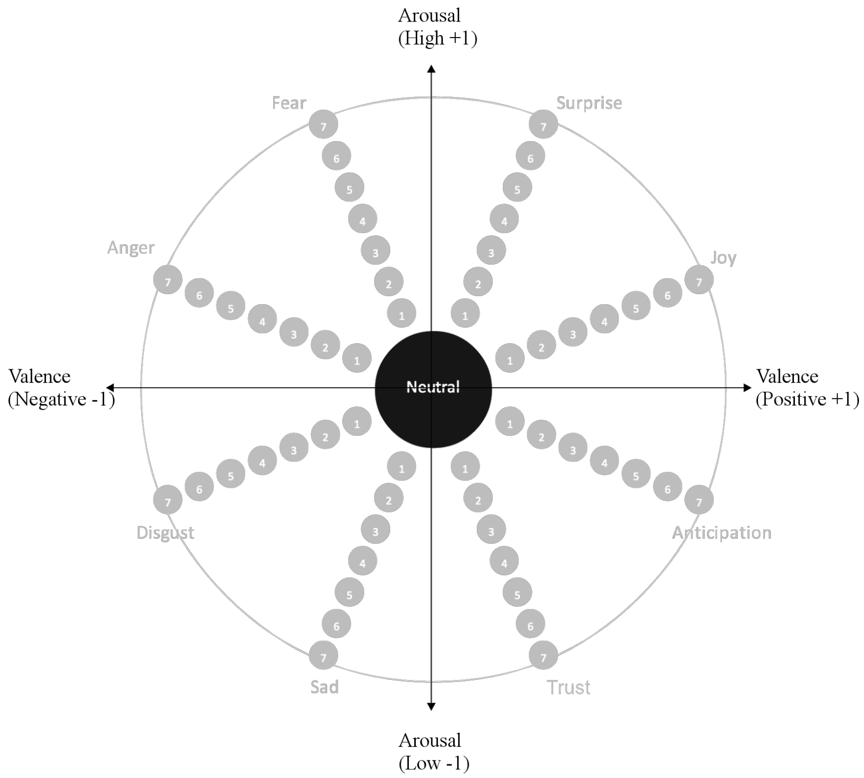


Figure 4.2: Activation-evaluation wheel with arousal valence axes: The wheel encompasses the emotions joy, surprise, fear, anger, disgust, sadness, trust, anticipation, and has a neutral origin. Each emotion can have a strength of 1 to 7.

During the experiments, instead of using the full activation-evaluation wheel as shown on the left side of Figure 4.3, an edited version as shown on the right side was used, because the full activation-evaluation wheel did not fit onto the available screen real estate in its entirety due to the small form factor of the mobile device, as the display was too small to allow the accurate selection of strengths for the individual emotions. The activation-evaluation wheel was mapped to its mobile version as follows. The eight emotions from the original wheel were mapped onto an iOS Picker element (Apple Inc., 2018a). The Picker element is a scrollable list containing a set of unique values. Each of the eight emotions from the Plutchik emotion wheel was set as a value in the Picker. Included was also the neutral position as 'Neutral', indication a neutral emotional response, associated with the centre position of the activation-arousal wheel. The seven intervals of intensity were mapped to an iOS Slider element (Apple Inc., 2018b), which was displayed below the Picker element and could be set to any integer values from 1 to 7. Responses were recorded in terms of valence and arousal. How these values were derived is explained in Section 4.4.

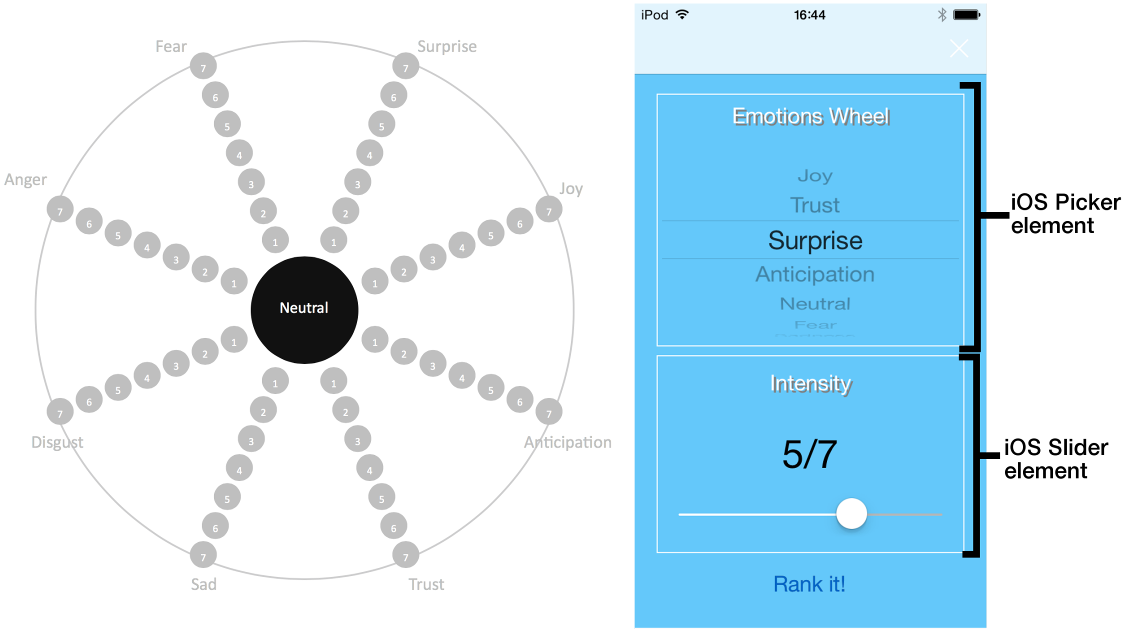


Figure 4.3: Activation-evaluation wheel and its mobile pendant.

4.4 Translating Verbal Descriptors of Emotion to Valence and Arousal Values

As derived from the literature, the verbal descriptors of emotional responses were converted into numerical values that were then used as the basis of statistical analysis (Cowie, Douglas-Cowie, Tsapatsoulis, et al., 2001; Pradana et al., 2014). As described in section 4.3, 8 primary emotions are arranged on a wheel according to their inherent arousal and valence levels. The horizontal axis of the wheel shows valence values, while the vertical axis represents arousal values. Therefore, the wheel can be split into four quadrants. The left top quadrant contains emotions that have a negative valence and high arousal, i.e. anger and fear. The right top quadrant contains emotions that have a positive valence and high arousal, i.e. surprise and joy. The bottom quadrants contain emotions with low arousal. The left of these quadrants further contains emotions with a negative valence, i.e. disgust and sadness, while the right of these quadrants contains emotions with a positive valence, i.e. acceptance and anticipation. The quadrants can be seen in Figure 4.4. When the emotions are spread out on a wheel, according to Pradana et al. (2014), emotions in the same quadrant have the same valence and arousal values.

Table 4.1 shows the numerical values for each of the emotions on the emotion wheel. Blue fields indicate a positive base valence or positive arousal; red fields indicate a negative base

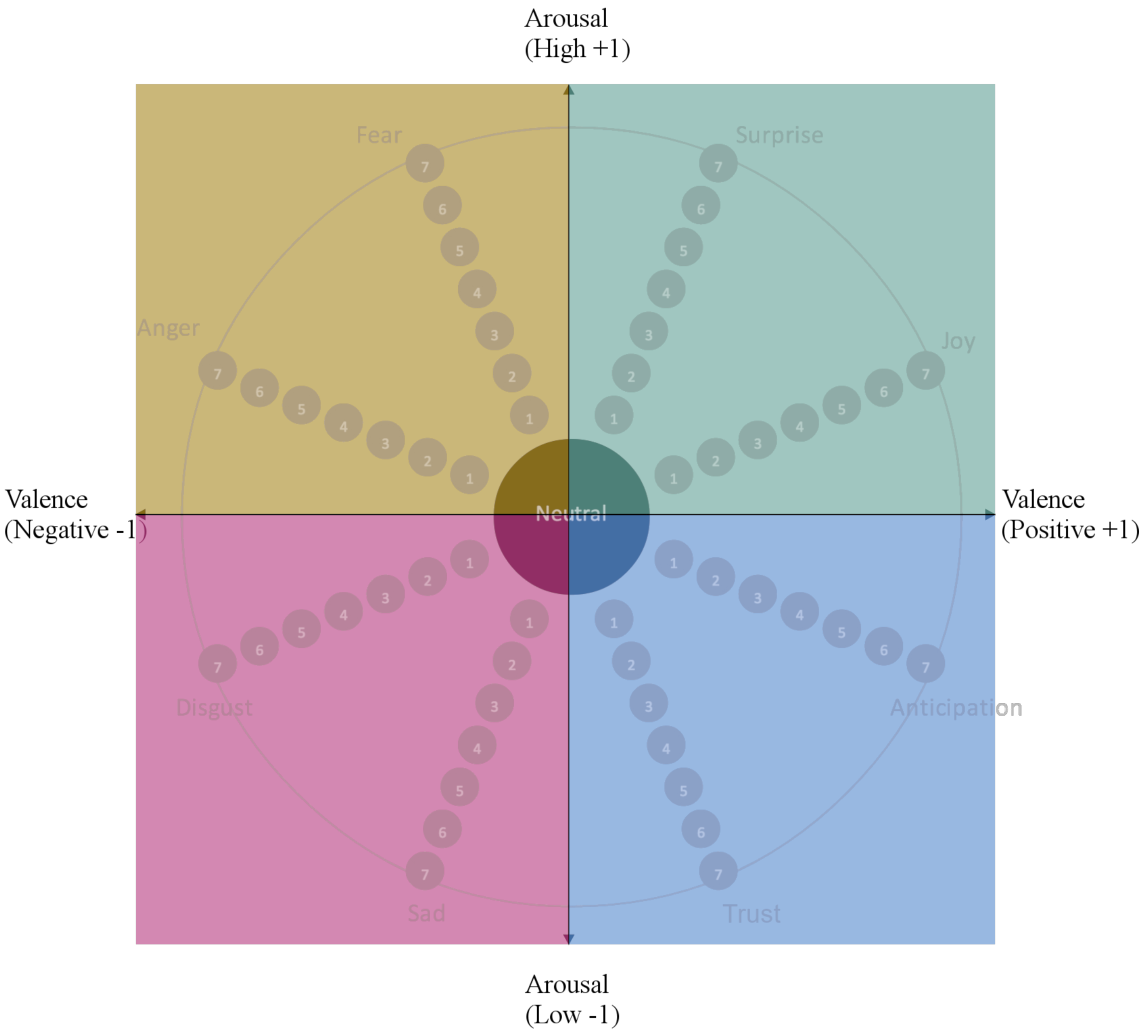


Figure 4.4: Quadrants of the activation-evaluation wheel.
Emotions in the top left quadrant have a base valence of -1 and a base arousal of +1.
Emotions in the top right quadrant have a base valence of +1 and a base arousal of +1.
Emotions in the bottom right quadrant have a base valence of +1 and a base arousal of -1.
Emotions in the bottom left quadrant have a base valence of -1 and a base arousal of -1.
Base values are multiplied with the selected strength of an emotion to deduce final arousal and valence scores for an emotion.

arousal or valence value.

To incorporate the strength of the responses that participants gave (on a scale of 1 to 7), the base score i.e. -1 or 1 was multiplied by this value. As an example: A participant's response was trust with a strength of 6. The arousal value for this response would be -1 * 6 = -6 (as trust is on the bottom right quadrant of the wheel), while the valence score would be 1 * 6 = 6 (once again, as trust is on the bottom right quadrant of the wheel). Through this conversion, each response was converted into a pair of valence and arousal values, each of which could range from -7 to 7. Neutral responses were recorded as a valence and arousal value of 0.

	Emotion								
	Anger	Fear	Surprise	Joy	Anticipation	Trust	Disgust	Sadness	Neutral
Arousal	+1	+1	+1	+1	-1	-1	-1	-1	0
Valence	-1	-1	+1	+1	+1	+1	-1	-1	0

Table 4.1: Emotion choices from the Activation-Evaluation Wheel with corresponding base valence and arousal values. These values are then multiplied by the strength of the emotion selected by participants to gain the final valence and arousal scores.

4.5 Pilot Study Results

As described in section 4.2 Pilot Study, a set of 12 images was created and was rated according to emotional response using an edited version of activity-evaluation wheel. The final set of images used and their emotional valence are shown in Figure 4.5.

Figure 4.5: Final selection of images used.

Median and mean arousal and valence responses from the pilot study are shown in Table 4.2. As the number of participants that took part in the pilot study was rather small, these values should only be taken as a general indication of if an image falls within a certain arousal and valence group. To assure that the ratings were not only a result of the chosen participants and to receive concise results as to the emotional properties of each of the images, during the ensuing main study, participants were once again asked to rate the images without any accompanying olfactory stimulation. For a full set of raw results and full size images see Appendix A.

Arousal

Image	*Median*	*Mean*	*Std Dev*
Tool Box	0.00	0.17	0.37
Fire Extinguisher	0.00	0.33	0.47
Door	0.00	-0.33	0.75
Refrigerator	0.00	-0.17	0.69
Smiling Child	4.00	3.67	1.49
Panorama of Historical Town	2.00	1.00	2.58
Couple in Nature	3.00	2.17	2.91
Festive Dinner	-0.50	-0.33	4.19
Zombie Head	0.00	-0.33	3.09
Child in War Zone	-3.00	-1.83	3.29
Person in Trash	-2.00	-2.83	2.11
Pig's Heads	-3.50	-3.17	2.27

Valence

Image	*Median*	*Mean*	*Std Dev*
Tool Box	0.00	0.17	0.37
Fire Extinguisher	0.00	-0.33	0.47
Door	0.00	0.33	0.75
Refrigerator	0.00	-0.17	0.69
Smiling Child	4.00	3.67	1.49
Panorama of Historical Town	2.50	2.67	0.75
Couple in Nature	3.50	3.50	0.96
Festive Dinner	4.00	4.00	1.29
Zombie Head	-3.00	-3.00	0.82
Child in War Zone	-3.50	-3.50	1.38
Person in Trash	-2.00	-2.83	2.11
Pig's Heads	-3.50	-2.83	2.67

Table 4.2: Pilot Study Arousal and Valence Responses to Images.
cells represent positive arousal score
cells represent negative arousal score
Brighter colours, represent a greater magnitude of values.

4.6 Method

Following the preliminary results of the image and odour selection pilot, in this section I describe the methods used for the main experimental sessions.

4.6.1 Variable and Control Condition

This study used a quantitative experimental approach, aimed at examining the effects of odour cues on the emotional perception of digital images as described in the following sections. A single factor design approach with two independent variables and one dependent variable was applied. The independent variables (IV) within the framework of this experiment were: IV_1: the exposure to a digital image, combined with the display of an odour; IV_2: the exposure to a digital image without odour display; IV_3: The valence of an image; IV_4: The valence of an odour. Images were displayed via an application developed for the study, which also controlled odour display. The dependant variable (DV) was the perceived emotional response to an image. The exposure to an odour was the stimulus to which participants were subjected under the experimental condition and amplified or reduced an emotional response. Therefore, the measurement of the emotional reaction was composite and represented the selection of an emotion and a related intensity level. The emotion was selected on a nominal scale based on Plutchik's emotion wheel (Plutchik, 1994) and the activity-evaluation scale (Cowie, Douglas-Cowie, Tsapatsoulis, et al., 2001), which was previously used and validated in similar experiments (Pradana et al., 2014). The intensity level ranking was performed on an interval scale ranging from one to seven except for the neutral emotion which was always ranked with an intensity level equal to zero.

4.6.2 Perceptual Parameters

4.6.2.1 Images

In order to evaluate the effect of odour on ratings of the digital images, a set of odours and pictures was created each of which was marked for its emotional content. The 12 images selected during the pilot study were separated into two image sets (A, B). Each set of images contained two positive, two negative, and two neutral emotionally valenced images with the size of 640 x 640 pixels. The images used and their emotional valence are presented Figure 4.6. Full size images can be found in Appendix A.

The images were split into two sets to be able to record emotional responses to images only (without accompanied odour display) as well as emotional responses to images with accompanied odour display. The process is described in section 4.6.4.

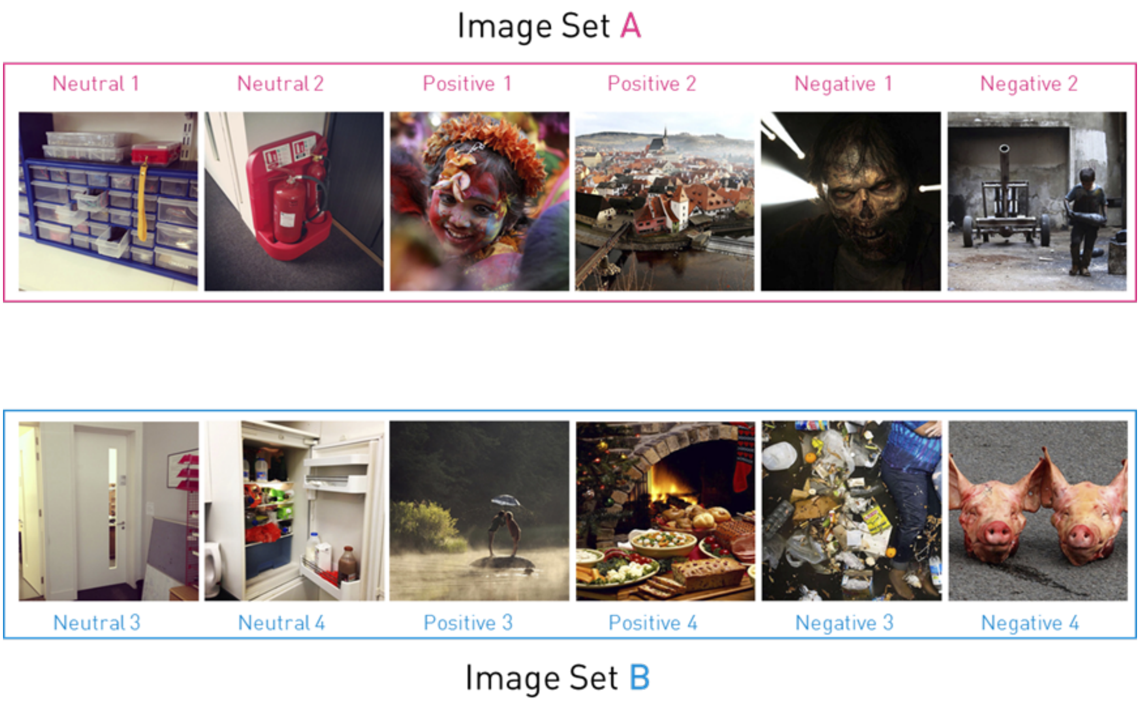


Figure 4.6: Image sets A and B: 6 images for each set; each set consists of 2 neutral images, 2 positive images, and 2 negative images.

4.6.2.2 Olfactory Display

As was shown in the Literature Review in Section 3.5, a multitude of technologies to display odours currently exists. Some of the most commonly used ODs use fans to disperse odours in a room. The downside of this technology is that odours can often linger in the vicinity, mixing with any odours that are displayed at a later time. A solution to this problem is the use of an olfactometer, large devices that can pump scented air towards a user's nose using an array of tubes. While these devices can exert great control over the amounts and concentrations of odour that participants are exposed to, the devices are cumbersome and obtrusive (as the pipes and mask to deliver the odour to the participant's nose must be worn on the face) and even though attempts have been made to reduce their cost, they remain prohibitively expensive (Karunanayaka et al., 2017). One possible way to overcome this limitation is to use a piezo-electric atomiser, which vaporises minute amounts of liquid odorant using a high-frequency pulse. The technology is small in size and is readily available off the shelf at low cost. One such device that is currently on the market is the Scentee (see Figure 4.7), which was used during this study. Scentee is a small OD (see Figure 4.8 for an indication of its size) that plugs into the audio socket of an iOS or Android device, using a 3.5mm four-conductor audio connector. Scentee releases odour using an ultrasonic atomiser that vaporises a pre-loaded odorant stored inside a small removable container, which can store up to 2ml of solution. The odour release is triggered through touchscreen input or via an incoming text message or social network notification. Only one odour can be released at a time, but odour containers can be exchanged.

Figure 4.7: Scentee consists of a motor unit and a tank for liquid odorants.

While Scentee can be purchased with a variety of odour capsules ranging from buttered potato to rose and coffee aroma, it is not intended, or even possible, to refill or fill odour capsules with other odours. To load the device with other odours certain modifications are necessary. As the base of the odour capsules is made of a soft plastic, a small hole of 1.5mm diameter was drilled into this surface of an empty capsule. In order to prevent any previous odours from mixing with future odours, the capsule was cleansed in an ultrasonic bath. The capsule was then filled with a new odour solution using a syringe and the resulting hole sealed using a water-resistant adhesive. Once attached to the body of the device the capsule can function as normal. Certain limitations for the type of solution that can be vaporised apply. The device does not function with oil based odorants and other solutions containing large particles as these quickly clog up the release mechanism. A solution is to disperse the oil using a surfactant or to use alcohol and water based odours, the latter of which was done during this study.

4.6.2.3 Odour Selection

Five odours were selected to be used as part of this study, two with a positive, two with a negative and one with a neutral odour. An initial selection of odours was conducted by a domain expert from the Crossmodal Research Laboratory at the University of Oxford. The selection of positively perceived odours was apricot, bilberry, cinnamon, orange, lemon, vanilla, and strawberry. The odours were purchased for assessment at the City, University of London site. Initial negative odours were: musk, rotten egg, and the chemical compounds skatole and putrescine. Purified water was selected as the neutral odour, as it does not have a discernible odour noticeable by humans due to habituation, as we are constantly exposed to the odour of water through the air. A sample was purchased for each of the available odours, which excluded bilberry and musk, as these were not available for purchase and the rotten egg odour, which was only available as in gas form as hydrogen sulphide and was therefore not usable with Scentee, which relies on liquid odorants. The chemicals putrescine and skatole were only available in powdered form at very high purity (>98%) and would have required careful mixing with a carrier substance to be able to be used with Scentee. As the substances are corrosive and toxic at these concentrations, and as suitable equipment to handle these chemicals was not available, they were excluded from the list of possible odours.

In terms of the positive odours, the cinnamon odour was excluded as it crystallised at room temperature and would not have been usable in a Scentee device. The remaining positive odours, apricot, orange, lemon, strawberry and vanilla were filled into one Scentee cartridge each and were informally assessed by the five members of the City University laboratory (4 male, 1 female), focusing on the perceived valence of each odour. The lemon odour however clogged the device, presumably due to being oil based and hence having a higher viscosity than the other odours, and was excluded, leaving the orange, strawberry, apricot and vanilla odours. Both the apricot and the vanilla odours were perceived as having a very chemical and artificial quality by all the members of the lab and were therefore excluded. This left the orange and strawberry odours, which were positively perceived by the members of the lab and were used during experimental sessions. Table 4.3 shows the initial list of odours chosen by the domain expert, which of these odours were used during the experimental session of the study, and why odours were rejected.

As all the negative odours had to be rejected, two more odours were purchased upon further consultation with the domain expert. These odours were both proprietary with undisclosed chemical compounds. The first was an odour called Earthworm that had the odour of mouldy soil. The second odour was called LiquidAss and had the odour of a mix of faeces and flatulence. Both odours were able to be used with the Scentee and were perceived as nega-

Valence	Odour	Odorant	Used	Reason for Rejection
Neutral	-	Purified Tap Water	✓	-
Positive	Orange	Natural Orange Aroma	✓	-
	Strawberry	Natural Strawberry Aroma	✓	-
	Apricot	Natural Apricot Aroma	x	Too chemical
	Lemon	Lemon Peel Oil	x	Clogged Scentee device
	Vanilla	Vanillin	x	Too chemical
	Cinnamon	Cinnamyl Alcohol	x	Crystallised at room temperature
Negative	Rotten Eggs	Sulphur	x	Dangerous to handle
	Something putrid	Putrescine	x	Dangerous to handle
	Faeces	Skatole	x	Dangerous to handle

Table 4.3: Initial odours selected by domain expert.

tive by all members of the laboratory. The final list of odours and corresponding valences used during this study are shown in Table 4.4.

Valence	Odorant	Supplier
Neutral	Water	Purified tap water
Positive	Natural Orange Aroma	Omikron-online.de, Germany
	Natural Strawberry Aroma	Omikron-online.de, Germany
Negative	Faeces - *LiquidAss*	Liquid ASSets Novelties, LLC., Ohio, United States
	Mouldy Soil - *Earthworm*	Demeter Fragrance Library, New York, United States

Table 4.4: Final set of negative odours and associated valences.

4.6.3 Setting and Participants

The study was conducted at the Centre for Human-Computer Interaction Design (HCID) at City, University of London and at the Crossmodal Research Laboratory of Department of Experimental Psychology of Oxford University. In London, experiments were carried out in a neutral and bright laboratory in order to not unsettle the participants. The room was well-ventilated via two windows and a fan so that odours did not linger in the room and did not have an undesirable effect on the perception of new odours during the experiment. Likewise, the selected setting in Oxford was a large lit meeting room with windows. Both testing locations were equipped with a table and chair where participants could sit to conduct the experiment (see Figure 4.8). The selection of participants was done on a non-probability, convenience sam-

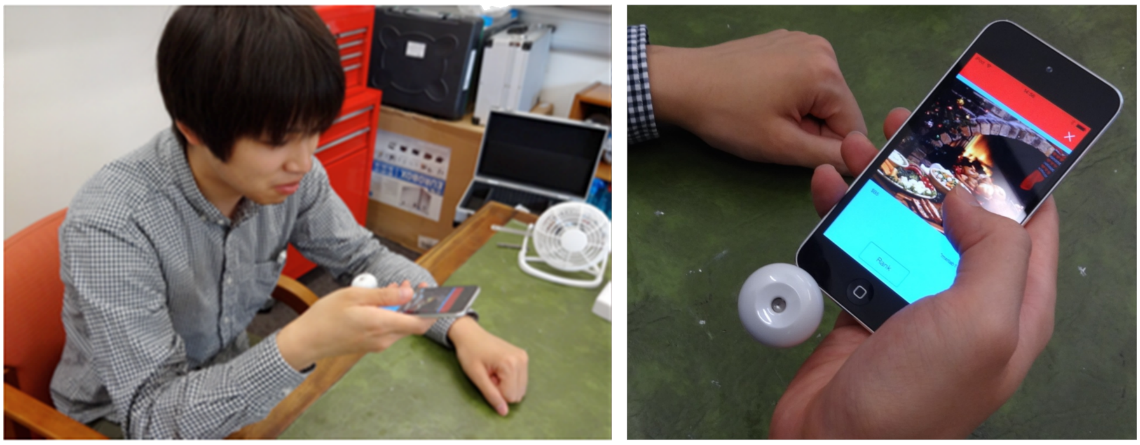


Figure 4.8: Participant during experiment: Participants were asked to look at images and rate their emotional response to one image at a time using a smartphone with a Scentee device.

pling basis. Participants were recruited via university mailing lists. 22 people in total took part in the study. Participants were 20 to 30 years old, consisting of undergraduate and graduate students at either City University London (15) or Oxford University (5) and working professionals (2). Participants were familiar with digital technologies and all participants reported having used a smartphone before. The participants were required to have a normal sense of smell and vision (or corrected-to-normal vision). Olfactory function was tested using Sniffin' Sticks (GmbH, 2018), which tests for odour threshold, odour discrimination and odour identification (Hummel, Sekinger, et al., 1997). The principle of Sniffin' Sticks is that participants smell each of 12 scented sticks that are in the shape of felt-tip pens, in a pre-defined order, and after smelling each stick indicate on a multiple-choice card, which of four odours they just perceived. The number of odours that a participant can identify determines the degree of olfactory function. No participants were excluded as a result of the test for olfactory function. Additionally, the participants were asked to refrain from wearing any fragrances on the day of the sessions and not to have any meal, coffee, or to smoke for an hour before the experimental session and were asked to report any smell related allergies or concerns in advance. As an incentive to take part in the study, the participants were given Amazon vouchers worth £10.

4.6.4 Experimental Procedure

Ethics approval for this study was granted by the City, University of London Computer Science Research Ethics Committee and all participants gave consent to taking part in the study through consent forms. Prior to the experimental sessions, the participants were divided into two groups. Each group was shown one set of six images with odour display and the other set of six images without odour display, so that both sets of images were tested once with and once without olfactory stimuli. By having participants rate a set of images without odours, the results from the pilot study could be verified and the effectiveness of the images could be assured.

Before the experiment, the participants were made familiar with the experimental equipment, which consisted of an Apple iPhone and Scentee. The individual parts were explained and participants were familiarised with the odour actuation of the Scentee device. The interface of the experiment app, used to display images, rate emotional response to images, and advance to the next image was also explained. Once the participants had stated that they were now familiar with the test equipment, the test procedure was explained. Furthermore, to ensure that participants were ranking their emotional response to the images rather than the odours themselves, the study supervisor explained that, for the tests, the entire experience of smell and vision should be considered as a single unit.

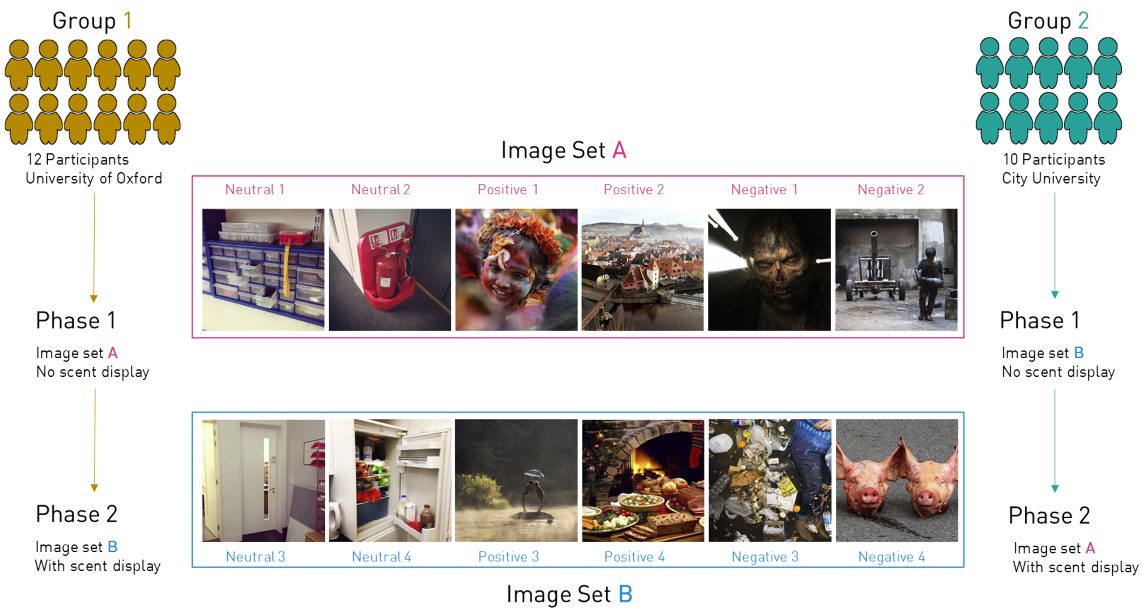


Figure 4.9: Experimental phases showing group and image set allocations.

During the experimental sessions, participants were shown images in two phases. Phase 1 was conducted using the mobile device with Scentee attached, however without any odour actuation. In this phase participants from group 1 were shown images from image set A, while participants from group 2 were shown images from image set B. Participants were asked to look at the shown images and to rate their emotional response to one image at a time, advancing to the next image when the participant felt comfortable with their rating, and not requiring any intervention by the conductor of the experiments. A flowchart of the procedure can be seen in Figure 4.10.

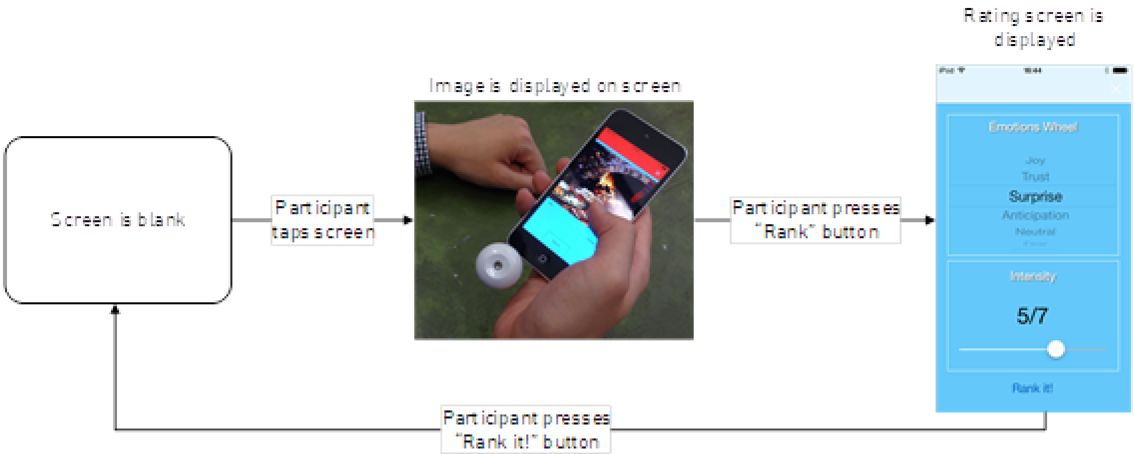


Figure 4.10: Procedure for Phase 1 exposures.

During Phase 2 of the experiment, participants viewed images accompanied by an odour, displayed via Scentee. Participants from group 1 were shown images from image set B, while participants from group 2 were shown images from image set A. Each image was displayed five times, each time with one of the five odours (strawberry, orange, water, mouldy soil and faeces); the order of both images shown and accompanying odours were randomised.

Participants were instructed to evaluate each photo 5 times but told that each evaluation of a photo would be performed with a different odour from the whole set of odours selected for the study. This phase required active intervention by a study supervisor whenever a person advanced to the next image to exchange the Scentee device and associated odour. The randomised order of odours and images was not predetermined and was calculated every time a participant advanced to the next image. To prevent a change in participants' expectations, the Scentee device was exchanged for all images, even if the random order would dictate the same odour be used in succession. As the next image to be displayed was chosen randomly, the prospective odour to be inserted into the device was always displayed in coded manner at the bottom right corner of the mobile device's screen. To prevent the participants from being able to determine the odour by its number prior to smelling it, the numbers were encoded and a sheet with code keys and associated odours was given to study supervisors prior to the experiments. The participants were given a 60 second break between each image and odour exposure to reduce any effect of lingering odours. The odours were triggered by double-tapping the screen at any position and participants could advance to the next image by swiping on the screen to the left. Both gestures were easily recognised and participants had no trouble in using the experimental equipment. A flowchart of the Phase 2 procedure can be seen in Figure 4.11.

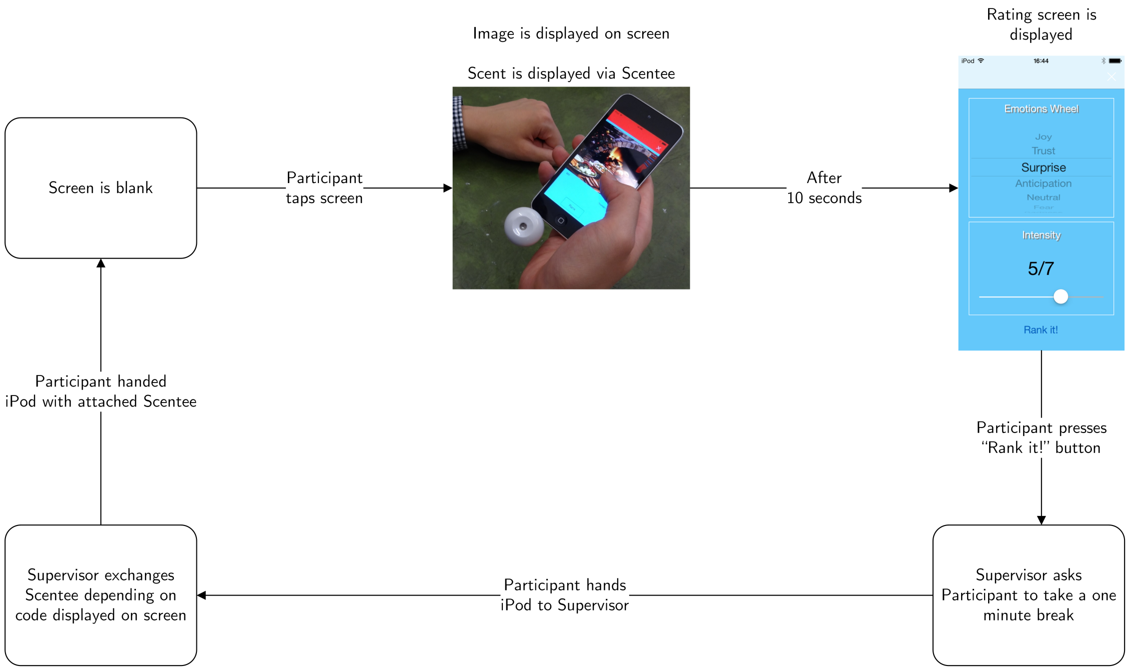


Figure 4.11: Procedure for Phase 2 exposures.

Upon completion of the experimental session, the participants were questioned to briefly give feedback on their experience about the experiment to gain insights into whether certain factors could be improved in follow-up studies and to determine possible factors that could have affected the results of the experiments in a negative way.

4.7 Data Analysis

In this section I describe the statistical tests that were carried out on the collected data. The results of this analysis can be found in Section 4.8.

The data collected during the experimental sessions was in the form of emotional responses to digital images that may or may not have been accompanied by an odour cue. The data was analysed as described below. Each response was recorded as the verbal descriptor for one of eight emotions on the activity-evaluation wheel, and with an associated strength value that could range from 1 to 7. The eight verbal descriptors were joy, surprise, fear, anger, disgust, sadness, trust and anticipation. Neutral responses were recorded as the verbal descriptor 'neutral' and had an associated strength of 0. A total of 792 responses were recorded. Emotional responses were converted to valence and arousal values as described by the literature and as covered in section 4.4 to be able to answer the research questions. Statistical analysis was carried out using the R language and software environment for statistical computing (R Core Team, 2013).

To ensure that the images were perceived as intended and to determine whether the different image groups would be interpreted by participants with the intended difference in valence and arousal, statistical tests were carried out to determine whether image type impacted emotional perception of the images. Single-factor ANOVAs were carried out between i) all neutral images and all positive images, ii) all neutral images and all negative images, and iii) all negative images and all positive images. This was carried out once comparing the valence responses and once to compare arousal responses. The results of this comparison for valence scores can be found in Section 4.8.1.1, while the results of the comparison for arousal scores can be found in Section 4.8.1.2.

4.7.1 $RQ_{exploratory}$: Do Odours Affect the Emotional Perception of Digital Images?

$RQ_{exploratory}$ was addressed by investigating the presence of a general effect on the DV perceived emotional response to an image by IV_1 the exposure to a digital image, combined with the display of an odour.

In order to do so, responses to images with odour actuation were compared with responses to the same image without odour actuation. As each image that was displayed with odour actuation was rated by one of the two groups only, and the control condition of the same image (without odour actuation) was rated by the other group, and the group sizes were unequal (Group 1 = 12 participants; Group 2 = 10 participants), the comparison was always made between unequal response numbers. For further clarification on why group sizes were unequal and which participant group saw which image and with or without odours, please refer to Figure 4.9.

There were two possible analysis techniques to investigate the relationship between odour display and emotional response to a digital image: a 2-sample t-test and a Mann-Whitney U-test. As the groups were of unequal size, accordingly, the non-parametric Mann-Whitney U-test was chosen as the appropriate test for investigating if IV_1 had an effect on the DV. Tests were carried out for both arousal and valence responses.

As these tests only allow for conclusions for the specific odour-image combinations, further tests were conducted to establish effects of odour valence groups (positive, negative and neutral odours) on the emotional perception of the three image groups (negative, neutral and positive). First, all responses for each image group (when perceived with odours) were collated and Kruskal-Wallis H tests were conducted on the data to test whether responses inside image groups varied significantly. The Kruskal-Wallis H test was conducted in place of a one-way ANOVA, as, once again, group sizes were not equal, as two images of an image group were rated by participant group 1 while the remaining two images of an image group were rated by participant group 2. The tests showed that there were no significant variances ($p < 0.05$) in the data for any of the image groups (with no odour actuation) in terms of valence.

In terms of arousal there was a significant variance in the sample for the positive image group (χ^2 (3, N = 44) = 8.26, $p = 0.037$) but not for any of the other groups. This would indicate that one or more of the images in the positive group did not result in the anticipated positive response. Pairwise Mann-Whitney U-Tests were conducted post hoc to determine which image was an outlier.

Image	**Median**	**U**	***p***
Positive 1	4	12.5	0.004
Positive 2	-2		
Positive 1	4	39.0	0.180
Positive 3	3		
Positive 1	4	32.5	0.080
Positive 4	0		
Positive 2	-2	30.0	0.050
Positive 3	3		
Positive 2	-2	58.5	0.974
Positive 4	0		
Positive 3	3	61.0	0.551
Positive 4	0		

Table 4.5: Statistics for pairwise comparison with Mann Whitney U-Tests of arousal responses of positive images.

Pairwise comparison of the images revealed that positive image two (the aerial view of a town) is the outlier. It is possible that this image was perceived as neutral or boring and hence did not produce high arousal responses. Removing the results for this image from the Kruskal-Wallis test produces a result that shows no significant variance (χ^2 (2, N = 34) = 3.70, $p = 0.148$), hence supporting the idea that positive image two is the outlier. Arousal responses for positive image two are therefore excluded from the remaining group analysis.

Further Kruskal-Wallis tests were conducted for all odour image-group combinations. For valence, once again, no significant variance could be found within the groups ($p < 0.05$), which allowed me to conduct further tests between these groups and the control no-odour image groups. For arousal, significant variance could only be found for the orange odour, with the negative images group (χ^2 (3, N = 44) = 8.577, $p = 0.034$). This combination was therefore excluded from further analysis.

Having a confirmation that individual images of a group have little variance between them, and can hence be treated as a group statistically, allowed me to analyse the effect of odours on the perception of images as groups and types and allows for conclusions that are more generalisable.

To test if odour had a significant effect on the emotional perception of images, further Mann-Whitney U-tests were conducted on image groups with odour in comparison to image groups without odour, for both valence and arousal.

To test whether any of the observable effects were caused by the odours alone and to determine whether the act of odour actuation using Scentee affected the DV, an initial comparison between water and the control (no odour) condition was performed. As water is not perceived to have a discernible odour by humans, it eliminates any effects that odours could have on the emotional perception of images, while producing the same visual stimuli of odour actuation using Scentee i.e., a short plume of vapour escaping the device.

As group sizes differed, a non-parametric Mann-Whitney U-test was used. Responses to images with the neutral (water) odour condition were compared to responses of the same image without odour actuation for both arousal and valence.

Lastly, to determine whether the addition of odours to an image significantly affected valence and arousal responses, a Mann-Whitney U-Test was carried out between all responses to images displayed with an odour, and all responses to images displayed without an odour. The results of the analysis carried out in response to $RQ_{exploratory}$ can be found in Section 4.8.1.

4.7.2 H_1: The Congruence of Image and Odour Valence Affects the Emotional Response to a Digital Image

To determine if congruence of image and odour valences affected emotional responses to images, the changes in mean valence responses to images were compared between an image viewed without odour actuation and an image viewed with odour actuation. Images were considered individually and as groups i.e., negatively valenced images, neutrally valenced images and positively valenced images. To establish if a general trend of congruence was present, images and odour combinations were grouped per their congruence. A list of congruent and incongruent combinations can be seen in Table 4.6.

Congruence	Image Group	Odour
Congruent	Positive	Orange
		Strawberry
	Negative	Earthworm
		Faeces
Incongruent	Positive	Earthworm
		Faeces
	Negative	Orange
		Strawberry

Table 4.6: Congruent and incongruent image-odour pairs.

Pairwise Mann-Whitney U-Tests were conducted on congruent image combination groups (pos-pos: Orange and Strawberry with positive images, neg-neg: Earthworm and Faeces with negative images) to test if a congruence effect was present for these groups. To test whether an overall congruence effect was present a Kruskal-Wallis *H* test was conducted on all four congruent groups. Values were converted to their absolute values to be able to compare them, as negative valence was represented with negative numbers. Furthermore, Mann-Whitney-U tests were conducted for individual images, between congruent odour pairs. This was done to establish if the effect on the valence perception of individual images could be attributed to the congruence of an odour.

The results of the analysis carried out in response to H_1 can be found in Section 4.8.2.

4.8 Results

This section gives details of the statistical analysis outlined in Section 4.7. The results of the statistical analysis towards $RQ_{exploratory}$ can be found in Section 4.8.1, while the results of the statistical analysis towards H_1 can be found in Section 4.8.2.

4.8.1 $RQ_{exploratory}$: Do Odours Affect the Emotional Perception of Digital Images?

$RQ_{exploratory}$ asked if there is a difference in emotional (valence and arousal) responses to digital images when they are displayed with an odour compared to when they are displayed without an odour? The results show that olfactory stimulation while viewing digital images appear to significantly affect the viewer's emotional responses to the images in terms of both valence and arousal, indicating that this is indeed the case, though not always. Sections 4.8.1.1 and 4.8.1.2 show the results for the statistical analysis detailed in Section 4.7.1 for valence and arousal respectively.

4.8.1.1 Valence

An initial data analysis of the valence responses to the different image types revealed that each image group was perceived as significantly different from the others: There was a significant effect of image type on valence responses between the neutral and the positive image group (F (1, 350) = 11.16, $p < 0.000$).

There was a significant effect of image type on valence responses between the neutral and the negative image group (F (1, 350) = 38.80, $p < 0.000$).

There was a significant effect of image type on valence responses between the positive and the negative image group (F (1, 352) = 87.72, $p < 0.000$).

Further data analysis showed that there were no significant changes for individual image-odour combinations in terms of valence for the earthworm odour. Orange showed mixed results for valence, with significant changes with Neutral image 1, Neutral image 2; Negative image 1, Negative image 3. Strawberry showed significant changes to the arousal responses vs the control for Neutral image 1, Neutral image 3, Neutral image 4; Negative image 1,Negative image 3; Positive image 2, Positive image 3. The faecal odour produced significant changes in terms of valence responses for all images.

The results for valence for the neutral images can be seen in Table 4.7.

Image	Mean (Image only)	Odour	Mean (Image with odour)	*U*	*p*
Neutral 1	0.0	Water	0.0	56.0	0.821
Toolbox		Orange	3.5	25.0	0.021
		Strawberry	4.0	24.0	0.017
		Earthworm	0.0	53.0	0.670
		Faeces	-4.0	14.0	0.002
Neutral 2	0.0	Water	0.0	59.5	0.974
Fire		Orange	3.0	23.5	0.014
extinguisher		Strawberry	0.0	45.0	0.346
		Earthworm	0.0	59.5	0.970
		Faeces	-5.5	0.0	0.000
Neutral 3	0.0	Water	0.0	56.0	0.821
Door		Orange	1.5	34.0	0.093
		Strawberry	3.5	12.5	0.001
		Earthworm	0.0	57.0	0.870
		Faeces	-4.5	28.0	0.036
Neutral 4	0.0	Water	0.0	53.0	0.674
Refrigerator		Orange	3.0	45.0	0.346
		Strawberry	3.4	25.5	0.021
		Earthworm	0.0	49.5	0.470
		Faeces	-6.0	20.0	0.007

Table 4.7: Mann-Whitney U test results for valence of neutral images.
indicates significant finding ($p < 0.05$)

The results for valence for the positive images can be seen in Table 4.8.

Image	**Mean (Image only)**	**Odour**	**Mean (Image with odour)**	***U***	***p***
Positive 1	4.0	Water	3.5	46.0	0.381
Smiling Child		Orange	4.0	57.5	0.872
		Strawberry	5.0	39.0	0.180
		Earthworm	3.0	39.0	0.180
		Faeces	-5.0	16.0	0.003
Positive 2	3.0	Water	2.0	43.5	0.283
Panorama of		Orange	3.5	47.5	0.418
Historic Town		Strawberry	5.0	27.0	0.030
		Earthworm	0.0	35.5	0.107
		Faeces	-5.5	3.5	0.000
Positive 3	3.0	Water	2.5	44.5	0.346
Couple in		Orange	4.0	36.5	0.140
Nature		Strawberry	5.5	29.5	0.043
		Earthworm	2.0	30.0	0.050
		Faeces	-4.5	11.5	0.001
Positive 4	4.0	Water	0.0	12.0	0.001
Festive Dinner		Orange	4.5	59.0	0.974
		Strawberry	4.5	50.5	0.582
		Earthworm	4.0	43.0	0.283
		Faeces	-5.0	5.0	0.000

Table 4.8: Mann-Whitney U test results for valence of positive images.
indicates significant finding ($p < 0.05$)

The results for valence for the negative images can be seen in Table 4.9.

Image	Mean (Image only)	Odour	Mean (Image with odour)	*U*	*p*
Negative 1	-3.5	Water	-2.5	37.5	0.140
Zombie		Orange	-1.5	31.5	0.059
		Strawberry	-1.5	20.5	0.009
		Earthworm	-3.0	52.5	0.674
		Faeces	-7.0	16.0	0.003
Negative 2	-4.0	Water	-3.0	40.5	0.228
Child in		Orange	-3.0	43.5	0.283
Warzone		Strawberry	-2.0	35.0	0.107
		Earthworm	-4.0	51.0	0.582
		Faeces	-6.0	24.5	0.021
Negative 3	-4.0	Water	-0.5	23.0	0.014
Garbage		Orange	-1.5	27.5	0.030
		Strawberry	3.5	21.0	0.009
		Earthworm	-2.0	41.5	0.228
		Faeces	-6.5	9.0	0.000
Negative 4	-3.5	Water	-3.0	52.0	0.628
Pigs Heads		Orange	0.0	38.0	0.159
		Strawberry	-1.5	39.0	0.180
		Earthworm	-4.0	53.5	0.674
		Faeces	-6.5	21.5	0.009

Table 4.9: Mann-Whitney U test results for valence of negative images.
indicates significant finding ($p < 0.05$)

Taking a look at individual image and odour combinations first, Table 4.7, Table 4.8 and Table 4.9 show mean and median valence responses for each odour and image condition. What becomes clear is that the faecal smell had the strongest overall effect, producing purely negative responses, no matter which image it was combined with. While the other odours do not fail to sway the reported values in the direction of the odour's valence, their effect is not as pronounced as the one from the faecal odour. On average, the faecal odour was able to reduce valence ratings by 4.80 points mean = -4.85, SD = 1.69), compared to an increase of 2.24 points for strawberry (mean = 2.16, SD = 1.65), the most positive odour.

Table 4.10 gives an overview of the median, mean and standard deviations of the neutral image valence results.

Image	Odour	Median	Mean	*SD*
Neutral 1	Image only	0.0	0.40	0.84
Toolbox	Water	0.0	0.17	2.48
	Orange	3.5	2.83	2.33
	Strawberry	4.0	2.92	2.27
	Earthworm	0.5	0.67	2.64
	Faeces	-4.0	-3.50	3.40
Neutral 2	Image only	0.0	-0.10	0.57
Fire	Water	0.0	-0.33	1.15
Extinguisher	Orange	3.0	2.33	2.50
	Strawberry	0.0	1.33	2.06
	Earthworm	0.0	0.25	2.30
	Faeces	-5.5	-4.75	2.90
Neutral 3	Image only	0.0	1.00	1.95
Door	Water	0.0	0.40	0.84
	Orange	1.5	1.60	1.71
	Strawberry	3.5	3.20	1.55
	Earthworm	0.0	-0.60	3.10
	Faeces	-4.5	-3.20	5.29
Neutral 4	Image only	0.0	1.00	1.95
Refrigerator	Water	0.0	1.20	1.62
	Orange	3.0	2.00	2.31
	Strawberry	3.5	3.50	2.22
	Earthworm	0.0	-0.30	4.35
	Faeces	-6.0	-3.70	4.55

Table 4.10: Neutral images valence results.
cells represent positive values
cells represent negative values
Brighter colours, represent a greater magnitude of values.

Table 4.11 gives an overview of the median, mean and standard deviations of the positive image valence results.

Image	Odour	Median	Mean	*SD*
Positive 1	Image only	4.0	3.70	1.77
Smiling Child	Water	3.5	2.83	2.04
	Orange	4.0	3.92	1.83
	Strawberry	5.0	4.50	2.35
	Earthworm	3.0	2.25	2.83
	Faeces	-3.5	-1.25	5.23
Positive 2	Image only	3.0	3.00	1.05
Panorama of	Water	2.5	1.92	2.31
Historic Town	Orange	3.5	3.59	1.98
	Strawberry	5.0	4.42	1.88
	Earthworm	0.0	0.42	2.57
	Faeces	-5.5	-4.67	2.77
Positive 3	Image only	3.0	3.50	1.45
Couple in	Water	2.5	2.40	2.12
Nature	Orange	4.0	4.30	1.25
	Strawberry	5.5	4.90	2.13
	Earthworm	2.0	1.60	2.68
	Faeces	-4.5	-3.80	4.10
Positive 4	Image only	4.0	4.67	1.50
Festive Dinner	Water	1.5	1.90	2.13
	Orange	4.5	4.60	1.58
	Strawberry	4.5	5.00	1.70
	Earthworm	4.0	3.60	1.65
	Faeces	-5.0	-3.90	3.41

Table 4.11: Positive images valence results.
cells represent positive values
cells represent negative values
Brighter colours, represent a greater magnitude of values.

Table 4.12 gives an overview of the median, mean and standard deviations of the negative image valence results.

Image	Odour	Median	Mean	*SD*
Negative 1	Image only	-3.5	-3.40	2.37
Zombie	Water	-2.5	-2.08	2.75
	Orange	-1.0	0.00	3.54
	Strawberry	1.5	0.92	3.45
	Earthworm	-3.0	-2.58	3.48
	Faeces	-7.0	-6.17	1.27
Negative 2	Image only	2.5	1.70	4.27
Child in	Water	2.5	1.25	3.55
Warzone	Orange	3.5	2.67	3.23
	Strawberry	2.0	1.00	4.07
	Earthworm	-4.0	-2.92	4.06
	Faeces	-6.0	-5.00	3.39
Negative 3	Image only	-4.0	-3.08	2.61
Garbage	Water	-0.5	-0.10	2.60
	Orange	-1.5	-0.10	3.25
	Strawberry	3.5	1.60	4.30
	Earthworm	-2.0	-1.10	3.73
	Faeces	-6.5	-6.30	0.82
Negative 4	Image only	-3.5	-2.42	3.97
Pigs Heads	Water	-3.0	-1.70	2.71
	Orange	0.0	0.00	4.08
	Strawberry	1.0	0.30	3.80
	Earthworm	-4.0	-3.40	2.59
	Faeces	-6.5	-5.80	1.61

Table 4.12: Negative images valence results.
Blue cells represent positive values
Red cells represent negative values
Brighter colours, represent a greater magnitude of values.

For a full set of raw results see Appendix A.3.

While considering the images and odour pairs individually already gives an indication of how odours can affect our emotional perception of images, these results are not generalisable and may not reveal the wider ranging effects. By grouping images according to their valence, these effects may be found. Figure 4.12, Figure 4.13 and Figure 4.14 show the mean results for valence of each image group plotted as box charts to highlight the change compared to the control group (no odour).

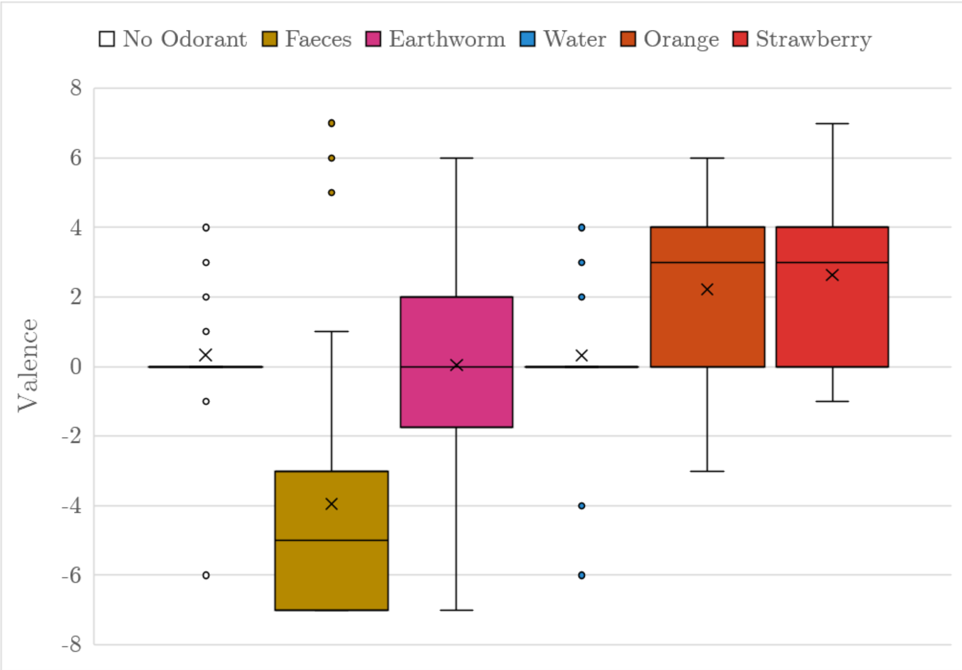


Figure 4.12: Box plot charts of mean valence responses for neutral image groups.

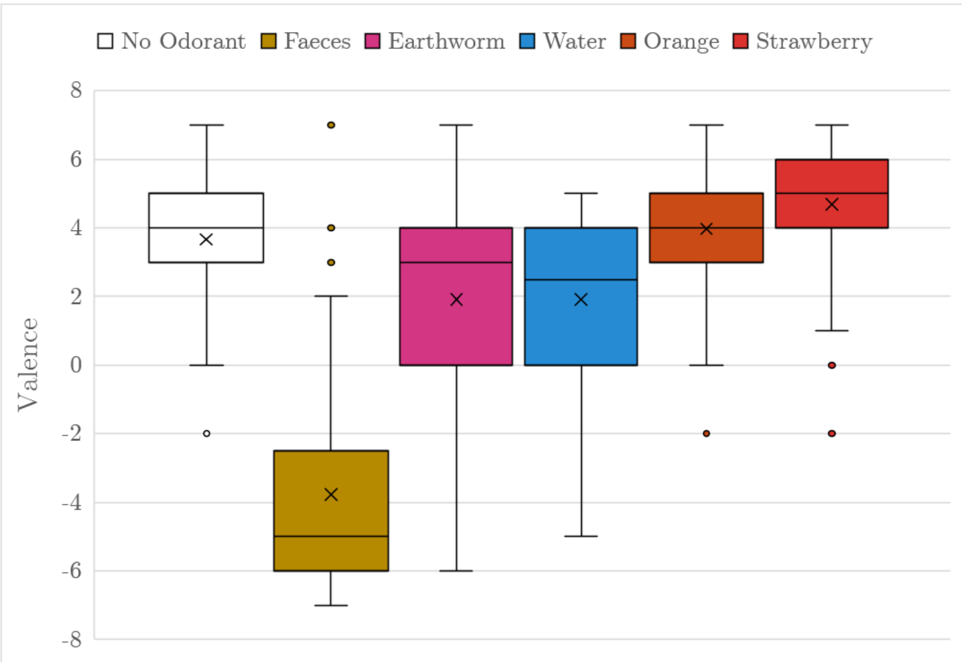


Figure 4.13: Box plot charts of mean valence responses for positive image groups.

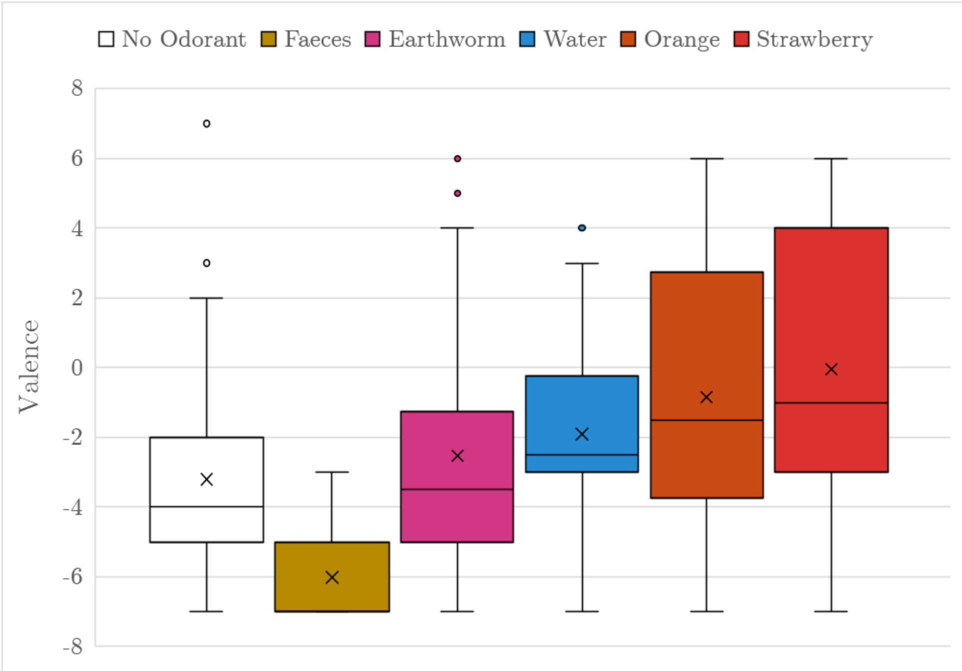


Figure 4.14: Box plot charts of mean valence responses for negative image groups.

The faecal smell produced significantly more negative scores than the image only condition (mean = -4.85, SD = 2.36). The magnitude of change for the perception of images with faecal odour compared to without odour actuation is greatest for the positive image group (7.43) then the neutral image group (-4.30) and the smallest effect can be seen for the negative image group (2.81). For valence, water produced significant changes in results for both negative and positive images and an overall change of mean = -0.16 (SD = 1.50). Similar to arousal scores, negative images were perceived less negative (image only mean = -3.20, SD = 2.81; image with water mean = -1.91, SD = 2.59) while positive images were perceived less positive (image only mean = 3.66, SD = 1.75; image with water mean = 1.91, SD = 2.46). Earthworm produced slightly more negative scores overall (mean = -0.45, SD = 1.22) with significant results for the positive images (image only mean = 4, image with earthworm mean = 3.00, U = 646.5, p = 0.001), which were perceived as less pleasant than images only (image only mean = 3.66, SD = 1.75; image with earthworm mean = 1.91, SD = 2.88). As with the other negative odour (faeces) the effect is greatest with images of the opposite valence - a negative odour with a positive image produced the greatest effect. Orange showed significantly more positive valence scores for negative (image only mean = -4.00, image with orange mean = -1.50, U = 569.5, p < 0.000) and neutral (image only mean = 0, image with orange mean = 3, U = 496.5, p = 0.000) image groups. Strawberry saw similar but stronger results across image groups (mean = 2.16, SD = 1.07). Once again, negative images saw a greater change (image only mean = -3.2, SD = 2.81; image with strawberry mean = -0.05, SD = 3.91) when compared to neutral (image only mean = 0.34, SD = 1.63; image with strawberry mean = 2.64, SD = 2.22) or positive images change (image only mean = 3.66, SD = 1.75; image with strawberry mean = 4.68, SD = 1.99).

Water showed significant changes ($p < 0.05$) to results in terms of valence for positive image 3 (couple kissing in nature) and negative image 2 (child in war zone), suggesting that the neutral odour water did not have a significant effect overall on the perception of valence of the images.

Image	Condition	Median	*U*	*p*
Positive 1	Image Only	4	46	0.381
	Water	3.5		
Positive 2	Image Only	3	43.5	0.283
	Water	2		
Positive 3	Image Only	3	44.5	0.346
	Water	2.5		
Positive 4	Image Only	4	12	0.000
	Water	0		
Neutral 1	Image Only	0	56	0.821
	Water	0		
Neutral 2	Image Only	0	59.5	0.974
	Water	0		
Neutral 3	Image Only	0	65	0.821
	Water	0		
Neutral 4	Image Only	0	53	0.674
	Water	0		
Negative 1	Image Only	-3.5	37.5	0.140
	Water	-2.5		
Negative 2	Image Only	-4	40.5	0.228
	Water	-3		
Negative 3	Image Only	-4	23.0	0.014
	Water	-0.5		
Negative 4	Image Only	-3.5	52	0.628
	Water	-3		

Table 4.13: Statistics for valence responses of image only vs image with water condition. ▇ indicates significant finding ($p < 0.05$)

Lastly, an overall comparison between the image only and with odour conditions revealed that there were no significant differences in terms of valence (image only median: 0.00, image with odour median: 0.00, U = 33558.00, $p = 0.511$.

4.8.1.2 Arousal

An initial data analysis of the arousal responses to the different image types revealed that there was a significant effect of image type on arousal responses between the neutral and the positive image group (F (1, 438) = 6.08.16, $p = 0.014$).

There was no significant effect of image type on arousal responses between the neutral and the negative image group (F (1, 438) = 1.43, $p = 0.233$).

There was a significant effect of image type on arousal responses between the positive and the negative image group (F (1, 438) = 11.29, $p < 0.000$).

In terms of arousal, earthworm showed significant changes for Positive image 1 and Positive image 3. Orange only significantly affected user perception in terms of arousal for Negative image 3. Strawberry did not significantly affect participants' perception of arousal of individual images. The faecal smell however showed significant changes in results for all images except Negative image 2, Neutral image 4, and Positive image 4.

The results for arousal for the neutral images can be seen in Table 4.14.

Image	Mean (Image only)	Odour	Mean (Image with odour)	*U*	*p*
Neutral 1	0.0	Water	0.0	45.0	0.346
Toolbox		Orange	0.0	49.5	0.497
		Strawberry	0.0	60.0	0.974
		Earthworm	-0.5	36.5	0.140
		Faeces	-3.5	25.5	0.021
Neutral 2	0.0	Water	0.0	48.5	0.497
Fire		Orange	0.0	50.5	0.582
extinguisher		Strawberry	0.0	29.5	0.043
		Earthworm	0.0	44.5	0.346
		Faeces	-4.5	20.0	0.007
Neutral 3	0.0	Water	0.0	54.0	0.722
Door		Orange	0.0	56.0	0.821
		Strawberry	-1.0	56.5	0.872
		Earthworm	-1.0	50.0	0.539
		Faeces	-6.0	16.0	0.003
Neutral 4	0.0	Water	0.0	51.5	0.582
Refrigerator		Orange	0.0	46.5	0.418
		Strawberry	3.5	30.5	0.059
		Earthworm	-3.0	37.5	0.140
		Faeces	-4.5	40.5	0.228

Table 4.14: Mann-Whitney U test results for arousal of neutral images.
▇ indicates significant finding ($p < 0.05$)

The results for arousal for the positive images can be seen in Table 4.15.

Image	**Mean (Image only)**	**Odour**	**Mean (Image with odour)**	***U***	***p***
Positive 1	4.0	Water	2.0	33.5	0.080
Smiling Child		Orange	4.0	54.5	0.771
		Strawberry	4.0	53.0	0.674
		Earthworm	-2.0	15.5	0.002
		Faeces	-4.5	23.5	0.014
Positive 2	-2.0	Water	-2.0	55.5	0.771
Panorama of		Orange	-2.0	57.5	0.872
Historic Town		Strawberry	-2.0	58.0	0.923
		Earthworm	0.0	57.0	0.872
		Faeces	-4.5	25.5	0.206
Positive 3	3.0	Water	-0.5	29.0	0.043
Couple in		Orange	0.0	51.5	0.582
Nature		Strawberry	5.5	29.0	0.043
		Earthworm	1.0	30.0	0.050
		Faeces	-4.0	31.5	0.059
Positive 4	0.0	Water	0.0	59.0	0.974
Festive Dinner		Orange	4.0	31.0	0.059
		Strawberry	4.0	35.5	0.107
		Earthworm	2.5	53.0	0.674
		Faeces	-5.0	39.0	0.180

Table 4.15: Mann-Whitney U test results for arousal of positive images.
indicates significant finding ($p < 0.05$)

The results for arousal for the negative images can be seen in Table 4.16.

Image	Mean (Image only)	Odour	Mean (Image with odour)	*U*	*p*
Negative 1	3.0	Water	-1.0	38.0	0.159
Zombie		Orange	-0.5	38.0	0.159
		Strawberry	3.0	54.5	0.771
		Earthworm	-1.0	43.5	0.283
		Faeces	-6.0	22.0	0.011
Negative 2	-2.5	Water	-3.0	58.5	0.974
Child in		Orange	-4.0	47.5	0.418
Warzone		Strawberry	1.5	35.5	0.107
		Earthworm	-3.5	58.0	0.923
		Faeces	-5.0	57.0	0.872
Negative 3	-4.0	Water	-1.5	33.5	0.080
Garbage		Orange	0.0	24.5	0.021
		Strawberry	0.0	32.0	0.069
		Earthworm	-2.0	41.5	0.228
		Faeces	-6.5	20.0	0.007
Negative 4	-2.5	Water	-3.0	58.0	0.922
Pigs Heads		Orange	0.0	48.0	0.456
		Strawberry	-1.5	49.0	0.497
		Earthworm	-4.0	50.0	0.539
		Faeces	-6.5	27.5	0.030

Table 4.16: Mann-Whitney U test results for arousal of negative images.
indicates significant finding ($p < 0.05$)

While considering the images and odour pairs individually already gives an indication of how odours can affect our emotional perception of images, these results are not generalisable and may not reveal the wider ranging effects. By grouping images according to their arousal, these effects may be found. Figure 4.15, Figure 4.16 and Figure 4.17 show the mean results for arousal of each image group plotted as box charts to highlight the change compared to the control group (no odour).

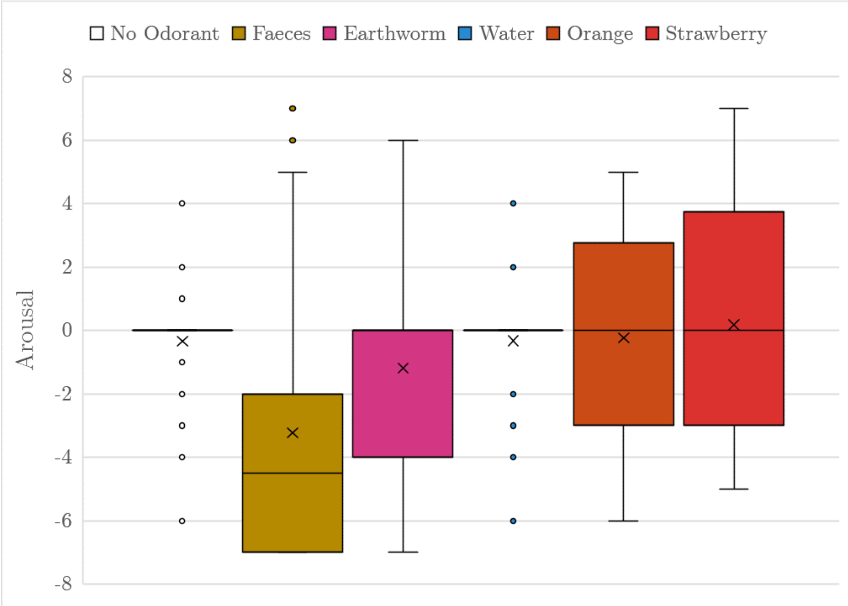


Figure 4.15: Box plot charts of mean arousal responses for the neutral image groups.

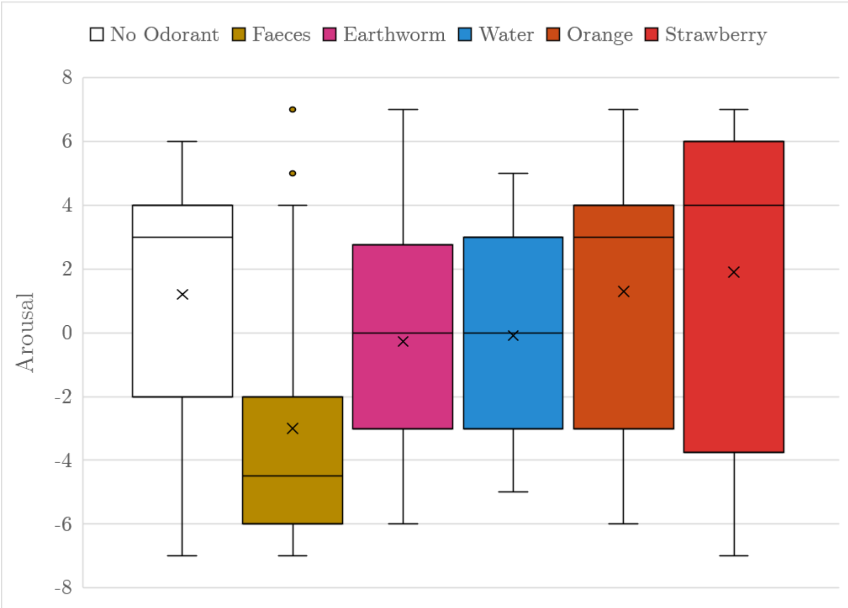


Figure 4.16: Box plot charts of mean arousal responses for the positive image groups.

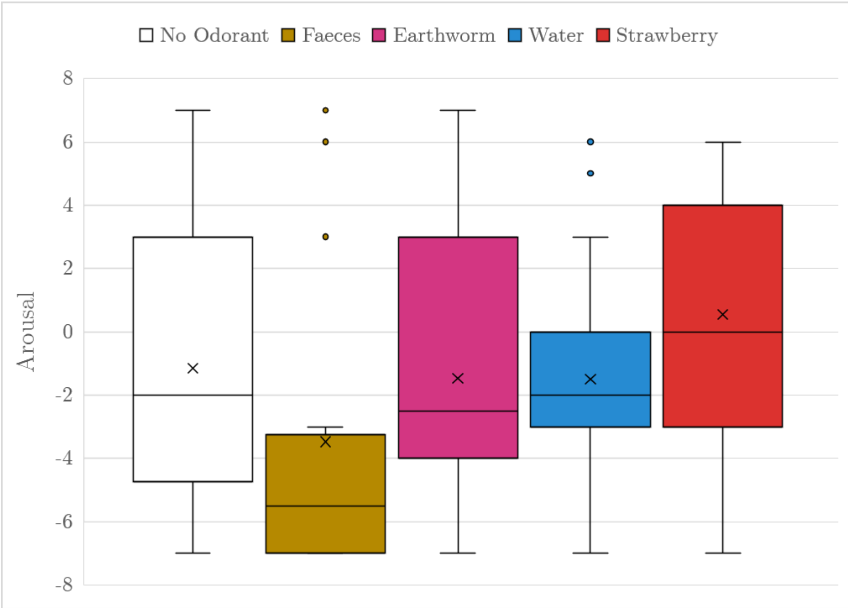


Figure 4.17: Box plot charts of mean arousal responses for the negative image groups.

What can be seen is a clear shift towards a negative arousal for the faecal smell, with a mean reduction of mean = 3.14 points (SD = 0.97). Water produced no significant change in arousal levels (mean = 0.54, SD = 0.68). What should be noted here is that negative and positive images showed more negative participant scores than the control group. Neutral images however saw no such decrease (change of 0.02 in positive direction). It is possible that the perception of the neutral images was not changed in terms of arousal levels as their base produced little arousal to begin with. Earthworm produced a reduction in arousal scores for all groups, (mean = 0.58, SD = 0.37), which is in line with its intended effect as a negative odour, however the reduction is minimal. Orange produced no significant change in arousal responses although a mean change of mean = 0.13 (SD = 0.02) was found. Strawberry on the other hand showed a significant change in arousal levels for positive images and overall produced more positive results (mean = 0.98, SD = 0.64), demonstrating that image perception in terms of arousal could be swayed to the positive.

Lastly, an overall comparison between the image only and with odour conditions revealed that there were significant differences in terms of arousal (image only median: 0.00, image with odour median: -2.00, U = 30713.00, $p = 0.034$.

4.8.2 H_1: Emotional Response to Congruence of Image and Odour Valences

Research question two asks if the congruence of image and odour valences can affect emotional responses to images. Results were mixed, with a general congruence effect to be observed between the positive images and positive odours, while negative images and negative odours showed no congruence effect.

Based on Table 4.11, Table 4.10 and Table 4.12, we can see that the positive odours modulated the perceived valence the most when in conjunction with negative images. The greatest difference in valence can be seen with the strawberry odour and negative picture 3 with a 2.75 point valence difference in the positive direction (mean no-odour = -3.4, mean strawberry = 1.6, p = 0.009). On the other hand, negative odours showed a similar characteristic by eliciting the highest difference in valence when in combination with positive pictures. The odour of faeces hereby showed the single greatest valence difference with 8.57 points in the negative direction for image positive 4, depicting the festive dinner (mean no odour = 4.67, mean faeces = -3.90, p = 0.00), and a mean valence difference of mean = 5.16 (SD = 1.92) in the negative direction for the positive images combined.

Pairwise comparison of congruent odours for grouped images showed that there was a significant difference between the earthworm and faeces groups (earthworm - negative images mean = -3.5, faeces - negative images mean = -7, U = 262.4, p = 0.000), indicating that they cannot be treated as one group, hence no congruence. The same result was observed between the orange and strawberry groups (orange - positive images mean = 4, strawberry - positive images mean = 5, U = 710, p = 0.029), indicating that there was no congruence effect on the positive image - positive odours group.

Treating all congruent image and odour combinations as groups revealed that there is a significant variance between them (χ^2 (3, N = 44) = 41.57, p = 0.000). A comparison between same-valence odour pairs and congruent images showed that there was significant variance between the earthworm and the faeces groups for all negative images (p < 0.05). Orange and strawberry groups however, showed no significance, indicating that they did indeed have similar effects on individual positive images. The full results for the individual images can be seen in Table 4.17.

Congruence	Image	Odour	Mean	*U*	*p*
Neg Neg	Negative 1	Earthworm	-3	20.0	0.002
		Faeces	-7		
	Negative 2	Earthworm	-4	25.0	0.006
		Faeces	-6		
	Negative 3	Earthworm	-2	4.5	0.000
		Faeces	-6.5		
	Negative 4	Earthworm	-4	21.0	0.029
		Faeces	-6.5		
Pos Pos	Positive 1	Orange	4	51.5	0.266
		Strawberry	5		
	Positive 2	Orange	3.5	50.5	0.219
		Strawberry	5		
	Positive 3	Orange	4	33.0	0.218
		Strawberry	5.5		
	Positive 4	Orange	4.5	44.0	0.684
		Strawberry	4.5		

Table 4.17: Variance between groups of same-valence-odours for individual congruent images. (blue) indicates significant finding ($p < 0.05$)

4.9 Discussion

The experiment reported in this chapter aimed to explore some of the emotional interactions between odours and images while using a mobile device. It also, significantly, served as an exploratory study for further work, to test a novel OD, and in order to gain insights in terms of a state of the art approach to odour selection, towards a novel and comprehensive method of odour selection, to be used consistently in Studies Two, Three, and Four. The results showed that odours can significantly affect a user's emotional perception of said images in terms of arousal as well as valence. While some odours produced more pronounced results, especially the faecal odour, all odours were able to shift responses in the direction of their associated valence. This includes the non-odour water, which had a dampening effect and was able to draw both valence and arousal values towards the neutral point 0. Perhaps unexpectedly, odours that were of opposing valence to images produced stronger changes in responses compared to images that were in this sense congruent with odours. While some researchers have begun to investigate the importance of semantic congruence between odour and media, valence has not been a part of this analysis (Ghinea and Ademoye, 2012a; Gottfried and Dolan, 2003; Sakai, 2005). The analysis so far has focused on higher and abstract levels of processing of congruence, such as the effects of inappropriately coloured fruit solution on the ability to sort these solutions according to odour intensity (Blackwell, 1995). The fact that congruence extends to valence, even for odours that are semantically unrelated to image content, raises the question of what the effects of congruence of valence would be on more established and higher level measurements such as user perceived QoE. These results however clearly demonstrate that valence of odour must be taken into consideration when selecting odours, as the valence of an odour significantly affects users' emotional perception and thereby their user experience. However, it must be noted that this effect was only observable for positive congruence, i.e. orange and strawberry odours combined with positive images. It is possible that this is a matter of choice of odours and that the orange and strawberry odours were perceived as quite similar, while the earthworm and faeces odour were perceived quite different. Throughout the experimental sessions it was noticed that the faecal odour triggered a concomitant avoidance response as is the case with negative odours that irritate the trigeminal nerve. It is therefore possible that negative odours that produce this kind of behaviour are perceived entirely differently from negative odours that do not, once again highlighting the importance of screening for the valence of an odour as part of an odour selection methodology. However, these results suggest that some odours can be used to universally change perceptions of valence through technology.

In terms of arousal, results were not as clear. This is somewhat expected as images as well as odours were primarily selected for their valence content and only secondarily for their arousal properties. An unexpected finding though was that odours of a negative valence often produced reductions in perceived arousal levels, while positively valenced odours produced an increase in arousal. This is perhaps caused by the emotion descriptors of the Plutchik emotion wheel where a faecal odour in combination with any of the images may have produced a response of 'disgust' (arousal of -1) rather than say a mere reduction of 'joy'. Similarly, the odour of oranges may have caused 'surprise' rather than a reduction of 'sadness' when viewing the image of a child working in a bomb factory. This is perhaps also a critique of the use of the Plutchik emotion wheel in HCI studies. The use of the descriptors allows for a level of abstraction by the experimental participant that is not intended. For example, does a response of 'anger' indicate that a participant feels anger at the content of the image modulated by the odour, or is the participant simply angry because the odour is semantically incongruent with the image? It is therefore difficult to judge whether participant responses are ratings of their emotional perception of the image (when using odour as a cue) or whether they are rating their perception of the odour. Perhaps this distinction is not vital, as the experience as a whole is affected by the use of odours, however when using odour cues it is vital to be able to distinguish between responses that rate the odours themselves and those that rate the perception modulated by the odour.

The use of the Scentee device was also examined during this study. While the weight of an object has been shown to affect a person's perception of the object (Spence, 2007), the added weight of the Scentee device and mere presence did not appear to have an effect on the emotional responses, as is demonstrated with the neutral odour, which was not perceived as significantly differently from the no-odour condition. The simple fact that Scentee was vaporising a liquid did not have an effect on the emotional response to pictures either, it is therefore also certain that the odours produced a modulation in rating of digital images. This shines a positive light on the use of piezoelectric atomisers (which is the technology inside Scentee that disperses the odour) as the base for an OD. While Scentee did not affect user ratings, several issues with the device were identified and its suitability in the context of its application to a VR setting is discussed in the following section.

4.9.1 The Suitability of Scentee as an Olfactory Display for User Based Studies

Lingering odours have been one of the main issues in the use of odours in HCI (see Section 3.5. None of the participants of this study mentioned that they felt that odours as if odours were lingering or mixing, however participants were not specifically asked to comment on the lingering of odours. Neither study supervisor at the two test sites noticed that odours were lingering. While this may have been partly due to giving participants sufficient breaks in between each odour exposure, it is possible that short puffs of vaporised odour as emitted by the piezoelectric atomiser of the Scentee played a role in their property to not linger as only minuscule amounts of odour are vaporised during each puff. These results therefore speak positively for the use of Scentee as an odour display. However, several shortcomings of the OD were identified that make it less suitable to use. One of the main issues of the Scentee device is that it can only be controlled using a mobile device running an iOS operating system. Furthermore, the OD uses proprietary cartridges that have to be purchased individually and are designed specifically to work with the provided odours. Using Scentee with my own choice of odours was only possible by modifying the device by drilling into the cartridge and emptying out the original odorant. This however meant that odour contamination could not be entirely excluded as minute amounts of the original odours may still have remained in the cartridge. Lastly, the type of piezoelectric atomiser used in the Scentee clogs up when used with oily and viscous liquids, restricting its use to water and alcohol based odorants or other liquid based odorants with low viscosity. However, other types of piezoelectric atomiser exist that are able to vaporise more viscous liquids.

4.10 Limitations, Reliability, and Validity

While the research reported here suggests that odour cues can modulate emotional perception of digital images, certain limitations apply. First of all, a limited number of participants in the pilot study meant that the ratings for the selected images were not reliable and could only give an indication of how they were generally perceived. A further limitation was that the number of images was reduced from an initial 60 images (which were selected by the lab members) to 12 images before the pilot study, rather than reducing this number after the images had been formally rated by pilot participants. While the selection process did produce images that were perceived as positive, negative, and neutral by the participants, the effect could have been more pronounced.

The participants were from a select circle of students and those otherwise associated with the Universities involved; and whilst certain stipulations were made, the participants cannot convincingly be said to be representative of the entire population overall as they were furthermore mainly from Western, Educated, Industrialized, Rich, and Democratic (WEIRD) societies (Henrich et al., 2010).

While the results show that odours do indeed affect emotional perception of digital images, the reasons behind the varying responses are not yet clear. For example, certain odours resulted in more extreme ratings than others. The most direct effect on emotional responses was shown by the odour of faeces. Whether this was due to the obvious incongruence of odour and most images, as would be suggested by literature (Piqueras-Fiszman and Spence, 2012) or if the odour was simply the most realistic or intense smelling is not clear.

Further limitations relate to the selection and display of odours, stemming from the novelty of olfaction as a sensory modality and a lack of prior methods for odour selection and their use in an HCI setting. The difficulties and limitations with the use of the odours became clear very quickly when a large number had to be excluded because they were either dangerous to handle or due to incompatibilities with the OD, causing restrictions in terms of the types of odours that could be used in the study. This forced a certain arbitrariness in terms of the initial selection of odours and raises a big issue for olfaction-related research in general. The initial selection of odours is mostly random due to a lack of meaningful and standardised odour categorisations (Lawless, 1997). It is therefore difficult to have an initially balanced selection of odours that covers the olfactory spectrum, and researchers are mostly left to their intuition in terms of deciding which odours to use. Making matters worse, a further level of randomness is introduced by the names and labels that manufacturers assign to the odours that they sell. It is impossible to tell what an odorant will smell like before actually perceiving its odour. For example, the *Demeter Fragrance Library* covers over 300 odorants (Demeter, 2018), but without being able to smell them, it is impossible to judge which ones are useful for a study. "A floral smell from one company may be completely different to that of another (and still not like a real floral smell)" (Brewster et al., 2006, p. 657). This was clearly evident in the results regarding the Earthworm odour. While this was selected as a negative odour (and the name also seems to imply an unpleasant odour), it had a mostly neutral effect on participant's ratings. Clearly, an improved odour selection methodology is needed, that eliminates the arbitrariness of the current odour selection approach, and that assesses odours in terms of how they are perceived by participants in terms of a set of perceptive properties.

Adapting the activity-evaluation wheel to fit a mobile screen may have affected user responses. The new arrangement of the wheel on a mobile screen was not compared to the original wheel in terms of the chosen emotional responses and it is hence not possible to say whether the new arrangement produced results different to what one might have expected from the activity-evaluation wheel. Lastly, while translating from the verbal emotion descriptors to numerical values was suggested by literature, it is not certain whether this approach delivered the desired results in the sense that it is not clear whether the numerical representations are an accurate rendition of the results. The current numerical translation removes gradations between the different emotions in terms of their position on the x and y axes. For example, when looking at the two positive arousal and valence emotions of Joy and Surprise on the Plutchik Emotion Wheel (Figure 4.2), these both would be represented numerically with an arousal rating of +1 and a valence rating of +1. This does not fully capture their position on the wheel, where visually, Surprise would have an arousal rating of +0.75 and a valence rating of +0.25, while Joy would have an arousal rating of +0.25 and a valence rating of +0.75. While these values are still an approximation, they would offer an improved representation of the verbal descriptors, taking into consideration details of their positioning on the Emotion Wheel.

4.11 Conclusion

To summarise, this study demonstrates that the introduction of odours is positively linked to the alteration of a person's emotional perception of digital images and therefore can suggest proof of hypothesis H_1. The probably universally negatively connoted smell faeces showed to enhance negative feelings associated with the images shown; positive odours such as fruit odours (strawberry and orange) tended to enhance emotional perception, and the neutral odour had little to no altering effect. One of the important results was that reactions were particularly strong when smell and image contents were incongruent. These results however came with certain limitations, which have been considered in detail.

In terms of odour selection methodology, the results show that a systematic method for odour selection is needed to overcome several of the shortcomings, such as shown by the negative odours, where the earthworm odour produced an effect more similar to the neutral odour, and the faecal odour, which produced a concomitant avoidance response, which is the case with odours of a high intensity that trigger a reaction via the trigeminal nerve. The results therefore indicate that an odour selection methodology should take valence, congruence of odour and intensity into consideration.

The study also gave insights into the use of a piezoelectric atomiser based OD. The results showed that the OD itself did not affect participant and observations made by the study supervisors indicate that the the odours displayed by the OD did not linger. Unfortunately, the OD suffered from shortcomings in terms of re-filling, use with third-party (especially viscous) odours, and was tied to a proprietary mobile app used to control the display of odours, making it unsuitable for my future studies. However, while this specific OD was deemed unsuitable, the technology used to display the odours via a piezoelectric atomiser was sound and appeared promising.

In the following Chapter 5 I describe the common methods used for Studies Two, Three, and Four. These include a systematic method for odour selection, that is based on the above insights as well as the literature discussed in Section 3.2. Furthermore, I describe a new type of OD, that is usable with VR Head-Mounted Displays (HMDs).

Chapter 5

Instrumentation

5.1 Introduction

In this chapter I describe the details of the common methods and instruments that were used for Studies Two, Three, and Four. As discussed in the introduction of this thesis, these studies are separate parts of the overall main study and therefore share the same basic methodology and setup including Virtual Environment (VE), OD, VR HMD, odour selection methodology, and assessment questionnaires, which are detailed in the following sections.

In this chapter I outline the methodology and research design used during Studies Two, Three, and Four, which form the main research body of this thesis and aim to answer the research questions:

RQ_1 *How does congruence of odour affect presence in virtual reality?*

RQ_2 *How do odours affect task performance in virtual reality?*

RQ_3 *Are olfactory notifications effective in virtual reality?*

The chapter begins with a description of the Virtual Environment (VE) used for the studies (Section 5.2, including a description of the VR headset (or Head-Mounted Display (HMD)) (Section 5.3), and VR Game (Section 5.3.2). This is followed by a section on the OD (Section 5.4) that was used in combination with the HMD. I then introduce a new and systematic method for odour selection (Section 4.6.2.2), and then describe the details of a Post-Game Questionnaire (PGQ) (Section 5.6.1), which assesses user-perceived QoE and sense of presence in VR.

5.2 Virtual Reality Environment

To date, most studies that examined how the addition of olfaction can affect the sense of presence in VR made use of low-fidelity VEs, that were limited in their immersivity due to the technology that was available at the time, whether in regard to the graphics engines and libraries that were available at the time, or the VR technology, limiting user tracking, display resolution and field of view. With the recent emergence of consumer-grade HMDs, such as the Oculus Rift, or the HTC Vive, a new degree of realism can be achieved due to improvements in head and hand tracking, as well as display quality through high-resolution displays, driven by improved graphics engines and graphics cards. All of these properties are quantifiable factors that increase the immersivity of a VE (see Section 3.4.4), meaning that the type of VEs that users can expect to find today are very immersive and in order to make use of these features, the decision was made to use a VE that reflects the type of environment that users would be able to find today. Therefore, a highly immersive VR game that is playable on the latest consumer grade VR headsets was considered. The choice to use an off-the-shelf game and VR headset was made due to time and cost constraints that would have been associated with developing my own solution. In the following section I describe the choice of VR headset that was used for Studies Two, Three, and Four.

5.3 Virtual Reality Head Mounted Display

At the time of selecting the VR headset, two main consumer oriented systems were available, the *Oculus Rift* (Oculus VR, 2017) and the *HTC Vive* (Corporation, 2017). The reason that the choice of VR headset fell to a consumer grade system was due to the large range of current games that each of these systems supports. Table 5.1 shows a comparison of technical specifications of the two VR HMDs.

	Oculus Rift	**HTC Vive**
		
Display Type	OLED	OLED
Resolution	2160 x 1200	2160 x 1200
Refresh Rate	90Hz	90Hz
Field of View	110°	110°

Table 5.1: Comparison of the technical specifications of the Oculus Rift and HTC Vive VR Headsets.

Both systems have identical technical specifications and the choice of system therefore was made due to availability. As the Oculus Rift HMD was available at the City, University of London Interaction Lab, I was able to use it for my Studies. The Oculus Rift consists of a HMD, two tracking sensors (see Figure 5.1) and two hand-held controllers (Oculus Touch controller - see Figure 5.2).

Figure 5.1: Oculus Rift tracking sensor

The system can be set up with one sensor, however in order to be able to use the Oculus Touch controllers, two tracking sensors are necessary. Each controller has a set of 3 buttons and one thumbstick on the top side of the controller, one thumb button, and one trigger, that can be used to interact with the VE (see Figure 5.2).

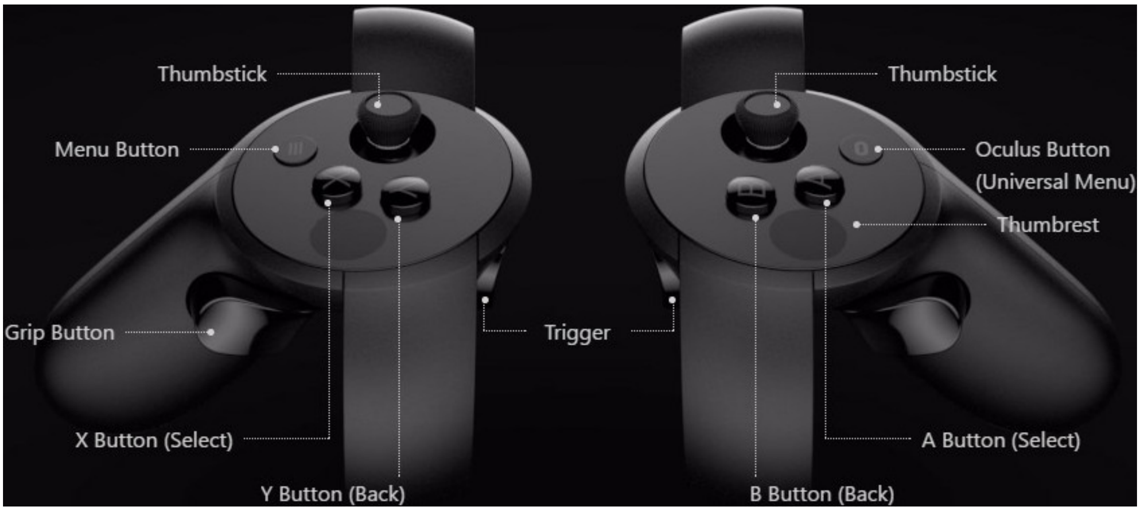


Figure 5.2: Oculus Rift Touch - VR controllers
This is a screenshot taken from the Oculus Rift setup program

The controllers track hand position in 3D space and are able to transfer hand pose and position into the VE (see Figure 5.3). The Touch controller is able to track if a finger is placed on a button and will update the ingame hand representation to resemble the real-world finger placement. For example, by pressing the grip button and lifting the thumb off the controller, the virtual hand will display a thumbs up pose (see Figure 5.3). The controllers can also give haptic feedback by vibrating.

Figure 5.3: Oculus Touch hand tracking in real world (left) and virtual representation (right) (Tauziet, 2016).

5.3.1 Virtual Reality Game Comparison and Suitability

Six factors were taken into consideration when deciding on a choice of game:

1. Odour emitting objects: The game should contain easily identifiable and recognisable odour emitting objects that can be interacted with by the participants and that are spread out throughout the environment to ensure that participants encounter them. The dispersed nature of the odour emitting objects was an important aspect for the selection of the virtual environment as this ensures that participants experience odours periodically rather than continuously. Continuous odours, such as environmental or ambient odours, result in a rapid onset of olfactory fatigue, whereby the participant does not perceive the odour any longer (Barfield and Danas, 1996). Periodic stimulation is therefore important to ensure that participants notice the odours for the duration of the experimental sessions.

2. Enjoyability: The game should be enjoyable for participants. This was measured using the average user score given to the game on the Oculus Experience site. The game should have a score of at least 3.5 out of 5 stars.

3. Touch Controller: In order to increase engagement with the game, I considered only those games that supported and made use of the Oculus Touch controllers.

4. Quick Uptake As the time of the study was limited, participants should be able to start playing the game in a relatively short period of time. This meant that all games which contained lengthy tutorials, or introduction sequences of over 5 minutes were rejected.

5. Nonviolence: Only nonviolent games were considered as participants may not wish to take part in a study that depicts scenes of strong violence. This was defined as a PEGI rating of 7 or lower (PEGI, 2018).

6. Price: As the Oculus store did not offer trial installations of games at the time when I was evaluating games, all games would have had to be bought prior to trying. Therefore, I limited my search to free games or to those which had previously been purchased by the City, University of London Interaction Lab. The previously purchased games were: *The Climb*, and *Arizona Sunshine*. Several games were also bundled with the Touch Controllers and were included in the selection process. These games were *Lucky's Tale*, *Medium*, *Toybox*, *Quill*, *Dead and Buried*, and *Robo Recall*.

I evaluated games from the Oculus Rift Store, the official repository for Oculus Rift compatible VR games. In order to evaluate a game, I downloaded and installed it on the PC connected to the Oculus Rift and tested the game for a period of 10 minutes. If the game failed to meet the criteria set by the 6 factors outlined above at any point, it was rejected.

The first game that matched all of the criteria was the game *The Climb* and is discussed in the following section.

5.3.2 The Climb: Virtual Reality Environment

The Climb is a rock-climbing game developed by CRYTEK (2018b) and released in 2016. The game received an average user score of 4 out of 5 stars on the Oculus Rift store page (Oculus VR, 2018) and has a PEGI rating of 3. In terms of factor 4 (quick uptake), the game features an optional tutorial that guides players through the basic climbing mechanics (described in Section 5.3.3) in approximately 5 minutes. The game supports Oculus Touch controllers and tracks a user's hand position and displays a virtual equivalent at the exact position in virtual space, allowing for more natural interactions with the environment. A hand as displayed by the game can be seen in Figure 5.4. There are three playable levels in *The Climb*, set in a tropical island, a snowy glacier, and in the Alps.

In terms of factor 1, odour emitting objects, there are flowers throughout the different levels of the game. *The Alps* level was the most suitable in regard to factor 1 as individual mountain flowers are scattered along the climbing path that could act as the odour emitting objects. An in-game view of *The Alps* level can be seen in Figure 5.4.

Figure 5.4: Ingame view of *The Climb* - *The Alps* level (CRYTEK, 2018b). The blue shape on the right side of the image is a player's virtual hand.

In the following section I introduce the different types of game mechanics in *The Climb*.

5.3.3 Game Mechanics

The following section gives an overview of the game mechanics in *The Climb*, and how they may afford the use of olfactory stimuli. The mechanics are stamina, climbing, chalk, and savepoints.

5.3.3.1 Stamina

Stamina decreases as a player climbs. The rate at which stamina decreases depends on the amount of chalk that is on one's hands. The amount of stamina is indicated by a blue band around the player's virtual wrists. The stamina indicator can be seen in Figure 5.5. This blue band turns red as stamina decreases. The virtual hands also become visibly more red and shiny. Stamina decreases when a player holds on to the wall with only one hand, i.e. the stamina of the hand holding onto the wall decreases. Once the stamina band turns completely red, the player can no longer hold onto a virtual hand hold until the stamina has replenished. In case that the stamina depletes, and the player is not gripping the wall with their other hand in time, the player falls and respawns at the last savepoint. Stamina can be replenished by letting go of a hand hold or by holding onto the wall with both hands simultaneously.

Figure 5.5: In-game stamina indicator displayed on players' virtual hands.

5.3.3.2 Climbing

Players can advance through the environment by climbing. A player can grip pre-defined points on a wall, i.e. hand holds. When holding on to a hand hold, a player is able to move around in the world by reaching for and gripping other hand holds according to the displacement of their hands from their position when grabbing on to a hand hold to the current position of the hands. Often enough, the path one needs to take to reach the finish line fastest is not immediately clear in that one has multiple hand holds that are within reachable distance at any given point in a climb.

5.3.3.3 Chalk

The amount of chalk on one's hands directly influences the rate at which the stamina of that hand decreases: the more chalk, the slower stamina decreases. The amount of chalk decreases with climbing, i.e. moving a hand from one hand hold to the next. The stamina available and the amount of chalk on each hand can vary. Chalk can be reapplied by letting go of the wall with one hand (by releasing the trigger button of that hand), and by then pressing the grip button and shaking one's hand simultaneously. Depending on how vigorously one shakes their hand, the hand is chalked faster or slower. Chalking with a relaxed shake takes longer than a vigorous shake. An audio indicator (a distorted ringing sound) lets players know that they are currently chalking their hands. If a player stops shaking their hand or releases the grip button, the process is terminated, and the chalking process has to be started over from the beginning again. The completion of the chalking process is indicated by a visual puff of chalk dust and a ringing sound, that is released from the newly chalked hand. As chalking requires the player to let go of the wall with one hand, stamina on the other hand decreases during the chalking process. This makes chalking a time-sensitive activity. First, as slow chalking can result in the player avatar's death if the stamina on the gripping hand is exhausted, and second, as longer periods of climbing without chalking one's hands depletes chalk levels, which causes stamina to drop rapidly while climbing, players have to ensure that they chalk their hands in regular intervals.

Chalk levels are indicated using a white band around the virtual wrists of the player. When chalk levels drop below a certain threshold, the message 'Re-Chalk' is displayed hovering over player's wrist. The chalk indicator and visual 'Chalk your hands' notification can be seen in Figure 5.6

5.3.3.4 Savepoints

There are several savepoints throughout the levels. Savepoints are represented by a carabiner attached to a rope, riveted to the wall. If a player holds on to a hand hold in the close vicinity of a savepoint, they become 'hooked in', indicated by the clicking noise of a carabiner falling shut. From this point onwards, if a player falls, he/she will respawn at this position until the next savepoint is reached.

Figure 5.6: Chalk hands indicator and notification.

5.4 Olfactory Display

The results from the exploratory study (Section 4.9) showed that the Scentee OD was successfully able to deliver odours to participants. However, several issues were identified, that made it less suitable for the ensuing studies. Firstly, Scentee uses proprietary cartridges that have to be purchased individually and are designed specifically to work with the provided odorants. Using Scentee with third-party odorants is only possible by modifying the device by drilling into the cartridge and emptying out the original odorant. This however means that odorant contamination cannot be excluded as small amounts of the original odorants may remain in the cartridge. Furthermore, the device is only usable with an iOS device, as the Android app at the time of writing was removed by Scentee inc. from the Google Play store, and the odour delivery can only be triggered using the Scentee app, restricting the usefulness of the device to research on mobile devices. Furthermore, the device could not be used with viscous liquids, as they would clog the piezoelectric atomiser. Therefore, to carry out the planned experiments it was necessary to develop a new OD that overcame these issues and that was also suitable for VR.

5.4.0.1 Olfactory Displays in Virtual Reality

Using odours with VR is relatively novel (see Section 3.4.4.2), and questions remain about what properties an OD needs if it is to be used with VR headsets. As the purpose of the OD is to deliver odours to a user and give the believable impression that the odour originates from within the VR environment, any form of distraction or hint that the odour originates from outside this environment must be kept to a minimum. Therefore the following factors must be taken into consideration when designing an olfactory display for VR:

Delivery speed: When in a VR environment, users will be in constant motion and hence there are two ways in which odours can be delivered to ensure that they are perceived by participants. Firstly, in an ambient manner, which involves filling the entire physical space with an odour that is then perceived by participants. With current technology however, this process is slow and is not suitable for quick changes. Ambient ODs also suffer from producing lingering odours. Secondly, odours could be delivered in a localised manner, meaning that the OD deliver odours directly to the nose or the area around the nose. This process has the potential to be very fast, as odour particles only have to travel short distances to reach the olfactory bulb, and is hence preferable.

Lingering odours: A recurring issue for olfactory displays is that the displayed odours can linger, and that this can produce unwanted interactions when users perceive an odour that does not match what they are otherwise experiencing, such as when changing scenes or changing location by moving through virtual space. While this is an issue for systems where users are static, such as in a cinema, the issue can be assumed to be more prolific in virtual reality, where changes in scenery can occur very rapidly and can be unforeseeable, as they are dependent on where the user decides to move.

Unobtrusiveness: An olfactory display should not be perceivable by users in any way other than through the odours that it displays. Sensory factors that are not part of the virtual environment, but are perceivable by users, have been shown to disturb one's sense of presence (Slater and Steed, 2000). Hence, an olfactory display should not emit sensory stimuli such as sounds from a motor, wind from a fan or pressure and temperature from droplets of the odorant.

5.4.1 Keylia Odour Diffuser

Taking the above criteria of delivery speed, lingering odours and unobtrusiveness into account, a low-cost, off-the-shelf olfactory display for virtual reality systems was developed. The OD is able to actuate two scents and can be easily attached to an Oculus Rift VR headset. The device uses the *Aroflora Keylia USB ultrasonic odour diffuser* (Aroflora, 2018), which is able to atomise liquids that are stored inside a refillable cartridge that holds approximately 1.5ml of solution (Figure 5.7). These devices are typically used to dispense scents in rooms and cost less than $20. While most liquids can be vaporised using the Keylia, oil based liquids can clog the device and, when this occurs, do not produce an even plume of vaporised odorant. Hence it is advisable to mix the odorant with a light carrier oil or alcohol, which decreases its viscosity.

Figure 5.7: Aroflora Keylia Scent Diffuser

The odour diffuser requires an external power source, supplied via USB-A. Hence, the diffuser was connected via a standard USB-A extension cable that was plugged into a USB port on a computer. The extension cable had a length of 4m, which is the same length as the HDMI and USB cords connecting the Oculus Rift headset with the host PC. Due to its length and to ensure that the OD received a constant supply of power, an active extension cable was used. Once power is supplied, the device immediately atomises a small quantity of liquid for 0.5 seconds that is ejected in an approximately 15cm long cloud of vapour. The device can be set to atomise on an interval, which can be set to 10 seconds, 30 seconds and 5 minutes. While this functionality is available, odours in a VR context are expected to be triggered on demand, rather than at interval. To do so, a switch was attached to the USB cable, which enables the power to the diffuser to be switched on and off as required, and an almost immediate display of the odours. The delay between activating the switch and display of odours for the device was 0.2 seconds. This was measured by taking a video recording of the switch operation and odour display and by comparing the timestamps of the switch operation and the first visual sign of odour display. The diffuser was attached to the VR headset using the USB cable and by placing it behind the rail connecting the display and head strap of the headset (see Figure 5.8). This produced enough force to keep the odour diffuser in place, even during strong movements of the head while a user was interacting with the VE. Figure 5.8 below shows a user wearing the VR headset with two attached olfactory displays.

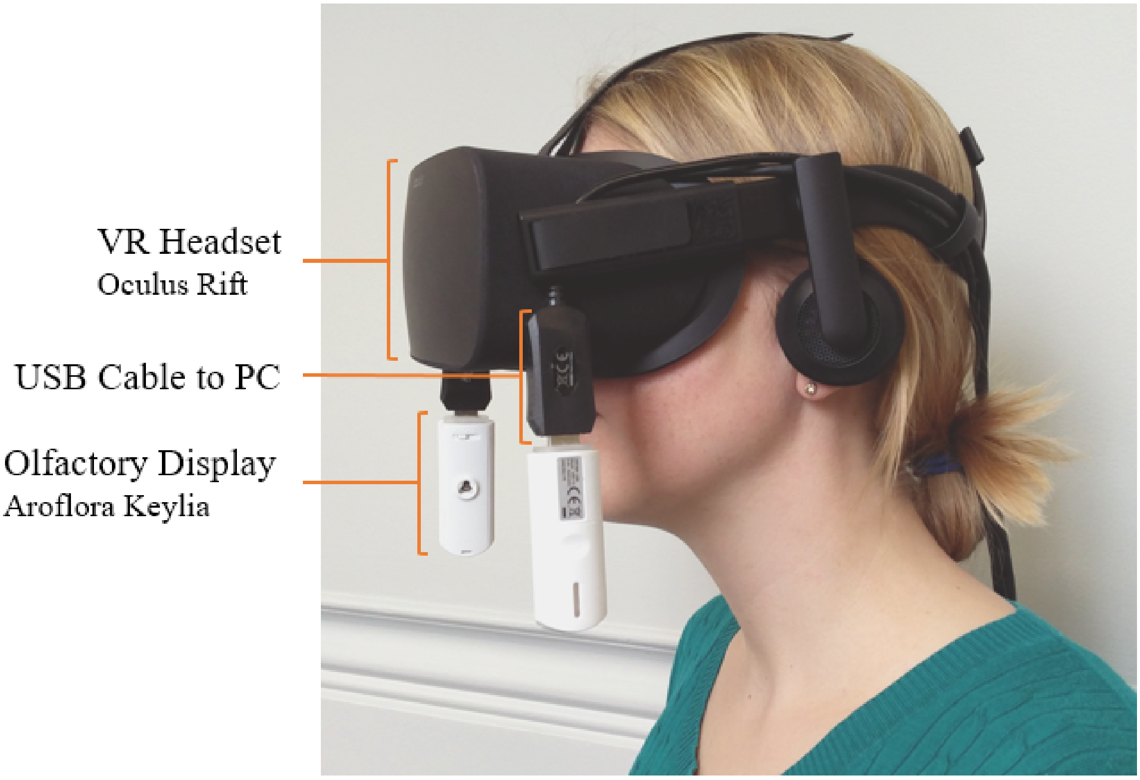


Figure 5.8: Virtual Reality Headset with Olfactory Display

5.5 Odour Selection

It became clear from the results of the exploratory study that current odour selection methodologies do not produce viable odours to be used for studies as their effects on participants cannot be sufficiently predicted beforehand. Therefore a new odour selection method is required that a) produces odours that achieve a desired result, and b) produces a set of odours that can be easily reproduced.

To achieve this, the selection method should be based on the basic dimensions of odour perception, namely intensity, valence and, familiarity, as were discussed in Section 3.3.1. While a wider list of dimensions has been suggested in the literature (Kaeppler and Mueller, 2013; Kermen et al., 2011; Wise et al., 2000), these can be attributed to contextual effects, such as from verbal cues or colour of odorant, and can therefore be controlled. Intensity, valence and familiarity however appear to be intrinsic to the odour perception and can be perceived without any auxiliary or contextual cues. There are however strong effects between these dimensions, which should therefore be controlled for. For example, Kaeppler and Mueller (2013) note that in many odour classification studies, participants have been instructed to ignore differences in intensity when assessing odours, based on the assumption that intensity is a distinct dimension of odour perception. The authors state that this is a false assumption as the valence of an odour and its intensity interact considerably and a shift in one dimension is often accompanied by a shift in the other. Therefore participants have difficulties ignoring an odour's intensity even if instructed to do so, as the perception of the quality of an odour is directly affected by its intensity (Gross-Isseroff and Lancet, 1988).

The following sections describe a new odour selection methodology based on these criteria. Section 5.5.1 describes a set of questions that forms the Odour Selection Questionnaire (OSQ). Section 5.5.2 describes how to administer the questionnaire to assess odours. Section 5.5.3 describes how the responses to the OSQ should be analysed to determine appropriate odours.

This odour selection methodology was used during Studies Two, Three, and Four.

5.5.1 Odour Selection Questionnaire

The OSQ consists of a general part which contains questions concerning an odour's intensity, pleasantness, and familiarity with the odour and an application specific part, which ensures that odours are perceived as congruent with the VE.

Table 5.2 below shows the OSQ that was developed to capture users' perceptions of odours. The questionnaire draws closely on the wording of the ISO 5496:2006 Sensory analysis – Methodology – Initiation and training of assessors in the detection and recognition of odours standard (ISO, 2006), which is usually used in the context of testings subjects' abilities of smell.

The OSQ includes one question to ensure that participants can perceive an odour at all: '1. Do you perceive a scent?'. In order to determine the familiarity with the odour, three questions were included. First, ‘2. Do you recognise the scent?’, which establishes whether a participant has previously encountered the odour and is able to remember it. Second, ‘3. Name of the Scent’, which establishes how familiar a participant is with an odour. According to Cain (1979), identification of odours depends largely on how often an odour is encountered, how long-standing the connection between an odour and its name is, and auxiliary cues that facilitate its identification, such as the colour of the odorant. When one of these three items is not available, identification is impaired greatly, and any correct identification of an odour despite the lack of auxiliary cues - as is the case when administering the OSQ (see Section 5.5.2) - would indicate that the odour has either been encountered repeatedly, or for a long time, or both. Using odours that participants can readily identify therefore potentially reduces cognitive load, as participants have an easier time recalling the odour. The third item included to determine familiarity with an odour is a prompt for a description of the odour and any associations that participants may have ‘4. Description of scent or an association’. This item was included to capture the variety of associations that participants may have with the odour, and to determine whether there are certain common themes among the associations or if there are any unwanted averse associations with an odour.

The next item allows participants to rate the intensity of an odour on a 5-point Likert scale with endpoints ‘1 - Low intensity’ to ‘5 - High intensity’ ‘This scent’s intensity is...’. Intensity is recorded to ensure that all odours are perceived at a moderate level, i.e. not with a very low or very high intensity, to ensure that they are easily perceived, but do not overpower an experience. Lastly, in the general part of the questionnaire, the valence of an odour is assessed with responses to the statement ‘I liked this scent...’ on a 5-point Likert scale ranging from 1 - Not at all, to 5 - Very much.

	Question	**Response**
1.	Do you perceive a scent?	Yes / No
2.	Do you recognise the scent?	Yes / No
3.	Name of the scent	Short text answer
4.	Description of scent or an association	Short text answer
5.	This scent’s intensity is...	Five-point Likert scale
		1 - Low Intensity, to 5 - High Intensity
6.	I liked this scent...	Five-point Likert scale
		1 - Not at all, to 5 - Very much

Table 5.2: General part of the Odour Selection Questionnaire (OSQ)

While the general part of the OSQ captures how an odour is perceived in terms of the basic dimensions of odour perception, other factors might be relevant in deciding if an odour is suitable for a specific application, such as for a VE. In my studies, I was specifically interested in the concept of congruence - the degree to which an odour is perceived to match an in-game object. For each in-game object (I was interested in two types of flowers), I therefore asked participants to answer the question '7. Does this scent match this flower?', while displaying one of the two flowers found in the VE. Responses were given on a 5-point Likert scale ranging from 'Not at all - 1' to 'Very much - 5). Responses to this question can be used two-fold, firstly in order to determine whether the odours are perceived to match the virtual object, and secondly to ensure that an odour is only associated with one type of object only. The analysis of these results can be found in Section 5.5.3.

5.5.2 Odour Selection Questionnaire Procedure

While the OSQ was designed to capture the subjective perception of an odour, it must be used in conjunction with a procedure that eliminates contextual cues. In this section I describe this procedure.

On the day of the experiment, participants should be asked to refrain from smoking, eating or drinking (other than water) within the 2 hours prior to the study and from wearing perfumes. The classification should take place in a well ventilated room, to ensure that odours do not linger. The room should be void of any odours other than the ones participants are subjected to as part of the classification. Odours will be presented to participants via application of a drop of 0.1ml of liquid odorant to the end of a cotton bud. The odorant should be applied to the cotton bud shortly before handing it to the participant, to ensure that the odours do not change their properties by being exposed to air, and to limit odour contamination of the space. The order in which participants are presented with the odours should be randomised. The experimental procedure is as follows:

1. Test participants for olfactory dysfunction, such as with three item Quick Smell Identification Test (Jackman and Doty, 2005), or Sniffin' Sticks (Hummel, Sekinger, et al., 1997).

2. Ask the participant to be seated at a table.

3. Hand the participant a cotton bud with odorant applied to the tip.

4. Instruct the participant to smell the cotton bud once, and then to place the bud on a sheet of paper, approximately 1m away from the participant.

5. Instruct the participant to fill out the questionnaire items.

6. The experimenter discards the cotton bud to prevent olfactory contamination after the participant completes the evaluation for the current odour by placing the cotton bud inside an air-tight container.

7. When a participant completes evaluating an odour, a break of at least 30 seconds should be taken before moving on to the next odour, to reduce olfactory fatigue and any overlapping effects from previously perceived odours.

8. Repeat for the remaining odours.

5.5.3 Odour Selection Questionnaire Analysis

In this section I describe how the responses to the OSQ can be analysed. Generally any values that are set should be determined by the researcher in regard to the application that they intend to use the odours with. The purpose of the general part of the OSQ is to set threshold values as cut-off points for odours. The approach is based on the idea that more than one odour could potentially be suitable for a specific scenario, but also that none of the odours assessed during the odour selection phase may be suitable.

The values described in this section are for guidance only and should be amended to suit the specific domain. In this section, I assume that the researcher is looking for two odours that suit two particular objects in a VE. The odours should be easily perceived by participants, should be pleasant, and should uniquely match one of the virtual objects in the VE each. Therefore any odour where participants respond with a 'No' to item 1 of the OSQ should be rejected. In this scenario, responses to items 2 - 4 should be examined to determine whether participants generally perceive the odours as intended, e.g. if the odours should match in-game flowers, then this should be reflected in participant responses in terms of the names, associations and descriptions of the odours (items 3, and 4). In terms of item 5 - intensity, for a medium intensity level, which is consciously and easily perceived by participants, but that does not overpower and distract from an experience, a range of median intensity scores of between 3.0 and 4.0 could be selected. All other odours should therefore be rejected. In terms of item 6 - valence, all odours of a median valence score of below 3.50 should be rejected as they are not perceived as pleasant by most participants, as was required in this scenario. As stated previously, the thresholds could have also been set to select for odours that participants only perceive subconsciously or ones with a negative valence.

The remaining odours can now be assessed for their congruence to the chosen virtual objects. As was described in Section 5.5.1, the purpose of OSQ item 7 is two-fold, to i) determine whether the odours were perceived as congruent with either of the virtual flowers and ii) to ensure that an odour is only associated with one type of flower only. Therefore, i) all odours that have not been rejected in a previous step should be examined for their responses to OSQ item 7 and should be rejected if they do not have a median response of 3.00 or above for either of the flowers. For ii), a Friedman test can be carried out between the congruence scores of the first flower to determine if the odours were perceived significantly differently in terms of congruence to the first flower. If no significant differences are found then any of the remaining odours can be chosen for the first flower, but the remaining odours should be rejected as they could cause confusion for participants as they could also easily be interpreted as originating from the same flower as the selected odour. If significant differences are found however, this indicates that some odours are perceived as significantly more congruent with the flower than the other remaining odours. The same test should then be repeated for the responses to the second flower. If significant differences are found, post-hoc Wilcoxon Signed-ranks tests can be carried to determine which of the odours were perceived as significantly more (or less) congruent to the other odours. Ideally, one odour should be significantly different to the remaining odours for each flower, which would then be selected for the use in the VE. In order to ensure that a suitable match can be found through the selection process, a large number[1] of odours should be assessed.

5.6 Measuring User Experience in VR

In this section, I discuss different methods used to measure user experience in VR, and give details of the different types of measurements that were used in Studies Two, Three and Four.

As discussed in Section 3.4.4.1, the sense of presence is the defining feature of VR, and therefore should play a large part in the user experience of a VE. How to measure the sense of presence in VR is a contested topic and a variety of approaches exist. The most common approach to measuring the sense of presence is to use questionnaires, which often focus on specific domains, such as gaming (Jennett et al., 2008), or aspects of presence, such as spacial presence and engagement (Lessiter et al., 2001) or realism (Wiederhold et al., n.d.) by splitting presence into several subscales. No consensus exists on the different aspects of presence, or which subscales to use to assess the sense of presence, and thus a large variety of presence

[1] Around 20 odours were initially purchased for each of the studies in this thesis.

questionnaires have been developed. By 2003, 32 presence questionnaires were in use (Youngblut, 2003), and between 2016 and 2017 alone, researchers used at least 11 different types of presence questionnaires across 41 studies (Hein and Mai, 2018). The most commonly used presence questionnaire is the Witmer and Singer presence questionnaire (Witmer and Singer, 1998), which has also been used in multisensory VR (Ranasinghe, Jain, et al., 2017), and therefore seems appropriate to use when assessing the effect of olfaction on the sense of presence. However, the questionnaire does not claim to give an overall score that determines the sense of presence, but rather gives an indication of how various factors (sensory, distraction, realism, and control) which the authors believe contribute to the sense of presence, are perceived. Researchers have therefore suggested to supplement questionnaire data with further measures such as observations of participant behaviour or even physiological responses (Barfield and Weghorst, 1993; Regenbrecht, Schubert, and Friedmann, 1998). Physiological responses as measured for example through skin-conductance or heart rate have however not always been conclusive in terms of capturing finer-grained changes in the sense of presence, such as with the introduction of new sensory modalities (Ranasinghe, Eason Wai Tung, et al., 2018). I therefore decided to record observations of participant behaviour and any remarks made while participants were inside the VE and after the experimental session concerning their sense of presence. These measures can also be used to gain a better understanding of the general user experience of the VE. Post-session interviews could have also been used in this manner, however, as sessions were already very lengthy with the selected measures (sometimes lasting over 1.5 hours, though mostly around 1 hour) and due to the lengthy process of familiarisation with the VR equipment including calibration of the HMD and assessment of olfactory ability, I decided against their use, but nevertheless I do see their value and can imagine introducing interviews following a shorter experiment set up in the future.

Lastly, as I am using a game-based VE, I have also decided to use a domain-specific questionnaire, namely the Jennet et al. presence questionnaire, which is described in Section 5.6.1. However, as stated previously, the measurement of presence as determined by questionnaires must be supplemented with contextual information such as through observations of participant behaviour, and therefore only in a combination of the results of the presence questionnaires as well as supplementary data from observations and Quality of Experience (QoE) measurements (as described in Section 3.4.1) can a judgement over the sense of presence be made.

While presence is the major aspect defining the user experience in VR, I was specifically interested in assessing the effect of the odours on the user experience. As discussed in Section 3.4, little guidance exists on how to measure the impact of odours on a user's experience. The main measure, and the only one which has seen recurring use is that of QoE. The QoE questionnaire therefore posed an established tool that captures several relevant odour related information, such as perceived congruence, relevance and realism, which also apply in the context of the sense of presence. QoE is a unique measure, in that it also specifically examines how odours are perceived by participants, such as by including whether the odours and the environment were congruent and whether the odours impacted on participants' enjoyment of the game, for example by being annoying, unpleasant or distracting.

5.6.1 Post Game Questionnaire

In this section I describe the Post-Game Questionnaire (PGQ), which participants filled out after having experienced each of the experimental conditions. The purpose of the PGQ was to record the user experience of the VE.

The questionnaire measured participants' Quality of Experience (QoE), which was measured using five questions from (Ghinea and Ademoye, 2012a), and the sense of presence, which was measured using five questions from Jennett et al. (2008) and three questions from Witmer and Singer (1998). The QoE questionnaire is based on Ademoye and Ghinea's research into how odours can affect QoE of video based multisensory media applications (see Section 3.4.3). Item 1 was adapted from the original context of video clips to that of VEs as follows: from the original 'The smell was relevant to what I was watching' to 'The smell was relevant to what I was seeing.'. Item 2 'The smell heightened the sense of reality whilst watching the video clip' was adapted to read 'The smell heightened the sense of reality whilst experiencing the virtual environment'. Item 5 was adapted from the original context of video clips to that of VEs as follows: from the original 'I enjoyed watching the video clip' to 'I enjoyed the virtual environment.'.

This is the first time this questionnaire has been used in the VR domain. As the items of the QoE questionnaire specifically enquire about the perception of odours, it was only used after participants were exposed to an odour during their previous run. The questions can be found in Table 5.3.

	Statement	Rating 1	 5
1.	The smell was relevant to what I was seeing.	Not at all	A lot
2.	The smell heightened the sense of reality whilst experiencing the virtual environment.	Not at all	A lot
3.	The smell was distracting.	Not at all	A lot
4.	The smell was annoying.	Not at all	A lot
5.	I enjoyed the virtual environment.	Not at all	A lot

Table 5.3: Quality of Experience (QoE) Questionnaire.

As the VE is based on a VR game, I based the evaluation of presence on a questionnaire developed by Jennett et al. (2008) which captures presence in computer games. As stated in Section 3.4.4.1, Jennet et al. use the term immersion, but this matches the definition of the term presence as I use it for this PhD thesis. While the original questionnaire consists of 31 questions that evaluate a mixture of person- (cognitive involvement, real world dissociation and emotional involvement) and game-factors (challenge and control) (Jennett et al., 2008, p. 657), Jennet proposed a shortened 5 item version of their questionnaire where these 5 items have been demonstrated to give high prediction of the score on all other questions (personal communication, 2017) . The shortened questionnaire can be seen in Table 5.4.

	Question	Rating 1	 7
1.	To what extent did you feel you were focused on the game?	Not at all	A lot
2.	To what extent were you aware of yourself in your surroundings?	Not at all	Very aware
3.	At any point did you find yourself become so involved that you were unaware you were even using controls?	Not at all	Very much so
4.	Were there any times during the game in which you just wanted to give up?	Not at all	A lot
5.	To what extent did you feel emotionally attached to the game?	Not at all	Very much so

Table 5.4: Jennet et al. Presence Questionnaire (JPQ)

Presence was further measured using questions based on Witmer and Singer's presence questionnaire (Witmer and Singer, 1998) and has been previously used to assess the sense of presence in multisensory VR (Ranasinghe, Jain, et al., 2017). Its questions are associated with one of four presence related factors: sensory factors, distraction factors, realism factors and control factors. As many of the questions concern themselves with haptic and auditory modalities, and since I wanted to specifically elicit whether olfaction affects presence, I chose questions from each of the factors, while ensuring that the questions could be related to an olfactory sensory impression. The questions can be seen in Table 5.5.

		Rating	
	Question	**1**	**7**
1.	How completely were all of your senses engaged?	Not complete at all	Very complete
2.	How inconsistent or disconnected was the information coming from your various senses?	Not disconnected at all	Very disconnected
3.	How much did your experiences in the virtual environment seem consistent with your real-world experiences?	Not consistent at all	Very consistent

Table 5.5: Witmer and Singer Presence Questionnaire

While most researchers use questionnaires to assess the sense of presence in VR, other measures have previously been suggested to supplement this data. Objective measures such as the use of unexpected fast moving objects that cause reflexive reactions from participants, have for example been used (Held and Durlach, 1992; Regenbrecht, Schubert, and Friedmann, 1998), however these types of measurements rarely relate to the sense of smell, which has been mostly overlooked in regard to its effect on presence, to date. Physiological responses have also previously been collected to assess the sense of presence in VR, however, once again, these measures do not generally reflect types (Ranasinghe, Eason Wai Tung, et al., 2018).

5.7 Summary

The aim of this chapter was to define a common set of methods that could be used to address research questions RQ_1, RQ_2, RQ_3. This included a review of current VR technology and specifically headsets in Section 5.3 and a list of factors that were used to select an appropriate VE for Studies Two, Three, and Four. The VE is based on the VR game *The Climb* and uses the *Oculus Rift* HMD. Based on insights gained during the exploratory Study One, I then described an OD based on a piezoelectric atomiser, which can be used to display odours with VR headsets. In order to ensure that the odours of my studies were appropriate for the context of the research questions, I describe a systematic methodology for odour selection, based on an odour selection questionnaire, that assesses how odours are perceived by participants, in terms of the basic dimensions of odour perception. In a final section, I described a set of questionnaires that I used to assess the sense of presence and QoE in VR, both of which can give an indication of the user experience of a VE.

In the following Chapter 6 I use this methodology to assess how congruent, pleasant odours affect presence in VR.

Chapter 6

Study Two

6.1 Introduction

Affordable VR technology is now widely available and there is increasing interest in whether using sensory modalities in addition to vision and sound can enhance VR experiences (see Section 3.4.4). Smell has a strong influence on how we experience the world, for example, odours can modulate moods (see Section 3.3.2), trigger memories (see Section 3.3) and affect alertness. Recent research has found that unpleasant odours can enhance the sense of presence in VR (Baus and Bouchard, 2017). Using a low cost, off-the-shelf olfactory display (OD), I demonstrate for the first time that congruent pleasant odours can enhance the sense of presence in VR. Adding odours to a VR mountain climbing game significantly increased users' reported sense of focus, and their performance. Furthermore, participants in this experiment reported an enhanced sense of realism and attributed it to smell, rather than to vision or sound, suggesting that there is a potential market for digital olfaction in VR systems.

Therefore this study aims to answer the following research questions of this PhD thesis:

RQ_{1a} *How do pleasant, congruent odours affect perceived presence in virtual reality?*

RQ_2 *How do odours affect task performance in virtual reality?*

The main hypothesis H_1 for RQ_{1a} is that:

H_1 *Pleasant, congruent odours increase presence in virtual reality.*

For RQ_2, the main hypothesis H_2 is that:

H_2 *Pleasant, congruent odours increase task performance in virtual reality.*

6.2 Odour Selection Task

There are two types of flowers in *The Alps* level of *The Climb*, and the aim of the selection task was to select two congruent and pleasant odours that could be emitted by the OD when participants interacted with the two flower types. The flowers can be seen in Figure 6.1. The odour selection task followed the method of odour selection described in Section 5.5.

Figure 6.1: Two kinds of flowers found in *The Alps* level of *The Climb*. Left purple flower, right yellow flower.

6.3 Task Design

I purchased an initial set of 7 liquid floral odours from Dale Air (now known as AromaPrime) (Air, 2017), who have been widely used in olfaction based research in HCI (Brewster et al., 2006; Ghinea and Ademoye, 2012b; Murray, Lee, et al., 2016a). The odours were called: Hawthorn, Roselle, Roses, Sweet Pea, Violets, Wallflower, and Wisteria. During an odour selection task, I evaluated these odours for congruence, intensity and pleasantness with 5 participants, (3 female, 2 male, mean age = 37.60 years (SD = 9.79 years). Participants were asked not to smoke an hour before the study and not to wear any perfumes on day of the experiment. Initially, participants were screened for olfactory dysfunction using the three-item Quick Smell Identification Test (Q-SIT) (Jackman and Doty, 2005). The test consists of the three odours smoke, banana, and chocolate. For each of the odours, participants are asked to identify the odour using a multiple choice question with five alternatives. For example, the alternatives for the smoke odour were: smoke, dill pickle, grass, peach, and none / other. In order to pass the test, participants must correctly identify 2 out of the 3 odours. While 'Sniffin' Sticks' (Hummel, Sekinger, et al.,

1997) were used to assess olfactory function in Study One (see Section 4.6.3), the test took approximately 15 minutes to complete including giving instructions, assessment, and evaluation of results, which would have considerably lengthened the experimental sessions and therefore the Q-SIT was used instead. Despite using only three odours (as opposed to the 16 odours of the 'Sniffin' Sticks' test), the Q-SIT was shown to have a sensitivity of %93 and a specificity of 45% for detecting anosmia (Jackman and Doty, 2005). No participants were excluded due to olfactory dysfunction Ethics clearance was received from the City, University of London Computer Science Research Ethics Committee.

Participants were seated at a desk in front of a 24" computer screen that displayed a Google Form containing the Odour Selection Questionnaire (OSQ) (see Table 5.2), which participants used to record their responses. The order in which the odours were assessed was randomised prior to the experimental session. For each odour, the experimenter applied a 0.1ml of odorant to a cotton bud and passed this on to the participant, who was verbally instructed to smell the tip of the bud and then to answer the OSQ. Participants were allowed to smell the cotton bud repeatedly while answering the questionnaire. Once they had answered the questionnaire for an odour, they placed the cotton bud on a sheet of paper, approximately 1m away from them, which was then discarded by the experimenter. Participants then were instructed that they now had to wait for one minute before they would be given the next odour. This one minute break was given to participants to reduce olfactory fatigue (Grosofsky et al., 2011; Hummel, Knecht, et al., 1996). These steps were repeated until the participant had assessed all the odours.

When assessing this initial group of odours, all participants described the odours as synthetic and chemical and as having associations with air freshener. None of the odours were perceived as pleasant. An odour was considered as pleasant when it had a mean score of greater than 3.00 in response to the statement 'I like this scent ...' (anchors were 1 - 'Not at all' and 5 - 'Very much'). This lead to the conclusion that none of the seven odours were appropriate for the main study and so a new set of 12 floral odours was purchased. This new set consisted of fragrance and essential oils purchased from a variety of manufacturers, a list of which can be seen in Table 6.1. The suitability of each of these odours was assessed in a second selection task, which followed the same procedure as the first.

6.3.1 Selection Task Results

A total of 8 participants took part in this second selection task (5 female, 3 male, mean age 36 years (SD = 12.2), once again, no participant was excluded due to olfactory dysfunction,

Odour	Type	Manufacturer
Chamomile	Fragrance Oil	EL
Freesia	Fragrance Oil	EL
Honeysuckle	Fragrance Oil	EL
Forget Me Not	Fragrance Oil	EL
Mimosa	Fragrance Oil	AA
Passion Flower	Fragrance Oil	AA
Gardenia	Fragrance Oil	AA
Lily of the Valley	Fragrance Oil	AA
White Rose	Fragrance Oil	AA
Bergamot	Essential Oil	Muji
Geranium	Essential Oil	Muji
Lavender	Essential Oil	AA

Table 6.1: Odours evaluated during the selection task.
Manufacturer key: EL - Essex Liquid, AA - Amphora Aromatics.

measured by a three item Quick Smell Identification Test (Jackman and Doty, 2005) and they were again asked not to smoke an hour before the study and not to wear any perfumes on day of the experiment. As the aim of the selection task was to find a set of odours that would be perceived as congruent to the flowers in the game *The Climb*, only floral odours were displayed to participants. Hence participants to a large degree labelled the odours as being floral, see Table 6.2.

Participants did not perform well at identifying the odours. While participants were able to name general qualities of the scents, e.g. that they were floral or fresh, participants' odour labels did not match the manufacturer-given labels to a large degree. The only direct matches were for the lavender odour, where all participants that recognised the odour also gave a matching label. In addition, participants who were able to identify the lavender odour rated it significantly higher than those who did not, as was revealed by a Spearman's Rho between the ability to correctly identify the odour and the responses to *I like this scent* (rs = 0.91, $p = 0.019$).

Participants responses to giving a description of- and any association with the odour were very similar to the name they gave an odour. However, the usefulness of making a distinction between giving a name to an odour i.e. label, while requesting a separate response for association or description is questionable, as the descriptions always matched the given label. Furthermore, as only participants that recognised an odour were asked to name the odour, this represents concise information that is potentially missed. Hence it is more plausible to ask all participants to label an odour while also asking them separately if they recognise the odour. As participant descriptions of odours were often rather lengthy, a table with these descriptions is included in Appendix B.2.

Participant	Mimosa	Passion Flower	Gardenia	Lily of the Valley	White Rose	Forget Me Not
P1	-	-	-	-	-	Peony
P2	Cotton flower	-	Cotton flower detergent	-	Body oil	-
P3	Peach	Lavender	Iris	Rose	Lavender	Lime or Oak
P4	Orange blossom	-	Baby powder	Rose hips	Baby powder	-
P5	-	-	-	-	Almond	Lavender
P6	Persimmon or some sort of melon	-	-	-	-	-
P7	-	Sandalwood	Lavender	-	-	Jasmine
P8	-	Preparation h	Generic handsoap	-	-	Dial Soap

Participant	Freesia	Honeysuckle	Chamomile	Bergamot	Geranium	Lavender
P1	Jelly Beans	Violets	-	Wood	Grapefruit skin	Lavender
P2	-	Flower honeysuckle	Green apple	-	Citronella or mosquito	Lavender
P3	Sherbet	-	Apple	Citronella	-	-
P4	Orange blossom	Rose something or soft rose	-	Lemon citrus	Citrus mint	Lavendar
P5	-	Some flower / chamomille	-	-	Zitronenmelisse	Lavender
P6	-	-	-	Citrus	-	Lavender
P7	-	Jasmine	-	-	-	-
P8	-	Dandylion	Cola	-	-	Lavender

Table 6.2: Participant labels given for each odour they recognised. '-' denotes that the participant did not recognise the odour.

To determine which of the odours was most suitable for the VE, unsuitable odours were eliminated, according to their intensity (responses to the statement 'This scent's intensity is...') and pleasantness ratings (responses to the statement 'I like this scent...'). Only odours which were perceived with a median intensity score of between 3.0 and 4.0 were considered suitable. This range was set to counteract issues that were found in previous research, such as Baus and Bouchard (2017) and Bodnar et al. (2004), where odours were not noticed by all participants or where odours were perceived as too strong, almost overpowering. In terms of pleasantness, only those odours with a median score of 3.50 or greater were considered as suitable, to ensure that the odours were overall perceived as pleasant. This rejected the passion flower, gardenia lily of the valley, forget me not, honeysuckle, bergamot, and geranium odours. The median intensity and pleasantness scores for the odours evaluated during the odour selection task can be found in Table 6.3.

Odour	Intensity (median)	Pleasantness (median)	Recognise Odour (%)	Congruence Purple Flower (median)	Congruence Yellow Flower (median)
Mimosa	4.00	4.50	40	3.00	2.00
Passion Flower	3.00	2.00	30	2.00	1.00
Gardenia	3.00	3.00	60	4.00	1.50
Lily of the Valley	3.00	3.00	20	3.50	2.50
White Rose	3.50	3.50	40	2.00	1.00
Forget Me Not	4.00	3.00	50	2.00	3.00
Freesia	3.50	3.50	40	2.00	3.00
Honeysuckle	3.00	3.50	60	3.00	4.00
Chamomile	4.00	3.50	30	3.00	3.00
Bergamot	4.00	2.00	40	2.00	2.00
Geranium	4.00	3.00	40	1.00	3.00
Lavender	3.50	4.00	60	3.50	2.00

Table 6.3: Odours evaluated during the selection task.
Odours with an intensity score of $i < 3.50$ and $i > 4.50$ were rejected. Odours with a pleasantness score of $p < 3.50$ were rejected. Red values indicate that this odour was rejected due to falling outside the specified intensity range, or below the pleasantness and congruence thresholds. Underlined scores indicate the value that caused the rejection of the odour. Colour highlights indicate that the odour was selected for the Yellow Flower, Purple Flower.

Following the reduction in the number of viable odours that could be used with the VE, the congruence of the odours with the virtual flower was assessed. The remaining odours were mimosa, white rose, freesia, chamomile, and lavender. In this step, only those odours which had a median congruence score of 3.00 or greater for either of the two flowers were considered. This caused a rejection of the white rose odour, which had median congruence scores of 2.00 (purple flower) and 1.00 (yellow flower).

While the remaining odours (mimosa, freesia, chamomile, and lavender) all fell within the pre-determined requirements for the use in the VE, I wanted to determine whether any of the odours was perceived significantly more congruent to a type of flower than the other odours and if there were any odours which were perceived as significantly different to each other in terms of both purple and yellow flower congruence. This final comparison is necessary to ensure that participants perceive the two odours sufficiently differently and do not become confused in regard to their meaning. Therefore, to determine if there were significant differences between the purple flower congruence scores for the remaining odours, a non-parametric Friedman test of differences among repeated measures was conducted and rendered a Q-stat score of 8.39, which was significant with $p = 0.039$. Post-hoc pairwise Wilcoxon Signed-ranks tests revealed that there were significant differences between the purple flower congruence scores of the lavender and the freesia odour (lavender median = 3.50, freesia median = 2.00, $p = 0.035$). To determine if there were significant differences between the yellow flower congruence scores for the odours, a non-parametric Friedman test of differences among repeated measures was conducted and rendered a Q-stat score of 8.12, which was significant with $p = 0.043$. Post-hoc pairwise Wilcoxon Signed-ranks tests revealed that there were significant differences between the yellow flower congruence scores of the lavender and the freesia odour (lavender median = 2.00, freesia median = 3.00, $p = 0.033$). These results show that the lavender odour is the most appropriate odour for the purple flower, while the freesia odour is the most appropriate odour for the yellow flower. The lavender odour was perceived with a sufficient intensity score of 3.50, very pleasant with a score of 4.00, and was perceived as congruent with the purple flower (purple flower congruence score of 3.50). The freesia odour was also perceived with sufficient intensity (median 3.50), was perceived as pleasant (median 3.50) and was perceived as congruent with the yellow flower (median yellow flower congruence score = 3.00). The odours were also perceived significantly differently to each other both in terms of purple flower congruence and yellow flower congruence, ensuring that there was no confusion as to which odour represents which flower for participants.

6.4 Main Study

The purpose of the main study was to investigate whether pleasant congruent odours can affect the sense of presence in a VR environment. For this study, I recruited 22 participants. Participants were selected on a non-probability, convenience sampling basis and were recruited via university mailing lists and noticeboards. The participants were required to have a normal sense of smell and vision (or corrected-to-normal vision). Participants who required corrective vision aids were asked to wear contact lenses, as not all glasses fit inside the Oculus Rift headset. Participants were screened for olfactory dysfunction using the three-item Q-SIT (Jackman and Doty, 2005) (see Section 6.3). No participants were excluded as a result of the test for olfactory function. Additionally, the participants were asked to refrain from wearing any fragrances on the day of the sessions and not to have any meal, coffee, or to smoke for an hour before the experimental session and were asked to report any smell related allergies or concerns in advance. Two participants were unable to take part in the study due to an onset of fear of heights as soon as they began climbing, reducing the number of participants that completed the experiment to 20 (11 male (mean age = 31.9 years, SD = 4.46) and 9 female (mean age = 29.4 years, SD = 4.42). All participants were required to have had previous experience with VR. No compensation was given to participants and clearance from the City, University of London Computer Science Research Ethics Committee was received. The study was designed using a within subjects repeated measures setup.

The main study took place at the City, University of London Interaction Lab, a large open space that only contained one desk towards the rear end of the room, allowing for a an approximately 5m x 5m open area that could be used for the VR environment. A desk was placed at one end of the room, on which a 24" screen, a mouse, and a keyboard were placed as well as the two Oculus Rift sensors that are required to track the user. The screen mirrored the in-game view of the participant and allowed the experimenter to observe what the participant was seeing. During the gameplay part of this study, participants were standing approximately 1.5m away from the screen, facing it directly. As participants were wearing the HMD, they were not able to see the screen while inside the VR. A second desk with a computer, which was placed by the wall opposite the VR desk, was used as an assessment PC where participants answered a PGQ. The PGQ is described in Section 6.4.1. The room outline can be seen in Figure 6.2.

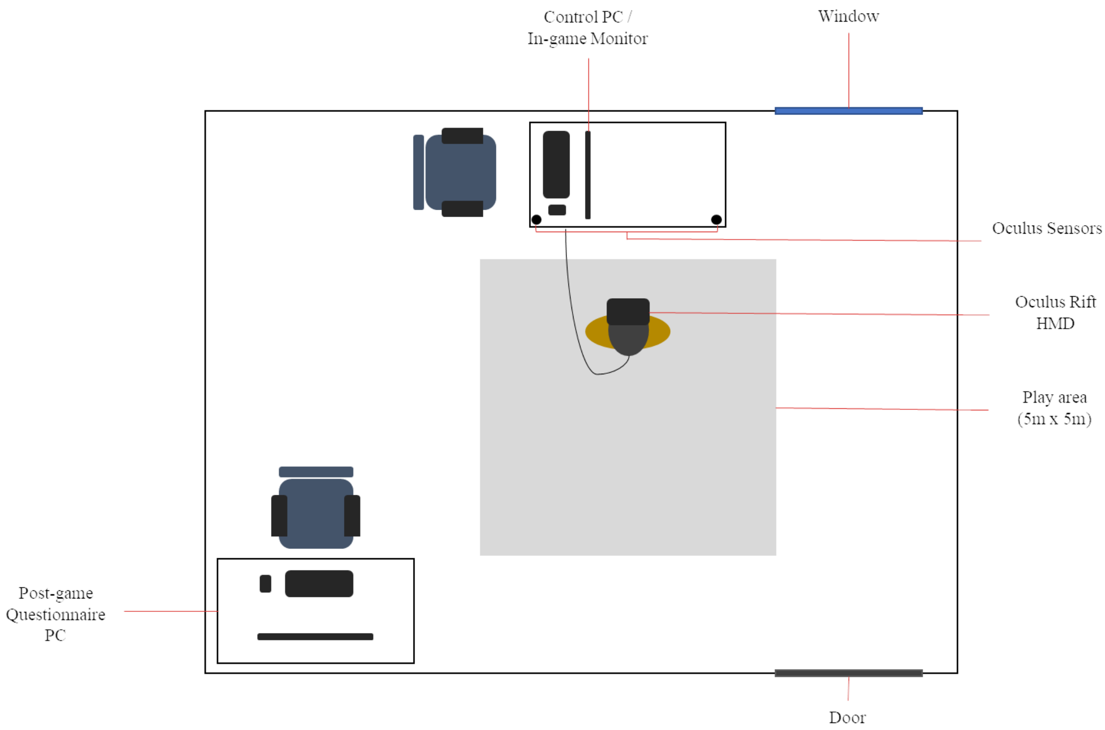


Figure 6.2: Room Layout (not to scale)

6.4.1 Experimental Session

A total of 45 minutes was allocated for each experimental session. After signing consent forms and screening for olfactory dysfunction, all participants were familiarised with the VR headset including calibration and fitting the headset. Calibration of the headset included entering the participant's height in the *Oculus* device management settings to ensure that the floor position was set correctly. This is an important step to calibrate the VR system for a user, as an incorrect height could potentially negatively affect the VR experience, as the participants would feel like they are floating in space (if height is too high) or partially submerged in the ground (if height is too low). The calibration was concluded by adjusting the lens distance and straps of the HMD. The *Oculus Rift* touch tutorial was then run to familiarise participants with the touch controller and to being inside the VE. Then the *The Climb* tutorial was launched. After participants confirmed they were comfortable with the environment the main experiment began.

Each participant played the game twice and participants were separated into two groups of 10 participants. The first group (5 females, 5 males) received odours during their first run of the game and no odours during their second run (Odour - No Odour group, which I will refer to as the O-NO group). The second group (4 females, 6 males) received no odours during their first run of the game and received odours during their second run of the game (No Odour - Odour group, which I will refer to as the NO-O group). Participants spent 10 minutes (timed by the researcher) playing the game. They were given instructions to find and touch as many flowers as possible and were shown what the two flowers look like on a paper printout of the flowers as shown in Figure 6.1. Participants were further instructed to climb as far as possible in the game, and were told that they would be awarded one point every time they touched a new flower, and that only the first interaction with a flower would award them a point. The researcher aimed to trigger the release of odours via the OD exactly when the participant touched a flower, however, as the OD was triggered manually, slight fluctuations in timings will have occurred. These fluctuations however were not measures. The researcher triggered the release of the odours every time a participant interacted with a flower, to give a consistent response to interactions with the flowers, even though a point was only awarded for the first interaction. There was no communication with participants during these 10 minutes. During gameplay, the researcher recorded the number of flowers (both purple and yellow) participants interacted with and noted down observations on participants' experience that were related to the odours.

After the first game play, participants removed the HMD and were seated at the assessment PC where they were asked to complete the Post-Game Questionnaire (PGQ) on a PC. The PGQ consisted of a section related to the sense of presence and a section on QoE. Presence was recorded using the Witmer and Singer Presence Questionnaire (3 items - see Table 5.5) and the the Jennet et al. Presence Questionnaire (JPQ) (5 items - see Table 5.4). QoE was recorded using the QoE questionnaire (5 items - see Table 5.3). While participants were answering the PGQ, the researcher wiped down the HMD and controllers using a paper towel, to remove any perspiration. After completing the PGQ, participants again entered the VE for a second run of 10 minutes of game play. Participants that had received odours the first run did not receive odours during the second run; if they had not received odours during the first run, they now received odours during their second run. After completing their second run, participants were once again asked to complete the PGQ.

6.5 Results

In this section, I present the results of the main study. Results related to the sense of presence, can be found in Section 6.5.1, which includes results from the Witmer and Singer Presence Questionnaire (Section 6.5.1.1) and the Jennet et al. Presence Questionnaire (JPQ) (Section 6.5.1.2). I then present the results from the QoE questionnaire (Section 6.5.2) followed by performance related results (Section 6.5.3) and finally qualitative results (Section 6.5.4).

6.5.1 Presence

In this section I present the results of the statistical analysis of the presence related scores, which were recorded using the Witmer and Singer Presence Questionnaire and the JPQ. The analysis was conducted to answer RQ_{1a} *How do pleasant, congruent odours affect perceived presence in virtual reality?*. The aim was therefore to determine whether there were any significant differences between the Odour and the No-Odour conditions in terms of the responses to the individual questionnaire items of the Witmer and Singer Presence Questionnaire and the JPQ. The details of the analysis and its results for the Witmer and Singer Presence questionnaire can be found in Section 6.5.1.1, and for the JPQ they can be found in Section 6.5.1.2. For both questionnaires, the analysis followed the approach shown in Table 6.4.

No-Odour Condition	Statistical Test	Odour Condition	Reason
Run 1 (NO-O)	Mann-Whitney U-Test	Run 2 (O-NO)	Is there an ordering effect?
Run 2 (O-NO)	Mann-Whitney U-Test	Run 1 (NO-O)	
Run 1 (NO-O) + Run 2 (O-NO)	Wilcoxon Signed-Rank Test	Run 2 (NO-O) + Run 1 (O-NO)	Did odours affect the responses?

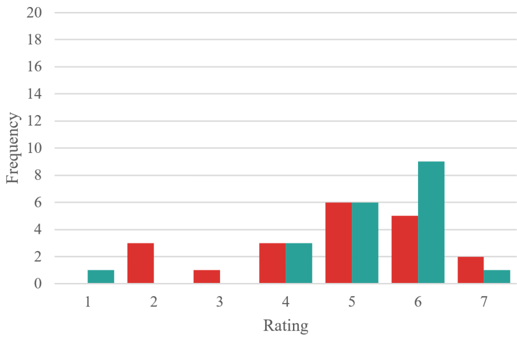
Table 6.4: Statistical analysis between the Odour and No-Odour conditions.

6.5.1.1 Witmer and Singer Presence Questionnaire

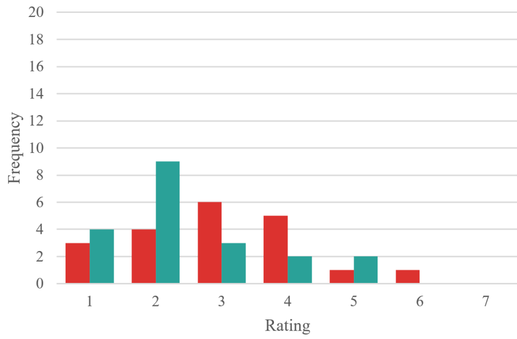
As an overview, Figure 6.3 shows histograms for the responses given to each of the images for both conditions.

As the order in which the NO-O and the O-NO groups experienced the conditions was reversed, there was a possibility that an ordering effect was present. I therefore conducted non-parametric Mann-Whitney U tests between the scores from the No-Odour condition (first run of the NO-O group against the second run of the O-NO group) and between the scores from Odour condition (first run of the O-NO group against the second run of the NO-O group), for each of the questionnaire items of the Witmer and Singer Presence Questionnaire.

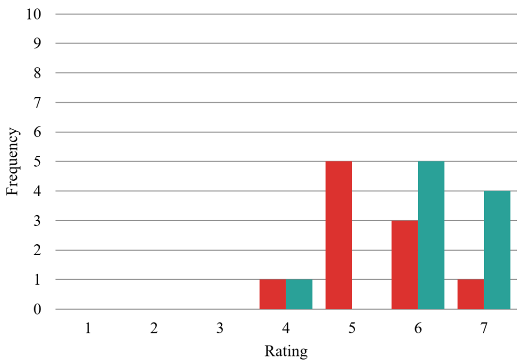
An ordering effect was observed for the NO-Odour condition of the question 'How completely were all of your senses engaged?' (O-NO median = 4.00, NO-O median = 5.00, U = 23.5 p = 0.043) and the results could therefore not be considered as originating from the same population. Further analysis of this question was therefore limited to separate comparisons between the Odour and the No-Odour condition of each group (i.e. between the Odour condition and the No-Odour condition of the NO-O group, and between the Odour condition and the No-



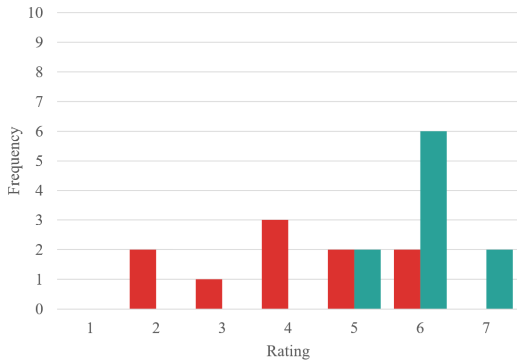
(a) How much did your experiences in the virtual environment seem consistent with your real-world experiences?



(b) How inconsistent or disconnected was the information coming from your various senses?



(c) How completely were all of your senses engaged? (NO-O)



(d) How completely were all of your senses engaged? (O-NO)

No Odour Odour

Figure 6.3: Histograms of the responses to the individual questions of the Witmer and Singer Presence Questionnaire for the Odour and No-Odour conditions. Emphasised text indicates significant difference between the mean scores of the conditions ($p < 0.05$).

Odour condition of the O-NO group).

For each questionnaire item for which no significant differences were found in the previous step, I conducted a Wilcoxon Signed Rank test between the combined conditions of the groups to be able to determine if the exposure to odours caused significant differences in terms of sense of presence. An overview of the result of this comparison can be found in Figure 6.4. Detailed results of the tests for each question are discussed under their respective headings below.

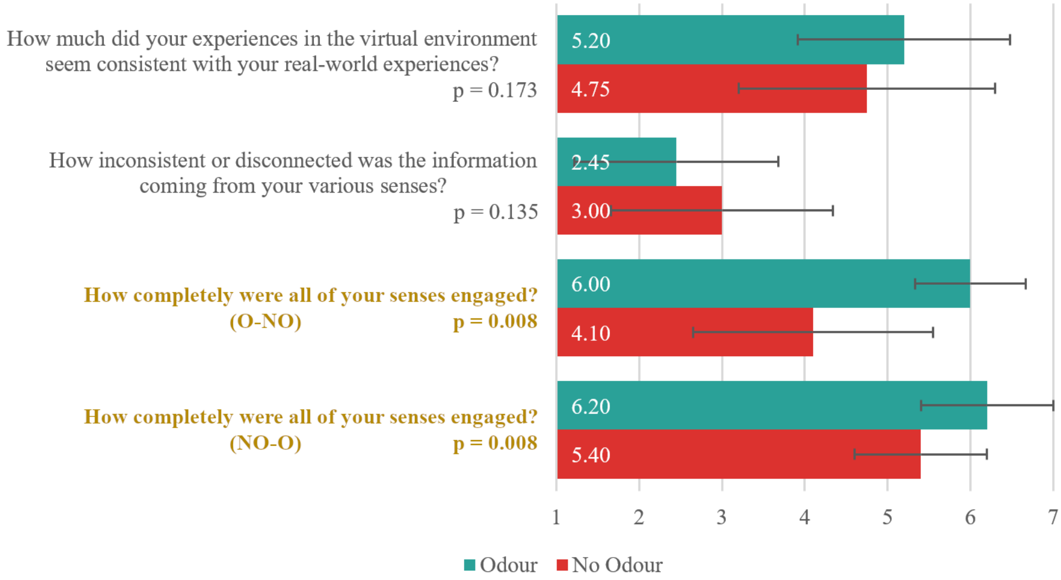


Figure 6.4: Presence mean scores for the Odour and No-Odour condition from the Witmer and Singer Presence Questionnaire. Emphasised text indicates significant difference between the mean scores of the conditions ($p < 0.05$).

How much did your experiences in the virtual environment seem consistent with your real-world experiences?

No significant differences were found between the Odour and No-Odour condition. However, the Odour condition resulted in a higher mean rating (No-Odour mean = 4.75, SD = 1.55, Odour mean = 5.2, SD = 1.28). While no significant difference could be observed, the Odour condition showed higher mean ratings. When examining the histogram of the responses (Figure 6.3a), it can be seen that most participants rated their response as a 6 for the Odour condition and generally lower for the No-Odour condition. However, more participants (2) rated their response as a 7 in the No-Odour condition, when compared to the number of participants during the Odour condition (1) that did so.

How inconsistent or disconnected was the information coming from your various senses?

No significant differences were found between the Odour and No-Odour condition. However, the Odour condition resulted in a lower mean rating (No-Odour mean = 3.00, SD = 1.34, Odour mean = 2.14, SD = 1.23). While no significant differences were found, the histogram (Figure 6.3b) of the responses to the question shows that most participants, in the Odour condition, rated their response as a 2, and while in the No-Odour condition, rated their response higher at a 3.

How completely were all of your senses engaged?

As an ordering effect was noticed between the No-Odour condition of the NO-O and O-NO groups, the groups were analysed separately. A Wilcoxon Signed Rank test was conducted on the scores of the No-Odour and Odour condition of the NO-O group and the output indicated that the Odour condition scores were significantly higher than the No-Odour condition scores (No-Odour mean = 5.40, Odour mean = 6.20, Z = 2.75, $p = 0.008$). A Wilcoxon Signed Rank test was conducted on the scores of the No-Odour and Odour condition of the O-NO group and the output indicated that the Odour condition scores were significantly higher than the No-Odour condition (No-Odour mean = 4.10, Odour mean = 6.00, Z = of 2.47, $p = 0.008$).

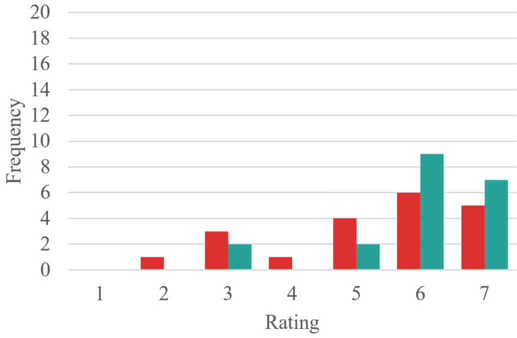
6.5.1.2 Jennet et al. Presence Questionnaire

As an overview, Figure 6.5 shows histograms for the responses given to each of the images for both conditions.

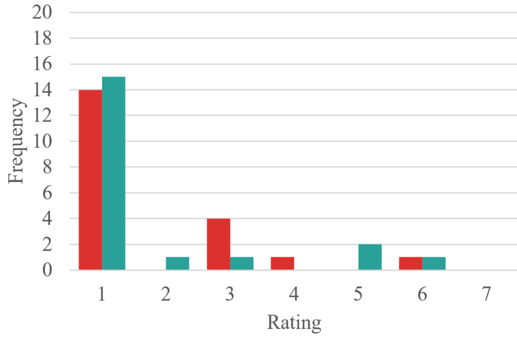
As with the responses to the Witmer and Singer Questionnaire, due to the order in which the NO-O and the O-NO groups experienced the condition, there was a possibility that an ordering effect was present in the responses to the JPQ. Non-parametric Mann-Whitney U tests were therefore conducted to determine if there was a significant difference between groups in the Odour condition, and between the groups in the No-Odour condition. No significant differences were found for any of the questions, indicating that there was no ordering effect for any of the responses to the questionnaire. This allowed me to treat all responses from the No-Odour condition as one group and all responses from the Odour condition as one group. I then conducted non-parametric Wilcoxon Signed-rank tests for each of the items of the JPQ, between the scores of the No-Odour condition and the Odour condition. The results of these tests for each questionnaire item are given below under their respective headings. Figure 6.6 gives an overview of the mean differences between each of the groups for all questions from the JPQ.

To what extent did you feel emotionally attached to the game?

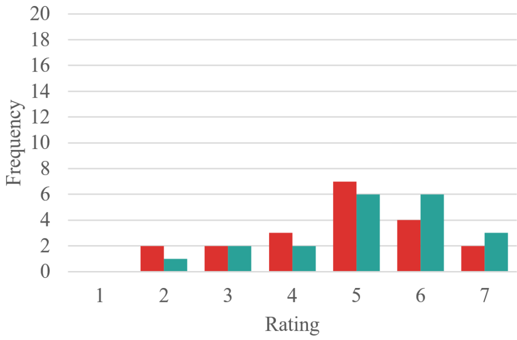
In both conditions scores were high, indicating the participants were emotionally attached to the game (No-Odour mean = 5.30, SD = 1.56, Odour mean = 5.95, SD = 1.19).



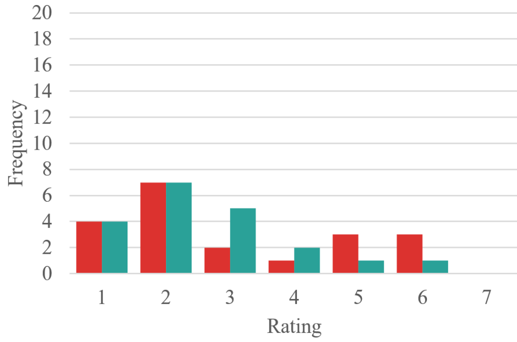
(a) To what extent did you feel emotionally attached to the game?



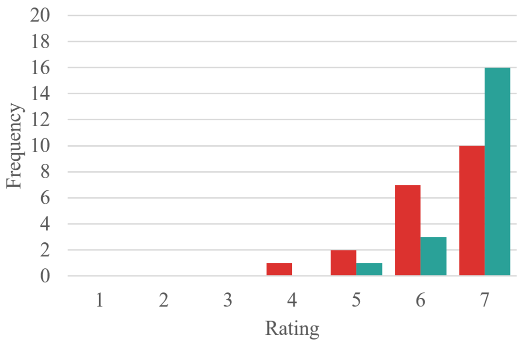
(b) Were there any times during the game in which you just wanted to give up?

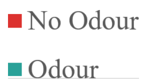


(c) At any point did you find yourself become so involved you were unaware you were even using controls?



(d) To what extent were you aware of yourself in your surroundings?





(e) To what extent did you feel you were focused on the game?

Figure 6.5: Histograms of the responses to the individual questions of the Jennet et al. Presence Questionnaire for the Odour and No-Odour conditions. Emphasised text indicates significant difference between the mean scores of the conditions ($p < 0.05$).

However, the Odour condition resulted in significantly higher results, indicating that the exposure to odours increased emotional attachment (Z = 2.16, $p = 0.042$). A histogram of the responses can be seen in Figure 6.5a. As indicated by the significant difference between the conditions, the responses of the Odour condition were swayed towards the higher end of the scale, with most responses giving a rating of 6 and 7. Responses to the

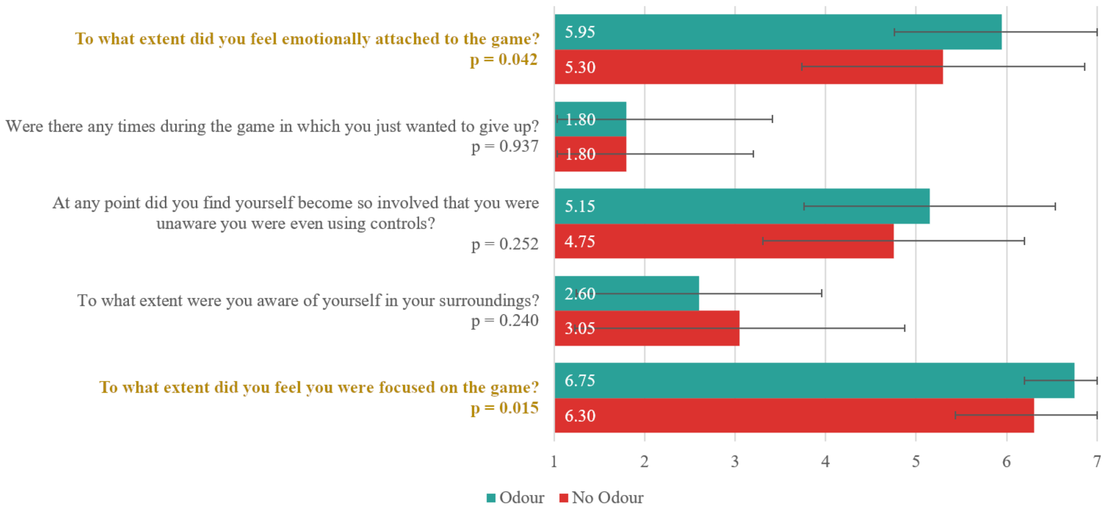


Figure 6.6: Mean presence response scores for Odour and No-Odour condition of the Jennet et al. Presence Questionnaire. Mean values are displayed at the base of each column. All responses were given on 7-point Likert scales ranging from 1 - 'Not at all', to 7 - 'Very much so'. Emphasised text indicates significant difference between mean scores.

No-Odour condition, while also trending towards the higher end of the scale are more spread out.

Were there any times during the game in which you just wanted to give up?

Participants were motivated to play the game, both in the Odour and No-Odour condition. No significant differences were found between the conditions. Both the Odour condition and No-Odour condition resulted in the same mean response (No-Odour mean = 1.8, SD = 1.39, Odour mean = 1.8, SD = 1.61, Z = 0.17, p = 0.937). A histogram of the responses can be seen in Figure 6.5b and shows that most participants (14 of the No-Odour condition and 15 of the Odour condition) responded with a 1 (the lowest possible score), showing that participants generally did not want to give up during the game.

At any point did you find yourself become so involved that you were unaware you were even using controls?

No significant differences were found between the Odour and No-Odour condition. Both conditions resulted in high mean scores (No-Odour mean = 4.75, SD = 1.44, Odour mean = 5.15, SD = 0.40, Z = 1.22, p = 0.252). A histogram of the responses can be seen in Figure 6.5c. The histogram shows that the responses for the groups were equally spread out across the scale, with a higher frequency of 5 and 6 point ratings for both conditions, indicating that odours did not affect the perception of the controls.

To what extent were you aware of yourself in your surroundings?

No significant differences were found between the Odour and No-Odour condition. However, the Odour condition resulted in lower mean results (No-Odour mean = 3.05, SD = 1.82, Odour mean = 2.60, SD = 1.35, Z = 1.27, $p = 0.24$). For this question, the surroundings were defined as the real-world surroundings rather than the surroundings of the VE. A histogram of the responses can be found in Figure 6.5d and shows that in both the Odour and the No-Odour condition, participants were generally not aware of their real-world surroundings, as indicated by a cluster of scores towards the lower end of the scale.

To what extent did you feel you were focused on the game?

Significant differences between the Odour and No-Odour condition were observed (No-Odour mean = 6.30, Odour mean = 6.75, Z = 2.46, $p = 0.016$). A histogram of the responses can be seen in Figure 6.5e. Even though scores were similar in their means, the histogram shows that there were significant differences in the distribution of the scores. While scores for the No-Odour condition are spread out between ratings of 4 and 7, 16 out of 20 participants gave a rating of 7 for the Odour condition.

6.5.2 Quality of Experience Questionnaire

The QoE questionnaire was used to assess how the odours impacted the experience of the participants while in the VE and consisted of 5 questions as shown in Table 5.3. As the QoE questionnaire is only conducted for the Odour condition, it is not possible to determine whether there were any significant differences between the conditions. All responses were given on a scale from 1 = No agreement, to 5 = High agreement, in response to the following statements. The responses to each questionnaire item is considered below. Figure 6.7 shows the mean responses to each of the questions. What can be seen is that participants generally felt very positive towards the use of the odours, stating that there was a high relevance of the odours, that the odours highly increased the sense of reality of the VE, that the odours were not distracting, that they were not annoying and that they generally highly enjoyed the VE.

The smell was relevant to what I was seeing.

Participants reported a high relevancy in terms of the odours and what they were seeing (mean= 3.90, SD = 1.07).

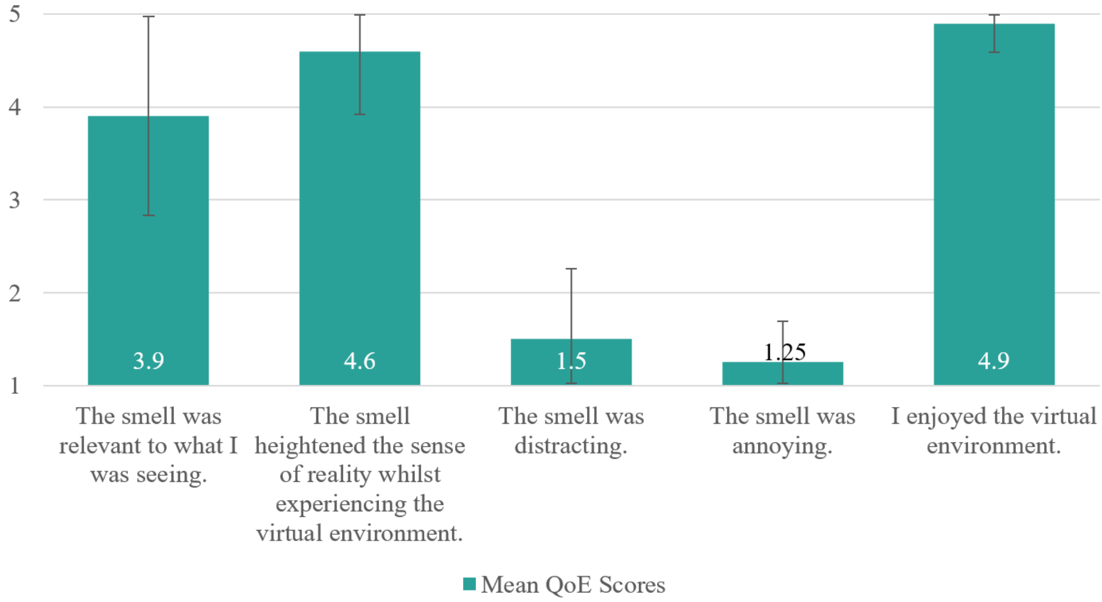


Figure 6.7: Mean Quality of Experience questionnaire responses.

The smell heightened the sense of reality whilst experiencing the virtual environment.

Participants reported that the odours highly increased their sense of reality of the (mean= 4.60, SD = 0.68).

The smell was distracting.

Participants reported that the odours were not distracting (mean= 1.50, SD = 0.76).

The smell was annoying.

Participants reported that the odours were not annoying (mean= 1.25, SD = 0.44).

I enjoyed the virtual environment.

Participants reported a high level of enjoyment of the VE (mean= 4.9, SD = 0.31).

6.5.3 Evaluation of Participant Performance

Participant performance was assessed by comparing how participants scored in terms of the flower interaction task, i.e. how many flowers they interacted with in the two conditions. As was described in Section 6.4.1, participants received one point for each flower they interacted with (touched) but only for the first interaction with each flower.

Even though players completed a basic climbing tutorial for *The Climb*, as players were new to the VR game, a certain learning effect was expected as participants naturally improve their climbing skills over time. To determine if this was the case, I compared the combined first play flower interaction scores of the NO-O group and the O-NO group against the combined second play scores of both groups. A Mann-Whitney U Test showed that there was a statistically significant difference between the two (combined first run median = 3, combined second run median = 20, U = 41, $p < 0.001$) indicating that there was indeed a learning effect and that participants generally performed better during their second run. All except one participant interacted with more flowers during the second run, regardless of the order in which participants were presented the odours.

To determine whether odours increased the number of interactions with plants above any learning effect, I compared the scores of the second play (odour) of the NO-O group against the scores of the second play (no odour) of the O-NO group. A Mann-Whitney U Test showed that there was a significant difference between the scores (odour median = 5, no odour median = 6, U = 21.5, $p = 0.014$) and that the Odour condition resulted in a higher mean score than the no Odour condition (Odour mean = 6.9, SD = 1.66, no Odour mean = 5, SD = 2.1). The odours significantly increased the number of flowers that participants interacted with, above the learning effect observed. The mean scores can be seen in Table 6.5.

Order	**1textsuperscriptst Run**	**2textsuperscriptnd Run**
NO-O	3.20	6.90
O-NO	3.00	5.00

Table 6.5: Mean Flower Interaction Scores

6.5.4 Qualitative Results

During the experimental sessions I recorded observations and unsolicited remarks made by the participants concerning their experience of the odours. The full list of observations and participant remarks can be found in Table 6.6. Furthermore, for all participants, the *Oculus Touch* controllers were covered by perspiration, which was observed when participants handed the controllers back to me before answering the PGQ. There were no observable differences between the Odour and No-Odour condition. Two participants were not able to partake in the study due to an onset of fear of heights as soon as they began climbing.

6.5.5 Gender Differences

As Jones et al. (2004) had found significant gender differences in terms of the perceived sense of presence of their VE, I conducted Mann-Whitney U tests, comparing the Male / Female responses for each of the questionnaires as well as the score achieved. No significant gender

ID	Age	Gender	Observations and Participant Remarks
NO-O2	29	Male	Had to steady himself for ca. 30 seconds upon entering The Alps level before being able to move.
NO-O5	34	Male	"Ahh so this is the smell."
NO-O6	28	Male	Stopped at a purple flower and repeatedly touched it to release the odour (for ca. 30 seconds).
NO-O8	29	Female	"MMhhh lavender."
NO-O9	27	Female	"The smells made the game seem so much more real." "I really thought that the smells were coming from the flowers."
O-NO2	33	Female	"This smells so nice."
O-NO3	32	Male	Stumbled in the real world while leaning into the virtual wall and expecting there to be something to lean against.
O-NO4	27	Male	"When I smelled the flowers I knew that I got a point."
O-NO7	28	Female	"Ahh the smell of fresh mountain air."
O-NO8	36	Male	Spent about 30 seconds interacting with one of the purple flowers repeatedly touching it and then said: "Why does the flower smell when I touch it? It should just smell when I am close."

Table 6.6: Observations of participants and their remarks made during the experimental sessions.

differences were found.

6.6 Discussion

This study set out to answer RQ_{1a}: Can pleasant, congruent odours enhance presence in virtual reality? The results from the Witmer and Singer Presence Questionnaire and the JPQ showed that odours significantly increased the focus on the game (item 1 of the JPQ - Table 5.4), emotional attachment to the game (item 5 of the JPQ) and the perception of how completely all of the senses were engaged (item 1 of the Witmer and Singer Presence Questionnaire - Table 5.5), indicating that the odours may have positively affected the sense of presence while in the VE. These findings are in line with those from previous research. Focus has been described as one of the main factors that contribute to presence (e.g. Schubert, Friedmann, et al., 1999; Witmer and Singer, 1998). Emotional attachment to the VE has also been directly linked to the perceived presence and has been shown to be an indicator of presence: VEs with a higher degree of emotional content produce higher levels of perceived presence (Riva et al., 2007).

Participants also felt that their senses were significantly more engaged during the Odour condition, which may seem unsurprising, as the display of olfactory information, i.e. flower odours being displayed when participants interacted with the virtual flowers in the VE, constitutes an increase in sensory fidelity. While the number of sensory modalities available is an immersive property of a VE, it is not always certain whether participants are able to perceive this difference and if it actually affects their perception of the VE. The results show that participants were indeed able to perceive the odours and that they significantly changed their reported engagement with the VE.

There were however several questionnaire items that did not show significant differences when comparing the Odour with the No-Odour test condition (Witmer and Singer Presence Questionnaire items 2 and 3, and JPQ items 2, 3 and 4). These items were mostly questions about properties that were not directly affected by odours, and it is perhaps not surprising that the results showed no significant changes between the conditions. No significant differences were found between the Odour and No-Odour condition in regard to participants' awareness of themselves in their surroundings. While answering the questionnaire, several participants asked the experimenter whether the 'surroundings' refer to the virtual or real world surroundings, showing that there seemed to have been a certain degree of misunderstanding regarding the wording of the question. Those participants who asked were told that the surroundings referred to their real-world surroundings (as intended by Jennett et al. (2008)), however several participants noted that they had expected this to refer to the virtual surroundings. It is therefore reasonable to assume that several of the participants who did not seek clarification on the question, may have misinterpreted it and therefore may have not answered it as was intended.

Interestingly, participants did not feel that odours significantly added to the consistency between their real-world experiences and the VE. Results for both conditions however showed a skew towards the higher end of the scale, i.e. participants generally felt that the VE was very consistent with their real-world experiences, even without added odours, and this may have led to a ceiling effect. The generally high ratings were not entirely unexpected - the VE is very immersive, which was also evident from participant's physiological responses such as that participants had sweaty palms during gameplay, that 5 participants had to steady themselves and 2 participants felt that they could not partake in the study in response to the feeling of standing at great height and the experience of the fear of heights in VEs has previously been linked to an increase in the sense of presence (Regenbrecht, Schubert, and Friedmann, 1998). The high results may have therefore been partly due to the high degree of engagement that was inherent to the game.

Participants felt that the sensory information was not inconsistent or disconnected in either of the conditions, showing that the odours were perceived as being consistent with the VE, a positive result for the selection method for the odours. This also shows that the VE was overall perceived as consistent in terms of the sensory information that was presented to participants.

Overall, the three key significant results of the presence questionnaire, that odours increased sense of focus and emotional attachment, and the degree to which participants felt that their senses were engaged, stand in direct contrast to the results from Baus and Bouchard's 2017 study, which showed that while an unpleasant odour was able to significantly increase perceived presence in VR, a pleasant odour was not able to do so (see Section 3.4.4.2). However, the odours used in my study were congruent with the VE, while Baus and Bouchard used (unverified) incongruent odours. The difference in results for the pleasant odours may therefore show that the pleasantness of an odour alone is not an indicator for a sense of presence in VR, and it would thus appear that the difference in results between this study and Baus and Bouchard's 2017 study is due to the difference in the congruence of the odours used with the VE. Another reason for this difference may be the limitations of the statistical analysis that was conducted in Baus and Bouchard's study: they report that most participants did not perceive the odours in their study, especially the pleasant odour, and hence the results are based on very small samples (only 3 participants perceived the pleasant odour while 12 perceived the unpleasant odour). Their results showed that only the unpleasant odour produced a significant change in perceived presence and the authors suggest that the lack of perception of the pleasant odour is the reason for this difference, and that this lack of perception was caused by a lower intensity of the pleasant odour.

In my study, participants did perceive the odours, as was seen by a significant increase in ratings for the Odour condition, of responses to the question 'How completely were all of your senses engaged?'. It is therefore possible that a lack of perception of odours was the cause for the difference in results between my study and Baus and Bouchard's study.

While the main focus of this study was to understand whether congruent pleasant odours could affect presence in VR, it also examined a novel method for odour selection. In this study, odour perception related results were recorded using the QoE questionnaire and could be used to verify the results of the odour selection task. The results showed that the selected odours were perceived positively and were in line with the selection task results. Participants felt that the odours were very relevant (QoE questionnaire item 1), that they heightened the sense of reality while experiencing the VE (QoE questionnaire item 2), and reported that they were not distracting or annoying (QoE questionnaire items 3 and 4 respectively). The results also show that the OD was able to display the odour in an unobtrusive manner that did not distract participants or make them aware of their real world surroundings. Overall there was no issue with the use of the novel OD. Previous olfaction-based studies in VR have reported issues with lingering odours, however, this appeared not to be a problem in this study, where no lingering odours could be detected. This is perhaps due to the minute amounts of odorant that were vaporised each time the OD was triggered, which was possible due to its close proximity to the participant's nose.

Lastly, this study evaluated participants' performance in terms of the number of flowers they managed to find and interact with, in regard to RQ_2: How do odours affect task performance in virtual reality?. The task was directly related to a participant's climbing ability (the better at climbing a participant is, the further in the game they can reach and the greater chance they have of encountering more flowers). A learning effect was expected, as participants will naturally become better at playing the game over time while they gain a better grasp of the controls, which was also shown in the results, as significant differences were found between the NO-O and O-NO groups flower interaction scores of the No-Odour condition, as well as the flower interaction scores of the Odour condition (see Section 6.5.3). However, the results also showed that odours were able to increase flower interaction scores above the observed learning effect, and participants scored significantly higher when they perceived odours, regardless of whether this happened in their first or second VE experience (see Section 6.5.3. This study demonstrates that if virtual objects emit congruent pleasant odours, then they are interacted with significantly more than non-odour emitting virtual objects.

In order to determine whether the difference in results is due to the congruence of the odours and the VE, or the intensity of the odours, it was necessary to conduct a further study that mirrors the setup of the study described in this chapter, but using incongruent odours of the same intensity (Chapter 7). By varying only the congruence of odour, but not intensity, it will be possible to determine whether congruence of odour and VE affects presence in VR.

6.7 Conclusions

There were three main aims for this study. First, to answer RQ_{1a}: *Can pleasant congruent odours enhance presence in virtual reality?* Second, to test the effectiveness of a new method for odour selection, which was developed on the basis of insights gained during Study One (see Section 4.9) as well as from the literature review. Third, to evaluate a novel type of OD for VR headsets, which was developed using affordable off-the-shelf technology.

In order to answer RQ_{1a}, first an odour selection task was conducted to produce two pleasant odours that were perceived as being congruent with two flowers, one purple and the other yellow (see Figure 6.1) that were part of the VE. The VE consisted of the *Oculus Rift* HMD with *Oculus Touch* controllers (Oculus VR, 2017) and ran the VR mountain climbing game *The Climb* (CRYTEK, 2018a) and a novel type of OD that was developed for this study. In the selection task, participants were asked to state whether they perceived the odour and then to rate the odours in terms of their perceived intensity, pleasantness, and congruence with two virtual flowers. Furthermore participants were asked to name the odour and give a description of the odour including any associations that were made with the odour.

The results of the selection task showed that participants were able to agree on the perceived congruence of the odours and flowers, and two odours matching two in-game flowers were selected, based on their perceived pleasantness and congruence to the yellow and purple VR flowers. Essential lavender oil was chosen to represent the purple flower, while a fragrance oil with the name *Freesia* was chosen to represent the yellow flower.

Results from the presence questionnaires showed that there was a significant increase in the degree of focus on the game, the emotional attachment to the game, and the degree to which the senses were completely engaged, when the participants were exposed to the odours. All three of these items have been directly linked to the perception of presence (Fontaine, 1992; Jennett et al., 2008; Slater, Lotto, et al., 2009; Witmer and Singer, 1998). These results therefore point in the direction that pleasant congruent odours may be able to increase the sense of presence in VR. This finding was further corroborated by results from the QoE questionnaire, where participants stated that the odours heightened the sense of reality while experiencing the VE, another factor influencing the perception of presence (Schubert, Friedmann, et al., 1999).

Results from the QoE questionnaire also gave indication that the introduced method for odour selection was successful at selecting odours which were pleasant and congruent with the virtual flowers. Participants stated that the odour were relevant to what they were seeing, that they were not distracting and that they were not annoying. Furthermore all participants stated that they had perceived the odours. The selection of odours has been an issue in olfaction-related research in HCI for nearly two decades (J. N. Kaye, 2001), with some researchers disregarding the basic factors of human odour perception, namely intensity, valence and familiarity (see Section 3.3.1). By controlling for these factors, the results of this study become far more robust as unwanted factors, such as low detection rates caused by low intensity odours (Baus and Bouchard, 2017), were prevented.

Lastly, performance results showed that participants scored a significantly higher number of flower points when they perceived an odour, demonstrating that odours can increase interactions with virtual objects. The contributions of this study are therefore as follows:

1. It provides novel empirical data which demonstrates that congruent pleasant odours can increase the sense of presence in VR.

2. It demonstrates that the display of pleasant congruent odours can lead to an increased number of interactions with virtual objects.

3. It introduces and validates a novel method for odour selection. This is the first systematic method for odour selection in HCI and takes into consideration the basic factors of odour perception, namely, valence (pleasantness), intensity, and familiarity, to ensure consistency and reproducibility of the odours.

4. It introduces a newly developed low-cost, off-the shelf OD for VR headsets that does not impact on participants' awareness of their real world surroundings and does not produce lingering smells in the experimental environment.

Chapter 7

Study Three

7.1 Introduction

Results from Study Two revealed that congruent, pleasant odours could significantly affect the sense of presence in VR, in terms of perceived focus, emotional attachment, and the perceived degree of sensory stimulation. These results were in contrast to previous studies, such as by Dinh et al. (1999), who found that odours did not affect presence, or Baus and Bouchard (2017), who found that only unpleasant odours could increase a sense of presence in VR. The positive results from Study Two therefore warrant a closer examination of the relationship between congruence and sense of presence in VR, specifically if incongruent pleasant odours can also enhance the sense of presence, which has not been studied to date. This study therefore aims to answer the following research question:

$\mathbf{RQ_{1b}}$ *How do pleasant, incongruent odours affect perceived presence in virtual reality?*

The results from Study Two (see Section 6.5), showed that congruent pleasant odours could significantly increase the sense of presence in VR, specifically in terms of the degree of focus, the emotional attachment, and the degree to which the senses were engaged. the main hypothesis H_1 for this research question is that:

$\mathbf{H_1}$ *Pleasant, incongruent odours increase presence in virtual reality.*

To be able to compare and contrast these results to those of Study Two (see Section 6.5), Study Three followed a similar study design, specifically the odour selection method from the odour selection selection task (see Section 6.2), and the method for the main study (see Section 6.4) and used the same OD (see Section 5.4.1) and VE (see Section 5.3.2). It will therefore also be possible further verify the effectiveness of the novel method for odour selection, as used in

Study Two, however this time for incongruent odours. Finally, Study Three will further evaluate the novel OD for VR headsets, which was first used in Study Two (see Section 5.4.1).

7.2 Odour Selection Task

This odour selection task followed the methods outlined previously in Section 5.5. This study used the same Odour Selection Questionnaire (OSQ) as in Study Two (see Table 5.2), to determine whether participants perceived and recognised an odour; how they perceived the odour's intensity; how they perceived the odour's pleasantness; and to what degree participants perceived the odour to match either of the two flowers (see Figure 6.1), i.e. the degree of congruence between odour and flower. Questions to derive if a participant could perceive and recognise an odour were identical to the questions in Study Two. To determine perceived odour intensity, and pleasantness, participants were asked to record their responses on a five-point Likert scale, only giving labels for end-point anchors, to the following statements: To determine odour intensity: 'This scent's intensity is...' on a five-point Likert scale (1 - Low Intensity to 5 - High Intensity), and to determine odour pleasantness: 'I liked this scent...' also on a five-point Likert scale (1 - Not at all to 5 - Very much). These statements were included in the OSQ (see Table 5.2).

While Study Two examined the effect of congruent odours on the sense of presence in VR, this study examined incongruent odours in the same context. The OSQ of Study Two was therefore set out to determine the degree of congruence between the odours and the flowers, and did not take incongruence into consideration. Therefore, the OSQ had to be adapted to test for the incongruence of odours. In order to determine if the odours were incongruent with the depicted flowers, participants were asked the question 'Does this scent match this flower:', followed by an image of either the purple or yellow flower that could be found in the game (see Figure 6.1). Participants were asked to rate their response on a seven-point Likert scale with labels only given for end-point anchors (1 - Not at all, to 7 - Very much). This was followed by the same question again, however in connection with a screenshot image depicting the other flower, i.e. if the purple flower was shown in the first question, the yellow flower was shown in the second question. The order in which the flowers were shown was randomised for each participant.

11 participants took part in the selection task (6 female, 5 male, mean age = 37.60 years (SD = 9.79 years), who had not previously taken part in the selection task of Study Two. Participants were screened for olfactory dysfunction using the three item Quick Smell Identification Test

(Jackman and Doty, 2005). No participants were excluded due to olfactory dysfunction.

7.2.1 Odour Selection Task Results

An initial set of 15 liquid odorants were purchased. Table 7.1 shows a list of the odorants as well as the producer that were used during the odour selection task. In total, 15 odours were evaluated during the selection task. These were apple, blueberry, bubblegum, cherry, chocolate-chip cookie, fresh hay, gingerbread, oud, rain, rainforest, strawberry, swimming pool, vanilla, lavender, and freesia. As the purpose of this selection task was to find two odours that were perceived as pleasant, with sufficient intensity, and incongruent with the VR flowers, odours that were perceived as clearly unpleasant were eliminated from this list. In an informal screening session prior to the pilot, three participants assessed whether any of the odours could be considered clearly unpleasant. This lead to the elimination of the following odours: blueberry, fresh hay, oud, rain, rainforest, and swimming pool, reducing the final number of odours to be evaluated to 9. While the purpose of this selection task was to identify an incongruent odour for each of the VR flowers, I also wanted to use this opportunity to validate the odours chosen for Study Two, and included the two chosen congruent odours of lavender (congruent with the purple flower) and freesia (congruent with the yellow flower). The final set of 9 odours can be found in Table 7.1.

Odorant Name	Type	Manufacturer
Apple	Fragrance Oil	Essex Liquid
Blueberry	Fragrance Oil	Essex Liquid
Bubblegum	Fragrance Oil	Essex Liquid
Cherry	Fragrance Oil	Essex Liquid
Chocolate-Chip Cookie	Fragrance Oil	Essex Liquid
Fresh Hay	Fragrance Oil	Demeter Fragrance Library
Gingerbread	Fragrance Oil	Essex Liquid
Oud	Fragrance Oil	Demeter Fragrance Library
Rain	Fragrance Oil	Demeter Fragrance Library
Rainforest	Fragrance Oil	Essex Liquid
Strawberry	Fragrance Oil	Essex Liquid
Swimming Pool	Fragrance Oil	Demeter Fragrance Library
Vanilla	Fragrance Oil	Essex Liquid
Lavender	Essential Oil	Muji
Freesia	Fragrance Oil	Essex Liquid

Table 7.1: Initial set of odorants purchased for the odour selection pilot.

The remaining odours were evaluated for their intensity, pleasantness and congruence to the flowers. The method follows the method of odour selection described in Section 5.5 and which was used in Study Two 6.3.1.

Odour Name	Apple	Bubblegum	Chocolate-Chip Cookie	Strawberry	Lavender
P1	-	-	-	Strawberry	Lavender oil
P2	Fresh apple	Bubblegum	Hazelnut	Orange soda	Lemon
P3	Fake apple scent	Bubblegum	Cookie or baking	Fruit shampoo	Lavender
P4	Strawberry	Mint bubblegum	-	-	Lavender
P5	My shampoo	Ment	Chocolate	-	Lavender
P6	-	Oral solution	Chocolate	Strawberry	Lavender
P7	-		-	Strawberry	-
P8	Apple	Spearmint	Burnt caramel	Pineapple	Pine
P9	-	Deep heat	-	-	Lavender
P10	Ointment	Antiseptic	Fruitcake-like	Monster energy (blue can)	Antiseptic-like
P11	Apple	-	Hazelnut	Watermelon	Lavender

Odour Name	Cherry	Vanilla	Gingerbread	Mint	Freesia
P1	-	-	-	Peppermint	-
P2	Cherry	Vanilla extract	Spices	Mint	Sweet Floral
P3	Cherry (fake)	Cookie-dough	Curry sauce	Mint	Flower
P4	-	Cookie	-	-	Sweet & Fruity
P5	-	-	Cinnamon	Ment	Floral
P6	Almond	Alcohol	Semolina	Mint	Washing liquid
P7	Almond	-	-	Mint	Parma Violets
P8	Cherry	-	-	-	Flowery
P9	-	Vanilla	-	Minty	Vaseline lotion
P10	Fruitcake	Sweet alcohol (like brandy)	Cinnamon	Peppermint	Parma Violets
P11	Cherry	Rum essence	Allspice	Mint	Lemon

Table 7.2: Participant labels for the odours evaluated for the selection task.

To determine which of the odours was most suitable for the VE, unsuitable odours were eliminated, following the method detailed in Study Two (Section 6.3.1), according to their intensity (responses to the statement 'This scent's intensity is...') and pleasantness ratings (responses to the statement 'I like this scent...'). Only odours which were perceived with a median intensity score of between 3.0 and 4.0 were considered suitable. In terms of pleasantness, only those odours with a median score of 4.0 or higher were considered as suitable, to ensure that the odours were overall perceived as pleasant. This rejected the bubblegum, vanilla, gingerbread, and mint odours. The remaining odours were therefore the apple, chocolate-chip cookie, strawberry, cherry, lavender, and freesia odours. The median intensity and pleasantness scores for these odours can be found in Table 7.3.

Odour	**Intensity (median)**	**Pleasantness (median)**	**Recognise Odour (%)**	**Congruence Purple Flower (median)**	**Congruence Yellow Flower (median)**
Apple	4.00	4.00	63.64	2.00	3.00
Bubblegum	4.00	3.00	72.73	1.00	1.00
Chocolate-Chip Cookie	4.00	4.00	63.64	1.00	1.00
Strawberry	4.00	4.00	72.73	2.00	2.00
Cherry	4.00	4.00	63.64	2.00	1.00
Vanilla	3.00	3.00	63.64	2.00	1.00
Gingerbread	4.00	3.00	45.45	2.00	2.00
Mint	3.00	3.00	81.82	1.00	1.00
Lavender	4.00	4.00	72.73	4.00	2.00
Freesia	4.00	4.00	36.36	1.00	3.00

Table 7.3: Odours evaluated during the selection task.
Odours with an intensity score of $i < 3.50$ and $i > 4.50$ were rejected. Odours with a pleasantness score of $p < 3.50$ were rejected. Red values indicate that this odour was rejected due to falling outside the specified intensity range, or below the pleasantness and congruence thresholds. Underlined scores indicate the value that caused the rejection of the odour. Colour highlights indicate that the odour was selected for the Yellow Flower, Purple Flower.

Following the reduction in the number of viable odours that could be used with the VE, the congruence of the odours with the virtual flower was assessed. As opposed to Study Two, where the selection was made for odours that were perceived as congruent with the purple and the yellow flower, in this study, the selection was made for odours that were perceived as incongruent with the flowers. In this step, only those odours which had a median congruence score of 2.50 or smaller for either of the two flowers were considered. This caused a rejection of the apple odour, which had a median congruence scores of 2.00 (purple flower) and 3.00

(yellow flower), as well as the lavender and freesia odours, which also had high congruence scores (lavender median congruence purple flower = 4.00, yellow flower = 2.00; freesia median congruence purple flower = 1.00, yellow flower = 3.00).

While the remaining odours (chocolate-chip cookie, strawberry and cherry) all fell within the pre-determined requirements for the use in the VE, I wanted to determine whether any of the odours was perceived significantly more incongruent to a type of flower than the other odours. Therefore, to determine if there were significant differences between the purple flower congruence scores for the remaining odours, a non-parametric Friedman test of differences among repeated measures was conducted and rendered a Q-stat score of 10.50, which was significant with $p = 0.005$. Post-hoc pairwise Wilcoxon Signed-ranks tests revealed that there were significant differences between the purple flower congruence scores of the chocolate-chip cookie, and strawberry odours(chocolate-chip cookie median = 1.00, strawberry median = 2.00, $p = 0.036$) and between the purple flower congruence scores of the chocolate-chip cookie, and cherry odours(chocolate-chip cookie median = 1.00, cherry median = 2.00, $p = 0.014$). This indicated that the chocolate-chip cookie odour was most appropriate as it was perceived significantly less congruent to the lavender odour than the strawberry and cherry odours. To determine if there were significant differences between the yellow flower congruence scores for the odours, a non-parametric Friedman test of differences among repeated measures was conducted and rendered a Q-stat score of 3.43, which was not significant with $p = 0.180$. This indicated that any of the three odours were suitable as an odour that is perceived as incongruent with the yellow flower. A final comparison was therefore made between the yellow flower congruence scores of the strawberry and cherry odours and the freesia odour, which was perceived as most congruent in Study One, and was also perceived as congruent in this odour selection task. The chocolate-chip cookie odour was not included in this analysis as it was already selected for the purple flower. A Wilcoxon Signed-Rank Test for Paired Samples was conducted on the yellow flower congruence scores of the strawberry and freesia odours, showing that there were no significant differences between the scores (freesia yellow flower congruence median = 3.00, strawberry median = 2.00, $p = 0.050$). A Wilcoxon Signed-Rank Test for Paired Samples conducted on the yellow flower congruence scores of the cherry and freesia odours showed that there were significant differences between the scores (freesia yellow flower congruence median = 3.00, cherry median = 1.00, $p = 0.034$). As there were significant differences between the freesia and cherry odours, but not in between the freesia and strawberry odours, the cherry odour was selected to represent the yellow flower in the VE.

7.3 Main Study

The purpose of the main study was to investigate whether pleasant incongruent odours can affect the sense of presence in a VR environment. 20 participants, who had not taken part in Study Two, 10 male (mean age = 30.4, SD = 8.49) and 10 female (mean age = 26.7 SD = 4.00) were recruited and took part. The selection of participants was done on a non-probability, convenience sampling basis. Participants were recruited via university mailing lists and noticeboards. Several exclusion criteria applied. All participants were required to have normal or corrected to normal vision and none had an olfactory dysfunction as assessed using the Quick Smell Identification Test (Jackman and Doty, 2005). Participants were asked not to smoke, eat or drink for one hour before the study and not to wear any perfumes or fragrances on the day of the experiment. Furthermore, participants who required corrective vision aids were asked to wear contact lenses, as not all glasses fit inside the Oculus Rift headset. Lastly, all participants were required to have previous experience with VR. No compensation was given to participants and full clearance from the City, University of London Computer Science Research Ethics Committee was received.

The study was set up as a within participants repeated measures experiment with one independent variable. The independent variable was IV_1: whether participants received odours or not. There were three dependent variables, DV_1: QoE responses; DV_2: Presence responses; and DV_3: How many flowers a participant interacted with. Participants were asked to play the same VR game that was used in Study One, *The Climb*, two times, once in the No-Odour condition which was without odour display, and once in the Odour condition, which was with incongruent pleasant odour display. The order in which each participant experienced the two conditions was randomised and counterbalanced between two groups. These groups were the No-Odour Odour (NO-O) group and the Odour No-Odour (O-NO) group. The NO-O group experienced the No-Odour condition in their first run, followed by the Odour condition in their second run. The O-NO group experienced the Odour condition in their first run and the No Odour condition in their second run.

7.3.0.1 Questionnaires

To ensure that results are comparable to Study Two on the effect of congruent pleasant odours on presence, the Post Game Questionnaire (PGQ) of Study Two was used (see Section 5.6.1).

The PGQ captured participant responses in terms of presence, as measured by the Witmer and Singer Presence Questionnaire (5 questions based on Witmer and Singer (1998) - see Table 5.5 for questionnaire items) and the Jennet et al. Presence Questionnaire (JPQ) (5 questions from Jennett et al. (2008) - see Table 5.4 for questionnaire items). The PGQ also captures perceived Quality of Experience (QoE) and was used to assess how the odours impacted the experience of the participants while in the VE. QoE was recorded using the QoE questionnaire (5 questions from Ghinea and Ademoye (2012a) - see Table 5.3 for questionnaire items). As 4 out of the 5 items of the QoE questionnaire (QoE questionnaire items 1-4) pertain to the experience of the odours specifically, e.g. item 1. 'The smell was relevant to what I was seeing.', the PGQ only contains the QoE questionnaire when participants respond to the Odour condition. However, as item 5 of the QoE questionnaire 'I enjoyed the virtual environment' is not odour-specific, this question was also asked when participants exited the VE after they had experienced the No-Odour condition, to be able to determine if incongruent pleasant odours affected participants enjoyment of the VE.

7.3.1 Experimental Protocol

A total of 45 minutes was allocated for each experimental session. After signing consent forms and screening for olfactory dysfunction, all participants were familiarised with the VR equipment including calibration and fitting the headset, as described in Section 6.4.1. Participants completed the Oculus Rift touch tutorial to familiarise themselves with the touch controller and to being inside the VE. Then the *The Climb* tutorial was launched. After participants confirmed they were comfortable with the environment the main experiment began.

The experimental session for each participant followed the below protocol:

1. The participant reads the participant information sheet and signs the consent form - 5min

2. The participant is screened for any olfactory dysfunction using the three item Quick Smell Identification Test (Jackman and Doty, 2005) - 2 min

3. The VR Head-Mounted Display (HMD) is adjusted and calibrated for the participant - 2 min

4. The participant completes the *Oculus First Touch* tutorial - 5 min

5. The participant completes the *The Climb* tutorial - 5 min

6. The experimenter starts the level *The Alps - Easy* and places the participant at the first checkpoint platform in the game - 1 min

7. The participant plays the game for the first time (the condition - Odour or No-Odour, is determined randomly). While the participant is playing the game, the experimenter records all flower interactions and notes down observations on the participant's odour-related experiences - 10 min

8. The participant removes the VR headset and is asked to complete the Post-Game Questionnaire (PGQ) on a PC. While the participant is answering the PGQ, the experimenter wipes down the controllers and HMD using a paper towel to remove any perspiration and returns the player avatar to the first checkpoint platform in the game - 3 min

9. The participant plays the game for the second time (and does the other experimental condition). During gameplay, the experimenter records flower interaction scores and observations - 10 min

10. The participant removes the VR headset and is asked to complete the PGQ on a PC - 3 min

11. End of the experimental session

12. The experimenter sanitises the VR headset and controllers using antibacterial wipes - 1 min

13. The experimenter asks the participant if she/he has any comments about the experience - 5 min

The method for the main study mirrors the method of Study Two (see Section 6.4). Each participant played the game twice and participants were separated into two groups of 10 participants. The first group (5 females, 5 males) received odours the first time they played the game, the second group received odours the second time they played the game (5 females, 5 males). Participants spent 10 minutes (timed by the researcher) playing the game. They were given the verbal instructions to find and touch as many flowers as possible while climbing as far as possible in the VE and were shown a screenshot of each of the flowers, which can be seen in Figure 6.1. Participants were told that they would be given a point for each new flower they interacted with. As in Study Two, points were only given for the first instance of interacting with a flower and any subsequent interactions with the same flower were ignored. The researcher aimed to trigger the odours exactly when the participant touched a flower, however, because the odours were triggered manually, slight fluctuations in terms of timing will have occurred. These fluctuations were not measured. There was no communication with participants while they played the game. After the first 10 minutes of playing in the VE, participants completed the PGQ on a PC, followed by another 10 minutes of game play in the second experimental condition.

7.4 Results

In the following section I describe the results of the main study. Data was collected in terms of the sense of presence in the VE, QoE, participant performance in terms of flower interaction scores, and qualitative data in terms of observations and remarks made by participants during and after the experimental sessions. The results from each of these metrics will be described in the following sections: presence scores were collected using the Witmer and Singer Presence Questionnaire (Table 5.5, the results of which are described in Section 7.4.1.1), and the JPQ (Table 5.4), the results of which are described in Section 7.4.1.2; QoE scores were collected using the QoE questionnaire (Table 5.3) and the results are described in Section 7.4.2; performance scores are described in Section 7.4.3; qualitative results are described in Section 7.4.4.

7.4.1 Presence

In this section I present the results of the statistical analysis of the presence related scores, which were recorded using the Witmer and Singer Presence Questionnaire and the JPQ. The analysis was conducted to answer RQ_{1b} *How do pleasant, incongruent odours affect perceived presence in virtual reality?*. The aim was therefore to determine whether there were any significant differences between the Odour and the No-Odour conditions in terms of the responses to the individual questionnaire items of the Witmer and Singer Presence Questionnaire and the JPQ. The analysis follows the same steps as those detailed in Study Two (Section 6.5.1).

The details of the analysis and its results for the Witmer and Singer Presence questionnaire can be found in Section 7.4.1.1, and for the JPQ they can be found in Section 7.4.1.2. For both questionnaires, the analysis followed the approach shown in Table 6.4.

7.4.1.1 Witmer and Singer Presence Questionnaire

To determine if any ordering effect was present in terms of responses to the questionnaire items, despite the counterbalanced groups, a Mann-Whitney U Test was conducted between the scores of the Odour condition (first run of the O-NO group against the second run of the NO-O group) and between the scores of the No-Odour condition (first run of the NO-O group against the second run of the O-NO group) for each of the questionnaire items of the Witmer and Singer Presence Questionnaire. No significant differences were observed for any of the questionnaire items, indicating that responses were not subject to an ordering effects.

In order to answer RQ_{1b} *How do pleasant, incongruent odours affect perceived presence in virtual reality?*, I conducted a Wilcoxon Signed Rank test between the Odour and No-Odour conditions of the groups to be able to determine if the exposure to odours caused significant differences in terms of sense of presence. Figure 7.1 gives an overview of the mean differences between each of the groups for all questions from the Witmer and Singer Presence Questionnaire. I will now consider each of the questionnaire items individually, giving details of statistics and results.

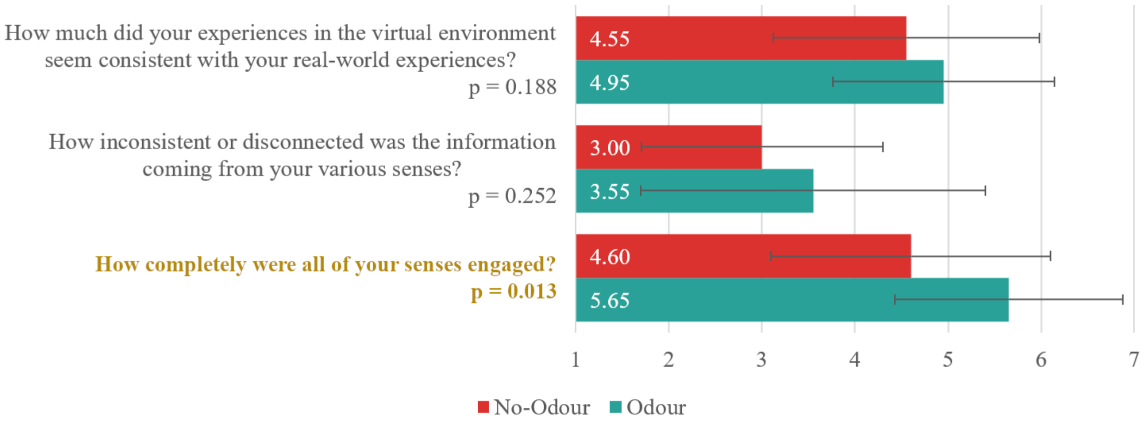


Figure 7.1: Mean responses to the Witmer and Singer Presence Questionnaire for Odour and No-Odour condition. Mean values are displayed at the base of each column. All responses were given on 7-point Likert scales ranging from 1 - 'Not at all', to 7 - 'Very much'.

How much did your experiences in the virtual environment seem consistent with your real-world experiences?

No significant difference was found between the Odour and No-Odour condition. However, the Odour condition resulted in a higher mean rating (No-Odour mean = 4.55, SD = 1.43, odour mean = 4.95, SD = 1.19, Z = 1.40, $p = 0.188$).

How inconsistent or disconnected was the information coming from your various senses?

No significant difference was found between the Odour and No-Odour condition. However, the No-Odour condition resulted in a lower mean rating (No-Odour mean = 3.00, SD = 1.30, Odour mean = 3.55, SD = 1.85, Z = 1.20, $p = 0.252$).

How completely were all of your senses engaged?

There were significantly higher responses in the Odour condition compared to the No-Odour condition ($Z = 2.460$, $p = 0.013$). The Odour condition had a higher mean response compared to the No-Odour condition (No-Odour mean = 4.6, SD = 1.50, Odour mean = 5.65, SD = 1.23).

7.4.1.2 Jennet et al. Presence Questionnaire

As the order of the Odour condition was in the first run of the O-NO group and in the second run of the NO-O group, there was the possibility that responses to the JPQ were subject to an ordering effect despite the counterbalanced groups. Mann-Whitney U tests were conducted for all questionnaire items, between the scores of the No-Odour condition of the NO-O group against those of the O-NO group, and between the scores of the Odour condition of the NO-O group against those of the O-NO group, to determine any ordering effects between the two groups. For the JPQ, no significant difference was observed for any of these tests, indicating that responses were not affected by any ordering effects. This allowed all the responses from the No-Odour condition to be treated as one group, and allowed all the responses from the Odour condition to be treated as one group.

In order to answer RQ_{1b} *How do pleasant, incongruent odours affect perceived presence in virtual reality?*, I conducted a Wilcoxon Signed Rank test between the Odour and No-Odour conditions of the groups to be able to determine if the exposure to odours caused significant differences in terms of sense of presence. Figure 7.2 gives an overview of the mean differences between each of the groups for all questions from the Witmer and Singer Presence Questionnaire. I will now consider each of the questionnaire items individually, giving details of statistics and results.

To what extent did you feel emotionally attached to the game?

No significant difference was found between the Odour and No-Odour condition. However, the Odour condition resulted in slightly higher mean results (No-Odour mean = 5.20, SD = 1.54, Odour mean = 5.80, SD = 1.11, $Z = 1.92$, $p = 0.067$).

Were there any times during the game in which you just wanted to give up?

No significant difference was found between the Odour and No-Odour condition. The No-Odour condition produced lower mean scores than the Odour condition (No-Odour mean = 1.90, SD = 1.41, Odour mean = 2.55, SD = 1.99, $Z = 1.13$, $p = 0.301$). While there

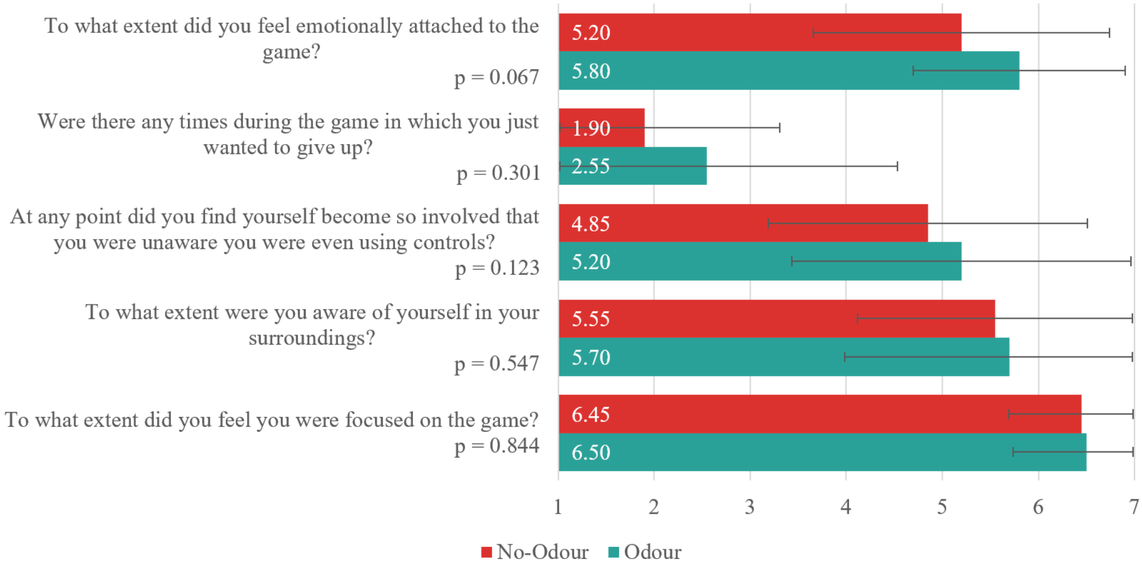


Figure 7.2: Mean responses to the Jennet et al. Presence Questionnaire for Odour and No-Odour condition. Mean values are displayed at the base of each bar. All responses were given on 7-point Likert scales with endpoints 1 - 'Not at all', and 7 - 'Very much so'.

were no significant differences between the two conditions, the means do vary by 0.65 and the Odour condition mean is thereby 34% greater than that of the No-Odour condition. However, due to a large standard deviation for both conditions, this did not reflect in a significant difference and it appears that participant responses were not affected by the presence of an incongruent odour.

At any point did you find yourself become so involved that you were unaware you were even using controls?

No significant differences was found between the Odour and No-Odour condition. While the Odour condition resulted in higher mean results, this difference is negligible at 0.35 points (No-Odour mean = 4.85, SD = 1.66, Odour mean = 5.20, SD = 1.77, Z = 1.71, p = 0.123).

To what extent were you aware of yourself in your surroundings?

No significant difference was found between the Odour and No-Odour condition. (No-Odour mean = 5.70, SD = 1.17, Odour mean = 5.85, SD = 1.5, Z = 0.71, p = 0.547).

To what extent did you feel you were focused on the game?

No significant difference between the Odour and No-Odour condition was observed (No-Odour mean = 6.45, Odour mean = 6.50, Z = 0.33, p = 0.844).

7.4.2 Quality of Experience Questionnaire

The QoE questionnaire contained 4 items (QoE questionnaire items 1 to 4 - see Table 5.3) that assessed user perception of the odours and 1 item (QoE questionnaire item 5) that assessed the enjoyment of the VE. Questions 1 to 4 were only carried out for the Odour condition, while item 5 was carried out in both conditions to determine if the odours affected the perceived enjoyment of the VE. All responses were given on a scale from 1 = No agreement, to 5 = High agreement, with labels only given for endpoint anchors.

Overall, participants had mixed reactions towards the odours. While participants reported that they felt that the odour increased their sense of reality while experiencing the VE (the mean response to the statement 'The smell heightened the sense of reality whilst experiencing the virtual environment' was 3.40), they felt that the odours were not relevant to what they were seeing (the mean response to the statement 'The smell was relevant to what I was seeing' was 2.05), that the odours were somewhat distracting (the mean response to the statement 'The smell was distracting' was 2.80) and annoying (the mean response to the statement 'The smell was annoying' was 2.15). The responses to each statement are described below and mean responses can be seen in Figure 7.3.

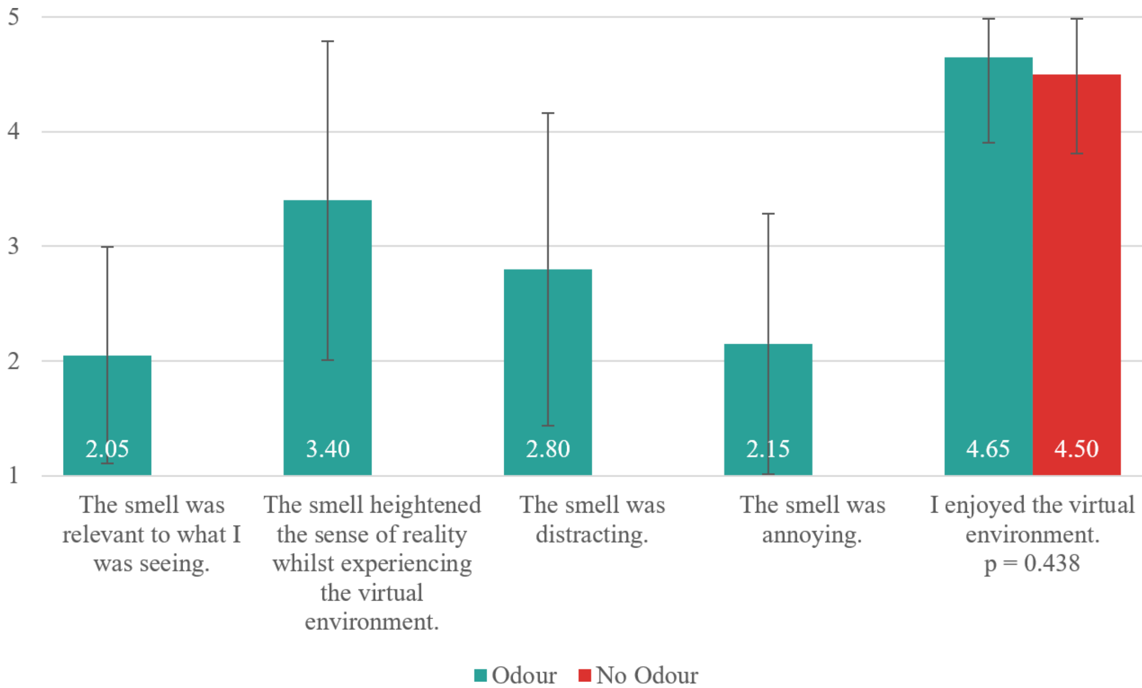


Figure 7.3: Mean Quality of Experience questionnaire responses.

The smell was relevant to what I was seeing.

Participants reported a low agreement with the statement (mean = 2.05, SD = 0.94). This is perhaps not unsurprising considering that the odour was selected to be incongruent with the VE, and is a confirmation of the odour selection method.

The smell heightened the sense of reality whilst experiencing the virtual environment.

Participants reported that the odours increased their sense of reality of the virtual environment (mean = 3.40, SD = 1.39).

The smell was distracting.

Participants reported that the odours were somewhat distracting (mean = 2.80, SD = 1.36).

The smell was annoying.

Participants reported that the odours were mildly annoying (mean = 2.15, SD = 1.14)

I enjoyed the virtual environment.

As the question 'I enjoyed the virtual environment' does not specifically relate to the odours, it was also asked during the No-Odour condition. I could therefore conduct a Wilcoxon Signed Rank test to determine if there was a significant difference between the No-Odour and Odour conditions. No significant difference was found between the Odour and No-Odour condition (No-Odour mean = 4.50, SD = 0.69; odour mean = 4.65, SD = 0.75, Z = 1.00, p = 0.438).

7.4.3 Participant Performance

Participant' performance was assessed by comparing how participants scored in terms of the flower interaction task. Participants received one point for each flower they interacted with (touched) but only for the first interaction with each flower.

		1st run	**2nd run**
NO-O	**M**	3.20	6.60
	SD	1.03	1.43
O-NO	**M**	4.40	3.00
	SD	1.17	1.41

Table 7.4: Mean flower interaction scores
M = Mean, SD = Standard Deviation.

Even though players completed a basic climbing tutorial for *The Climb*, as players were new to the VR game, a certain learning effect was expected, as participants naturally improve their climbing skills over time. To determine if this was the case, the combined first run scores of the No Odour-Odour group and the Odour-No Odour group were compared against the combined second run scores of both groups. A Mann-Whitney U Test showed that there was a statistically significant difference between the two (combined first run mean = 3, combined second run mean = 5, U = 51,textitp< 0.0001).

To determine whether odours increased the number of interactions with plants above any learning effect, I compared the scores of the second run (Odour) of the 'No-Odour Odour' group against the scores of the second run (No-Odour) of the 'Odour No-Odour' group. A Mann-Whitney U Test showed that there was a significant difference between the scores (odour mean = 7, No-Odour mean = 3, U = 4, p = <0.0001) and that the Odour condition resulted in a higher mean score than the No-Odour condition (odour mean = 6.60, SD = 1.43, No-Odour mean = 3.00, SD = 1.41).

7.4.4 Qualitative Results

During the experimental sessions I recorded observations and unsolicited remarks made by the participants. The full list of observations and participant remarks can be found in Table 7.5. One participants was not able to partake in the study due to an onset of fear of heights as soon as he began climbing.

ID	Gender	Age	Observations and Participant Remarks
NO-O 1	Male	35	"It felt like someone was climbing behind me and eating cookies. I couldn't see him, but I knew he was there."
NO-O 2	Female	30	"The scents were nice. It felt like it came from flowers." "It didn't matter that it was not the scent of a flower, the pleasantness of the scent was important to me" "The scents really relaxed me because the game was so hard. When I smelled a flower I could really stop and relax for a moment."
NO-O 3	Male	28	"The smells in general increased my immersion even though it didn't really match with the flowers. It helped me focus on plants."
NO-O 5	Female	24	"The scent took me out of the experience because it was not a flower [hazelnut] and [so] I remembered that the researcher is present, probably spraying the scents."
NO-O 8	Female	24	"I felt more immersed because of the scent even though it was cookies and not a flower." "I knew I was doing it right [collecting flowers] because of the smells."
O-NO 1	Male	26	Interacted with first flower several times and expected it to smell. Started interacting with other flowers and greenery to see if they also smelled.
O-NO 2	Male	31	"Were you eating biscuits? I was sure I could smell some biscuits."
O-NO 3	Female	40	"This is what I don't like about this game, this damn chalking."
O-NO 4	Male	49	"I thought the smell was coming from the flower." "It didn't smell like flower but I thought I am in a virtual world, and so this must be a cookie-smelling flower."
O-NO 8	Female	22	"I really liked the cherry smell and wanted more of it. It really was like a reward."
O-NO 9	Female	33	"Is it vanilla? [...] the flowers smelled like vanilla"

Table 7.5: Observations of participants and their remarks made during the experimental sessions.

7.5 Discussion

This study set out to answer the research question: Can pleasant incongruent odours enhance the sense of presence in virtual reality? As congruent pleasant odours, which were used in the first study, showed positive results, the hypothesis investigated was that pleasant incongruent odours could also increase presence in VR. The results of the study showed that this hypothesis could not be confirmed.

In terms of the presence questionnaires, a significant difference between the Odour and No-Odour condition was only found in the responses to the question 'How completely were all of your senses engaged' (from the Witmer and Singer presence questionnaire), where the Odour condition produced significantly higher results. This is an indication that there was indeed a change in perceived presence, however, there were no other significant findings in the study overall. As was discussed in Section 5.6, questionnaire results must be viewed in the light of supplemental data, such as from observations to gain a better understanding of their meaning. Supplementary data from observations and from participant remarks point towards the interpretation that there was a wide discrepancy in terms of the interpretations of the odours and that this may have even produced breaks in presence for some participants. While a significant finding for this item points in the direction that the sense of presence was affected, in the light of the observations of, and remarks made by participants, this result could also be interpreted as an indicator that they were able to perceive the odours, but that this did not necessarily affect their experience of presence, or even that it was detrimental to the perception of presence.

The results from the Quality of Experience questionnaire support this interpretation. All participants reported having perceived the odours during the Odour condition. Participants did not generally feel that the odours were annoying, however they did feel that they were moderately distracting and generally had a low relevance to what they were seeing.

Despite this lack in relevance, however, participants reported that the odours heightened the sense of reality whilst experiencing the VE. This is an interesting phenomenon, as the perceived reality of a VE is a main factor contributing to a sense of presence (Schubert, Friedmann, et al., 1999). To understand why this was the case, it is helpful to examine the qualitative observations and remarks made by participants during and after the experimental sessions.

As described in Section 7.4.4 above, the perception of the odours fluctuated between participants. There was some confusion about the origin of the odours: some participants thought that the odours were coming from within the VE, while others believed that they were coming from the real-world surroundings. One participant stated that they thought that the experimenter (myself) was eating chocolate biscuits and that the source of the odours was therefore coming from outside of the VE and not intended as part of it. This is an indication that the odours may have actually decreased a sense of presence, perhaps even producing a break in presence, as some participants were reminded of their real-world environment. Further research will have to be conducted to determine whether incongruent odours can cause breaks in presence. For those participants that perceived the source of the odours as coming from within the VE, there was also a degree of uncertainty concerning whether the odours were emitted from the flowers or another unrelated object. One participant for example mentioned that he imagined that there was a second climber following him, who was eating biscuits. Other participants on the other hand simply imagined that the flowers smelled like baked goods and cherries, while a final group of participants perceived the odours as general sweet floral odours and not as smelling like biscuits or cherries at all, hence almost congruent with the flowers. Even though the odours were triggered when participants interacted with the flowers, for many participants this alone was not sufficient to create the illusion that the flowers actually smelled like the odours that were being displayed.

In the real world we have expectations about what an object should smell like. This is quite apparently also the case for familiar objects within virtual worlds and must be taken into consideration when designing olfactory experiences. In the real world, we generally prefer congruence of sensory stimuli (Piqueras-Fiszman and Spence, 2012). For example, a coherent, congruent set of sensory stimuli leads to increased liking in food, while incongruent sensory stimuli go against existing expectations, which may result in a positive or a negative experience (Velasco, Michel, et al., 2016). This effect could also be observed when comparing the results from Study Two and this study. While congruent odours (Study Two) produced a coherent set of sensory stimuli and enhanced the sense of presence as well as enjoyment of the VE, incongruent odours did not do so and were met with surprise and sometimes confusion or even, possibly, decreasing presence. Overall participants also seemed to have much stronger opinions about the chocolate-chip cookie odour and only few mentioned the cherry odour in unsolicited comments post experiment. This could possibly be due to the different levels of pleasantness of the odours. The cherry odour had a slightly higher pleasantness rating (chocolate-chip cookie pleasantness mean = 3.64, cherry pleasantness mean = 4.18). Lastly, it is also possible that while the congruence ratings between the odours and the flowers were very low, (chocolate-chip cookie congruence mean = 1.27, cherry congruence mean = 1.55), the cherry odour was perceived as more congruent to the environment as a whole, seeing that it had a, albeit somewhat artificial, plant-like odour, whereas the chocolate-chip cookie odour was clearly foreign to the mountainous environment. Future research could determine whether there is a difference between object specific congruence and the congruence to the virtual environment as a whole.

While the incongruent odours did not produce a significant change in perceived presence, the results showed that participants interacted with significantly more flowers when these emitted odours in comparison to when they didn't emit an odour. Hence, pleasant odours emitted by virtual objects can increase interaction with the object, regardless of congruence with the object. If virtual objects emit pleasant odours, then they are interacted with significantly more than non-odour emitting virtual objects. There are two possible explanations for this effect. Firstly, as the odours were of a pleasant valence, the odours may have acted as a form of gratification to participants for having found a flower and interacted with it, reinforcing the task with positive feedback. Secondly, the odours may have acted as a form of notification or reminder. As there was no visual or auditory feedback for having gained a point by touching a flower, the only form of feedback was given via the olfactory display and the odours may have acted as a reinforcement of the task. The odours were clearly able to draw the participants' attention to the flowers, hence resulting in an increase of interactions.

7.6 Comparing the Results of Study Two and Study Three

Studies Two and Three both investigated the effect of congruence on the sense of presence in VR. While Study Three examined incongruent odours in this context, Study Two used congruent odours. I therefore conducted a statistical comparison of the results in order to determine whether there were any significant differences between the effect of incongruent and congruent odours on the sense of presence and perceived QoE. I describe the details of the results of a statistical comparison between the presence and QoE scores of Studies Two and Three in Section 7.6.1, and discuss these results in Section 7.6.2.

7.6.1 Results

As both studies used identical methods, and recorded scores using the Witmer and Singer Presence Questionnaire (see Table 5.5), the JPQ (Table 5.4), and the QoE Questionnaire 5.3), the results can be compared statistically. The results of the comparison for the presence questionnaires can be found in Section 7.6.1.1, while the results of the comparison of the QoE questionnaires can be found in Section 7.6.1.2.

7.6.1.1 Presence Questionnaires

In order to compare the results of the Witmer and Singer Presence Questionnaire and the JPQ from Study Two and Study Three, non-parametric Mann-Whitney U-Tests for Independent Samples were conducted between the scores of the Odour condition of Study Two and the Odour condition of Study Three.

How much did your experiences in the virtual environment seem consistent with your real-world experiences?

No significant difference was found between the Odour condition of Study Two and the

Odour condition of Study Three (Study Two Odour mean = 5.20, SD = 1.28, Study Three Odour mean = 4.95, SD = 1.19, U = 173.00, $p = 0.438$).

How inconsistent or disconnected was the information coming from your various senses?

A significant difference was found between the scores of the Odour condition of Study Two against the scores of the Odour condition of Study Three. Participants from Study Three felt that the information coming from their senses was significantly more inconsistent or disconnected than those from Study Two (Study Two mean = 2.45, SD = 1.23, Study Three mean = 3.60, SD = 1.79, U = 123.5, $p = 0.033$).

How completely were all of your senses engaged?

No significant difference was found between the Odour condition of Study Two and the Odour condition of Study Three (Study Two Odour mean = 6.10, SD = 0.79, Study Three Odour mean = 5.65, SD = 1.23, U = 157.00, $p = 0.215$).

To what extent did you feel emotionally attached to the game?

No significant difference was found between the Odour condition of Study Two and the Odour condition of Study Three (Study Two Odour mean = 5.98, SD = 1.19, Study Three Odour mean = 5.80, SD = 1.11, U = 178.50, $p = 0.532$).

Were there any times during the game in which you just wanted to give up?

No significant difference was found between the Odour condition of Study Two and the Odour condition of Study Three (Study Two Odour mean = 1.80, SD = 1.61, Study Three Odour mean = 2.55, SD = 1.99, U = 150.50, $p = 0.123$).

At any point did you find yourself become so involved that you were unaware you were even using controls?

No significant difference was found between the Odour condition of Study Two and the Odour condition of Study Three (Study Two Odour mean = 5.15, SD = 1.39, Study Three Odour mean = 5.20, SD = 1.77, U = 183, $p = 0.637$).

To what extent were you aware of yourself in your surroundings?

A significant difference was found between the scores of the Odour condition of Study Two against the scores of the Odour condition of Study Three. Participants from Study Three felt that the information coming from their senses was significantly more inconsistent or disconnected than those from Study Two (Study Two mean = 2.60, SD = 1.35, Study Three mean = 5.85, SD = 1.50, U = 30.5, $p < 0.000$).

To what extent did you feel you were focused on the game?

No significant difference was found between the Odour condition of Study Two and the Odour condition of Study Three (Study Two Odour mean = 6.75, SD = 0.55, Study Three Odour mean = 6.50, SD = 0.76, U = 161.50, $p = 0.194$).

The full results of this comparison can be found in Figure 7.4.

Figure 7.4: Mean responses from Study Two and Study Three to the Witmer and Singer Presence Questionnaire and the Jennet et al. Presence Questionnaire. Underlined scores indicate significant finding $p < 0.05$

7.6.1.2 Quality of Experience Questionnaire

To compare the results of the QoE questionnaire of Study Two and Study Three, non-parametric Mann-Whitney U-Tests for Independent Samples were conducted between the scores of the Odour condition of Study Two and the Odour condition of Study Three.

The smell was relevant to what I was seeing

A significant difference was found between the scores of the Odour condition of Study Two against the scores of the Odour condition of Study Three. Participants in Study Two felt that what they were seeing was significantly more relevant than those from Study Three (Study Two mean = 3.90, SD = 1.04, Study Three mean = 2.05, SD = 0.92, U = 43.00, $p < 0.000$).

The smell heightened the sense of reality whilst experiencing the virtual environment.

A significant difference was found between the scores of the Odour condition of Study Two against the scores of the Odour condition of Study Three. Participants in Study Two felt that the sense of reality was heightened significantly more than those from Study Three (Study Two mean = 4.60, SD = 0.66, Study Three mean = 3.40, SD = 1.36, U = 89.00, $p = 0.001$).

The smell was distracting.

A significant difference was found between the scores of the Odour condition of Study Two against the scores of the Odour condition of Study Three. Participants in Study Three felt that the odours were significantly more distracting than those from Study Two (Study Two mean = 1.50, SD = 0.75, Study Three mean = 2.80, SD = 1.33, U = 86.50, $p = 0.001$).

The smell was annoying.

A significant difference was found between the scores of the Odour condition of Study Two against the scores of the Odour condition of Study Three. Participants in Study Three felt that the odours were significantly more annoying than participants from Study Three (Study Two mean = 1.25, SD = 0.43, Study Three mean = 2.15, SD = 1.11, U = 102.50, p =0.003).

I enjoyed the virtual environment.

No significant difference was found between the responses of the Odour condition of Study Two and the Odour condition of Study Three (Study Two mean = 4.90, SD = 0.30, Study Three mean = 4.65, SD = 0.0.73, U = 169.00, $p = 0.204$).

The results of this comparison can be found in Figure 7.5.

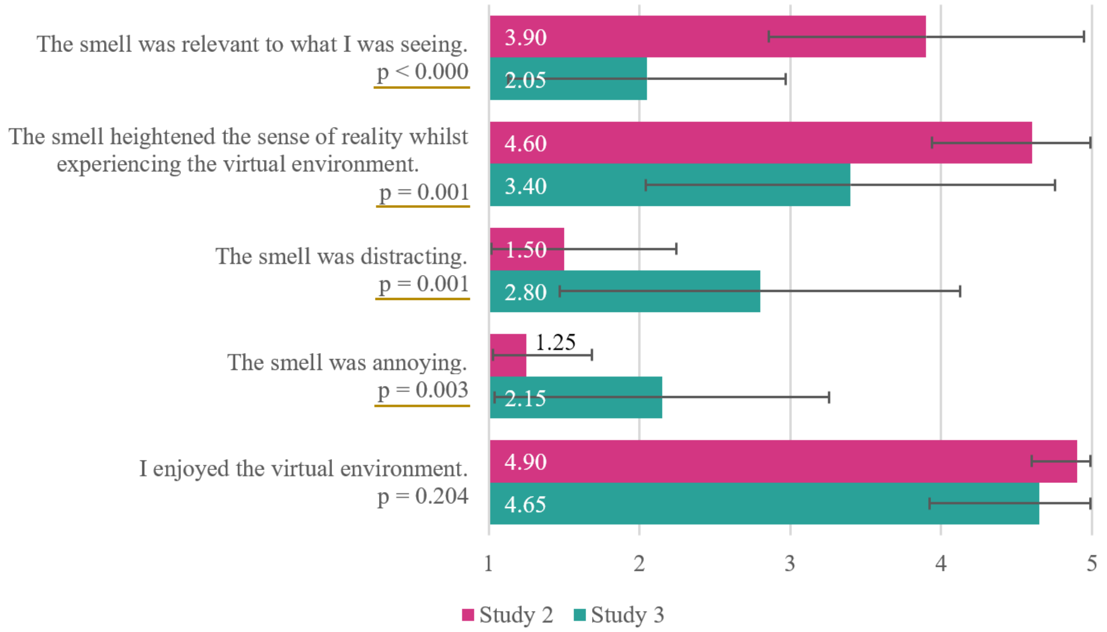


Figure 7.5: Mean responses from Study Two and Study Three to the Quality of Experience Questionnaire.. Underlined scores indicate significant finding $p < 0.05$

7.6.1.3 Task Performance

To compare the results of the QoE questionnaire of Study Two and Study Three, non-parametric Mann-Whitney U-Tests for Independent Samples were conducted between the scores of the Odour condition of Study Two and the Odour condition of Study Three.

No significant difference was found between the Odour condition of Study Two and the Odour condition of Study Three (Study Two Odour mean = 4.95, SD = 2.40, Study Three Odour mean = 5.50, SD = 1.66, U = 170.5, $p = 0.429$).

7.6.2 Discussion

The statistical analysis of the results of the Witmer and Singer Presence Questionnaire and the JPQ for the Odour conditions of Study Two and Study Three revealed that there were significant differences in terms of responses to the questions ‘To what extent were you aware of yourself in your surroundings?’ and ‘How inconsistent or disconnected was the information coming from your various senses?’. For both questions participants who experienced the VE with incongruent odours responded significantly higher, indicating that the incongruent odours were detrimental to the virtual experience and to the sense of presence in the VE, and highlighting the importance of selecting odours that are perceived as congruent with objects in the VE.

Similar results were found in terms of QoE, where significant differences were found in the responses to all of the QoE questionnaire statements except to "I enjoy the virtual environment". The incongruent odours were therefore seen as less relevant to the VE, heightened the sense of reality significantly less than the congruent odours, and were seen as significantly more distracting and annoying than the congruent odours, demonstrating that the incongruent odours were detrimental to the experience of the VE. These results again highlight the importance of selecting odours that are congruent with objects in the VE, thereby adding to an experience that is consistent across all sensory modalities.

7.7 Conclusions

There were three main aims for this study. First, to answer RQ_{1b}: *How do pleasant, incongruent odours affect perceived presence in virtual reality?* Second, to verify the effectiveness of a new method for odour selection, as used in Study Two, however this time for incongruent odours. Third, to further evaluate the novel OD for VR headsets, which was first used in Study Two. As results from Study Two had shown that pleasant congruent odours could increase a sense of presence in VR, hypothesis H_1 stated that pleasant incongruent odours could also increase a sense of presence in VR.

A user based study was conducted that mirrored the methodology and setup of Study Two. An odour selection task was conducted to select two odours that were perceived as incongruent with the two flowers of the VE. The results showed that participants were able to agree on the perceived incongruence of odour and flower, and two odours which were perceived as least congruent with the two in-game flowers were selected. The fragrance oil *Chocolate-chip cookie* was chosen to represent a purple flower, while a fragrance oil with the name *Cherry* was chosen to represent a yellow flower.

The two odours were used in the main part of this study, where they were displayed when participants interacted with the respective flowers. As in Study Two, participants were given the instructions to explore the game by climbing and to 'collect' as many flowers as they can, by touching them. Once again, four types of metrics were recorded. First, two questionnaires to capture the subjective perception of presence in the VE; second, a questionnaire to capture the QoE of the odours to evaluate the odour selection methodology; third, flower collection scores to measure participant performance; and fourth qualitative results via observations and participant remarks.

Results from the presence questionnaires showed that there were no significant differences between the Odour and No-Odour condition, except for the degree to which the senses were completely engaged (Witmer and Singer Presence Questionnaire item 1). However, as there were no other significant findings regarding presence in the study overall, this result would indicate that the participants were able to perceive the odours, but that this did not affect their experience of presence. These results indicate that incongruent pleasant odours do not increase the sense of presence in VR, contradicting hypothesis H_1. The results stand in contrast to the results from Study Two which showed that congruent pleasant odours were able to increase the sense of presence significantly. Comments made by participants after the experimental sessions showed that there was some confusion concerning the perceived origin and source of the odours. While one participant perceived the odours to come from the real world, e.g. from biscuits in the room, others perceived the source of the odours to be within the VE but could not pinpoint the origin e.g. one participant imagined another climber following him, while eating biscuits, and did not draw a connection between the flowers and the odours. A final group of participant did perceive the in-game flowers as source of the odours but did not think that the odours were floral. This shows that participants perceived the odours as incongruent and inconsistent with the flowers in the VE, which meant that the odours did not impact presence. As the odours were not perceived as being congruent with the VE, they did not constitute a coherent or connected set of stimuli, which is a necessary condition for the perception of presence (McGreevy, 1992; Witmer and Singer, 1998). Interestingly, there was no significant decrease in perceived presence, as was shown from the results of the statistical analysis of the Witmer and Singer Presence Questionnaire (see Section 7.4.1.1) and the JPQ (see Section 7.4.1.2). However, the incongruent, pleasant odours caused unforeseen reactions and perceptions by participants, which should be taken into consideration when conducting future olfaction based studies.

Even though the odours did not affect the sense of presence, participant performance was increased significantly. Flower scores were significantly higher in the Odour condition when compared to the No-Odour condition, producing results that were not statistically different to those from Study Two (see Section 7.6.1.3), where congruent odours were used. This shows that the pleasant odours, regardless of congruence, can increase interactions with virtual objects in VR. It is possible that the odours acted as a form of reward or gratification for touching the flowers, due to their perceived pleasantness. However, as some participants in this study reported that the odours were actually distracting (QoE questionnaire item 3. 'The smell was distracting.' mean response = 2.80) and only minimally relevant to what they were seeing (QoE questionnaire item 1. ‘ The smell was relevant to what I was seeing.’ mean response = 2.05), it appears that the odours instead may have acted as a notification that the point was registered, reinforcing the task at hand. The odours were clearly able to draw the participants’ attention to the flowers, resulting in an increase of interactions.

In this chapter and in Chapter 6, I examined the effect of both incongruent and congruent, pleasant odours, that were emitted by virtual flowers, on the sense of presence in the context of the VR game *The Climb*. In the following chapter, I examine the effect of congruent pleasant odours on the sense of presence and task performance in light of a new condition by changing the mechanism by which odour display is triggered in the VE. While the odours in Studies Two and Three were triggered when participants interacted with virtual objects (flowers), in Study Four, I examine how odours that are triggered by events, i.e. as notifications, can affect the sense of presence and task performance in VR.

Chapter 8

Study Four

8.1 Introduction

This thesis has so far examined the effect of congruent and incongruent pleasant odours on the sense of presence in VR and was able to demonstrate that congruent pleasant odours could increase the sense of presence. Both types of odour were also able to increase task performance in the VE in terms of a flower collection task. In Study Two and Study three, the display of odours was triggered by interacting with virtual flowers. In this study I expand on the insights gained in the two previous studies and move away from associating odours with virtual objects by examining how odours delivered as olfactory notifications affect presence, QoE, and task performance in VR.

This chapter is structured in the following way: Part A describes an odour selection task, similar to those from Study Two (see Section 6.2) and Study Three (see Section 7.2), but which is tailored to selecting odours for two specific olfactory notifications. I begin by describing the steps that make up the odour selection task (Section 8.3), followed by details about two types of VR game-related notification (Section 8.3.1). I then describe the odour selection task design in Section 8.3.2, the initial selection of odours that were used during Part A (Section 8.3.3), the procedure (Section 8.3.4), and the results of the odour selection task (Section 8.3.5).

Part B describes the main study, in which I used the olfactory notifications derived during Part A with 20 participants in the VR rock climbing game *The Climb*, which was also used for Studies Two and Three. I first describe three hypotheses that were investigated as well as the study design (Section 8.4), followed by a description of how the odours are triggered in the VE (Section 8.4.1) and the procedure for the experimental sessions (Section 8.4.3). I then give details of the results of the study (Section 8.5) in terms of QoE (Section 8.5.1), performance (Section 8.5.2), sense of presence (Section 8.5.3), and qualitative results from observations and unsolicited comments (Section 8.5.4). I discuss these results in terms of the main research question (Section 8.6) and three hypotheses in Section 8.6.1 (hypothesis H_1), Section 8.6.2 (hypothesis H_2), and Section 8.6.3 (hypothesis H_3). Finally, Section 8.7 summarises the main conclusions from the study.

8.2 Motivation and Research Questions

The aim of this study is to explore if odours can be used as notifications in VR to improve task performance. This study is in the vein of a recent study by Dmitrenko et al. (2017), where it was shown that odours (lemon, peppermint and rose) could be mapped onto certain driving related in-car notifications ('Slow down', 'Fill tank' and 'Point of interest nearby'). However, it was not confirmed whether these olfactory notifications affected users' driving behaviour. Using my virtual reality set-up in conjunction with the VR game, *The Climb*, I wanted to determine if it would be possible to notify players about certain changes in the VE and whether this would lead to improved performance. The intent of this study is thus to corroborate findings of Dmitrenko et al. (2017), who showed that participants were able to understand and differentiate between different olfactory notifications in a VR environment but to extend their research by investigating whether olfactory notifications can change users' behaviour, superficially, and lead to improved task performance in a VR game.

Having gained insights into the detailed mechanics of the virtual rock climbing game *The Climb* during my previous two studies, I identified two environmental changes that could be linked to olfactory notifications and potentially lead to an improved game performance. Firstly, participants had previously been given the task of finding and interacting with flowers in the environment. However, as the climbing task itself is quite demanding, player attention is often focused on finding the next safe hand hold, rather than surveying the area for flowers. In the previous two studies, this had resulted in participants sometimes not interacting with flowers that were in their immediate vicinity. By alerting participants that a flower is in their vicinity with an olfactory notification, I was aiming to see if this would lead them to find and interact with more flowers. Secondly, participants need to regularly chalk their hands to be able to climb safely (see Section 5.3.3.3). The purpose of chalking is not immediately clear at first and participants often forget to chalk their hands as their attention is focused on finding a safe hand hold. By alerting participants that their chalk levels are low and that they should chalk their hands, I was aiming to improve their climbing performance. The main research question for this fourth study was therefore:

RQ_3 *Are olfactory notifications effective in virtual reality?*

To answer RQ_3, in this Study I tested the following hypotheses:

H_1: *Participants can understand olfactory notifications.*

H_2: *Olfactory notifications increase performance in virtual reality.*

H_3: *Congruent pleasant odours when delivered as notifications increase the sense of presence in virtual reality.*

All three hypotheses relate directly to RQ_3, the purpose of H_2 also relates to RQ_2, which investigates how olfactory cues affect task performance in VR, while the purpose of H_3 also relates to RQ_1, which investigates how olfactory cues affect the sense of presence in VR.

The study was carried out in two parts. Part A consisted of selecting the odours for the olfactory notifications and is described in Section 8.3. Part B used the selected odours from Part A to answer the research questions (see Section 8.4).

8.3 Part A: Selecting Odours for Olfactory Notifications

In order to investigate how odours can convey specific game-related information, I focused on using two separate odours to notify participants of the following information: 'Chalk your hands' i.e. the level of chalk was low; 'There is a flower in your vicinity'. Three steps were necessary to determine the odours:

1. Determining the basic perceptual properties of the odours.
2. Determining the congruence of the odours and the notifications.
3. Evaluating the combined results from steps 1 and 2 to determine the odours that best convey the notifications in the virtual environment.

The below sections detail the process of selecting odours for olfactory notifications and constitute Part A of this chapter. Section 8.3.1 gives the details of two storylines that were shown to participants during the odour selection task to clarify the meanings of the notifications. I then describe the study design (see Section 8.3.2), methodology (see Section 8.3.3), the odours used for the selection task (see Section 8.3.4), and results (see Section 8.3.5) of the odour selection task.

8.3.1 Notification Storylines

The two identified notifications were to inform participants that they should chalk their hands due to low chalk levels ('Chalk your hands') and that a flower is now in their close vicinity ('There's a flower in your vicinity'). As there are different kinds of flowers throughout the game, and as each notification could only be displayed with one odour, the 'There's a flower in your vicinity' was restricted to purple flowers, which are the most common type of flower in the game. This simplified the odour selection task, as the odour had to be perceived as congruent with a single flower only.

In order to clarify the meaning of these notifications, each one was presented to participants in the context of a short story:

'*Chalk your hands*'

1. Anna has just started a new level in the Alps and begins climbing.
2. Becoming so focused on which path to take and which hand hold to grip, she forgets to chalk her hands.
3. At this point in time a scent on the VR headset is released that reminds Anna to chalk her hands.
4. Anna chalks her hands and continues climbing safely.

'*There's a flower in your vicinity*'

1. Jamie has been given the task to interact with purple flowers in the game.
2. He begins climbing and starts looking for the purple flowers.
3. Jamie becomes so focused on climbing that he temporarily forgets about interacting with the purple flowers.
4. A purple flower comes into Jamie's field of view, but he does not notice it.
5. At this point in time a scent on the VR headset is released that notifies Jamie that a purple flower is in his vicinity.
6. After perceiving the scent, Jamie knows that there is a purple flower in his vicinity.
7. Jamie looks for the purple flower and sees it.

8. He climbs to the purple flower and interacts with it.

As both notifications require a certain familiarity with *The Climb*, participation in the selection task was restricted to participants of Study Two or Study Three, who had already experienced the game and were familiar with chalking and the task of finding and interacting with flowers while climbing. For succinctness, from now on I will refer to the 'Chalk your hands' notification simply as the 'chalk notification' and to the 'There's a flower in your vicinity' notification as the 'flower notification'.

8.3.2 Odour Selection Task Design

The odour selection task followed an 8 (odours) x 2 (notifications) within participants experimental design and was conducted according to the following steps: 1. Determining basic perceptual properties of the odours, 2. Identifying which odours are perceived as being most congruent with the notifications, and 3. Evaluating the combined results from steps 1 and 2 to determine the odours that best convey the notifications in the virtual environment. Step 1 followed the odour selection methodology described in Section 5.5, which was used in Study Two (see Section 6.2) and Study Three (see Section 7.2). Step 2 was part of the odour selection methodology, however, instead of asking participants to rate whether they perceived the odours to be congruent with objects depicted by images, as was the case for studies Two and Three, the questionnaire referred to the storylines described in Section 8.3 and asked participants to rate how effectively an odour represents each of the notifications. Details of the adapted odour selection methodology for olfactory notifications can be found in Section 8.3.4. Step 2 also involved participants entering the VE to determine preferences in associating an odour with a notification, i.e. to confirm the congruence of the odours and the notifications in the VE.

A total of 10 participants took part in the odour selection task (mean age = 28.30 years, SD = 1.34), 5 female (mean age = 28.20 years, SD = 1.64) and 5 male (mean age = 28.40 years, SD = 1.14). All participants had previously taken part in either Study One or Study Two and were familiar with *The Climb*, the chalking mechanic, and the task of interacting with flowers while climbing. As such, the inclusion and exclusion criteria from Study Two (Section 6.4), and Study Three (Section 7.3) therefore applied. Besides the criteria that participants must have taken part in either Study Two or Study Three, the inclusion and exclusion criteria were not amended from these studies.

8.3.3 Initial Selection of Odours

Eight odours were included in the odour selection study. A list of odours can be found in Table 8.1 below. The odours consist of a variety of essential and fragrance oils. While Dmitrenko et al. (2017) refrain from using odours that are congruent with the chosen in-car notifications due to possible negative effects[1], this issue does not exist for this study, as the odour of both chalk or flowers should not cause the participants distress. Therefore, the lavender odour was included, which was previously determined to be congruent with the purple flowers found in *The Alps* level of *The Climb* during Study Two (see Section 6.3.1) and Study Three (see Section 7.2.1). Dmitrenko et al. (2017) had used a peppermint essential oil, a rose essential oil, and a lemon essential oil in their study. They noted that both peppermint and lemon odours have been shown to have an alerting effect on participants (Ilmberger et al., 2001), making them appropriate for notifications. Rose oil, while having been shown to have a relaxing effect (Hongratanaworakit, 2009) was also included as participants may consider it as congruent with the flowers of the VE, due to its floral nature. As chalk does not have a very distinct odour, to evaluate a potentially congruent odour, a baby powder odour was included. The reasoning was that both chalk and the baby powder odour had a dry quality, which could be considered as congruent by the participants. Similarly, a black pepper essential oil was included, which has similar dry and powdery properties. Dmitrenko et al. (2017) furthermore recommend the use of a cinnamon odour to convey notifications, which was proven to have an alerting effect on participants when used as to convey notifications (Raudenbush et al., 2009), which was therefore also included in the selection task.

Odour	**Type**	**Manufacturer**
Lemon	Essential Oil	Amphora Aromatics
Peppermint	Essential Oil	Amphora Aromatics
Rose	Essential Oil	Amphora Aromatics
Lavender	Essential Oil	Amphora Aromatics
Black Pepper	Essential Oil	Amphora Aromatics
Cinnamon	Essential Oil	Amphora Aromatics
Baby Powder	Fragrance Oil	Demeter Fragrance Library
Water	Purified Tap Water	Thames Water

Table 8.1: Odour evaluated in the selection task.

[1]Dmitrenko et al. (2017) give the example of using the odour of gasoline to represent the ‘Fill gas’ notification, the smell of which could be distressing as participants may interpret it as a gasoline leak instead.

8.3.4 Procedure

The odour selection task was conducted at the City, University of London Interaction Lab and follows the odour selection methodology described in Section 5.5 and which was used in Study Two and Study Three. Accordingly, for each odour, 0.1ml of odour was applied to the end of a cotton bud by the experimenter before being handed to the participant. All of the used odours were clear in colour and did not change the appearance of the cotton bud when applied. The order of the odours was randomised for each participant prior to the experimental sessions. The lab windows were opened for five minutes prior to each participant to clear out any lingering odours in the air.

To start the experimental session, participants were seated at a desk in front of a 24" computer screen that displayed a Google Form containing the Odour Selection Questionnaire Odour Selection Questionnaire (OSQ) (see Table 5.2). The experimenter then applied a 0.1ml of odour to a cotton bud and passed this on to the participant, who was instructed to smell the tip of the bud, to fill in questions related to the odour that were displayed on a screen in front of them and then to place the cotton bud on a sheet of paper, approximately 1m away from them. This cotton bud was discarded by the experimenter after the participant had completed the evaluation for the current odour. After completing the OSQ for an odour, a break of 1 minute was taken before moving on to the next odour, to prevent olfactory fatigue and any overlapping effects from previously perceived odours (Grosofsky et al., 2011; Hummel, Knecht, et al., 1996). These steps were repeated until the participant had assessed all the odours.

In addition to the questions in the OSQ (Table 5.2), participants also answered the question "How much do you think this scent represents the notification from this storyline?", which was presented on a Likert scale ranging from 1 = "Very little" to 7 = "Very much", only giving endpoints as anchors, and which can be seen in Figure 8.1. While the other questionnaire items of the OSQ use a 5-point scale, responses to this question were recorded on a 7-point scale. This was done to elicit more fine-grained results and in response to results of the odour selection pilots of Study Two, where congruence scores for various odours and in-game flowers were very similar (see Section 6.3.1). All except the final question are verbatim to the questions used in the selection tasks of Study Two (see Section 6.3.1) and Study Three (see Section 7.2.1) and allow for general comparisons of how these odours were perceived.

After rating each of the 8 odours, participants were asked to stand up and to put on the *Oculus Rift* headset. The VE was calibrated to the participant's height via the Rift's inbuilt

Figure 8.1: Additional question with Likert scale for the odour selection task.

height adjustment tool. The headset was adjusted for a correct fit using the appropriate straps and lens-spacing was set to a comfortable position. Participants were then handed the Oculus Touch controllers, and *The Climb* was started. Participants were instructed to start the *Old Mine* level of the *The Alps* environment and once this had loaded were instructed to climb freely. After 5 minutes, regardless of the current position of the participant in the level or action that was performed, the experimenter instructed the participant to stop climbing and the first odour was presented to the participant by holding the tip of a cotton bud, which contained 0.1ml of the odorant, approximately 5cm under the participant's nose. The experimenter then asked the participant the following question: "Which message does the scent convey? 1. There's a flower in your vicinity, or 2. You should chalk your hands? The message is currently not synchronised with your virtual experience.". Having given an answer, participants were instructed to continue climbing freely. After 1 minute (to prevent olfactory fatigue), the task was repeated with the next odour and so forth until all eight odours were covered. Once the final odour was rated, participants were instructed to remove the headset and controllers.

8.3.5 Odour Selection Task Results

In the following section I will give the results of the odour selection task according to the three steps that made up the task, which were: 1. Determining the basic perceptual properties of the odours (Section 8.3.5.1), 2. Determining the congruence of the odours and the notifications. (Section 8.3.5.2), and 3. Evaluating the combined results from steps 1 and 2 to determine the odours that best convey the notifications in the VE (Section 8.3.5.3).

8.3.5.1 Basic Perceptive Properties of the Odours

Mean responses were calculated from the ratings in the OSQ. Participant labels given to each of the odours can be seen in Table 8.2. Table 8.3 shows the mean responses to the questionnaire items 'This scent's intensity is...' (table column 'Intensity'), and 'I like this scent...' (table column 'Pleasantness'). Table 8.3 also shows the percentage of participants that responded with 'Yes' to the question 'Do you recognise the scent?' (table column 'Recognised') as well as the percentage of participants that correctly identified the odour (table column 'Identified'). Participants correctly identified an odour if their response to the OSQ item 'Name of the scent' matched the odour name.

ID	Lavender	Rose	Baby Powder	Peppermint
1	Floral	Rose oil	baby Powder	Mint
2		Flower	Talcum powder	Peppermint
3	Lavender	Rose	Kind of dry but sweet	Toothpaste
4	Lavender	Lilly	My niece	Mint
5	Kind of floral but fresh	Turkish rose	Cinnamon	Mint gum
6	Flowers	Sweet flower	So familiar	Fresh
7	My handsoap	Body lotion		Mouthwash
8	Lavender	Rose	Spicy	Cornetto mint
9	Citrussy	Flower	Perfume	Mint oil
10	Lavender	Rose perfume		Mint

ID	Lemon	Cinnamon	Black Pepper	Water
1	Lemon	Cinnamon	Musky oil	
2	Lemon	Spices	Strong bitter	
3	Citrussy	Christmas smell	Some spice	
4	Mimosa	Cinnamon	Mazbe cloves	
5	Lemon sherbet	Cinnamon	Pepper	Really faint flower
6	Vanilla	Something ina curry	Some kind of resin	
7	Citrus oil	Dried spice	Tea tree oil	Water
8	Tangerine	Cinnamon	Earthy	
9	Lemon peel	Cloves	Edible	
10	Lemon/citrus	Christmas spice	Pepper	

Table 8.2: Participant labels for the odours evaluated during the odour selection task.

All 10 participants stated that they recognised both the peppermint and the lemon odour, which, with 100% had the highest scores for the questionnaire item 'Do you recognise the scent?'. Participants least recognised the water odour, which only 1 participant stated they had recognised (10% of participants). This was perhaps due to the fact that 8 out of 10 participants (80%) stated that they did not perceive an odour when they were asked to assess the water odour (they responded with 'No' to the question 'Do you perceive a scent?'). The second lowest mean recognition score was given to the baby powder odour, which 2 participants (20%) stated that they had recognised. The baby powder odour was the only synthetic odour assessed during the odour selection task, all other odours (except water) were essential oils.

Peppermint was the most correctly identified odour. 7 out of 10 participants (70%) cor-

Odour	Intensity (mean)	Pleasantness (mean)	Recognised (%)	Identified (%)
Lavender	3.5	3.5	60	40
Rose	3.8	3.3	90	50
Baby Powder	3.4	3.1	20	10
Peppermint	2.6	3.9	100	70
Lemon	3.3	4.1	100	50
Cinnamon	3.9	3.6	90	40
Black Pepper	4.2	2.1	60	20
Water	1.1	3.1	10	10

Table 8.3: Odour Selection Questionnaire (OSQ) response scores. Intensity and Valence scores could range from 1 (lowest) to 5 (highest). The column 'Recognised' shows responses to 'Do you recognise the scent?', while the column 'Identified' shows the percentage of participants that responded with a label that matched the odour name.

rectly identified the peppermint odour. 2 of these 7 participants labelled the odour as 'peppermint', while a further 4 participants labelled the odour simply as 'mint' and a final participant labelled the odour as 'spearmint'. All of these labels were counted as a correct identification of the odour.

Figure 8.2 shows the mean response scores to the OSQ item: 'This scent's intensity is...'. Responses had a possible scores from 1 (lowest) to 5 (highest). The black pepper odour had the highest mean intensity score with 4.20, while the water odour had the lowest score of 1.10.

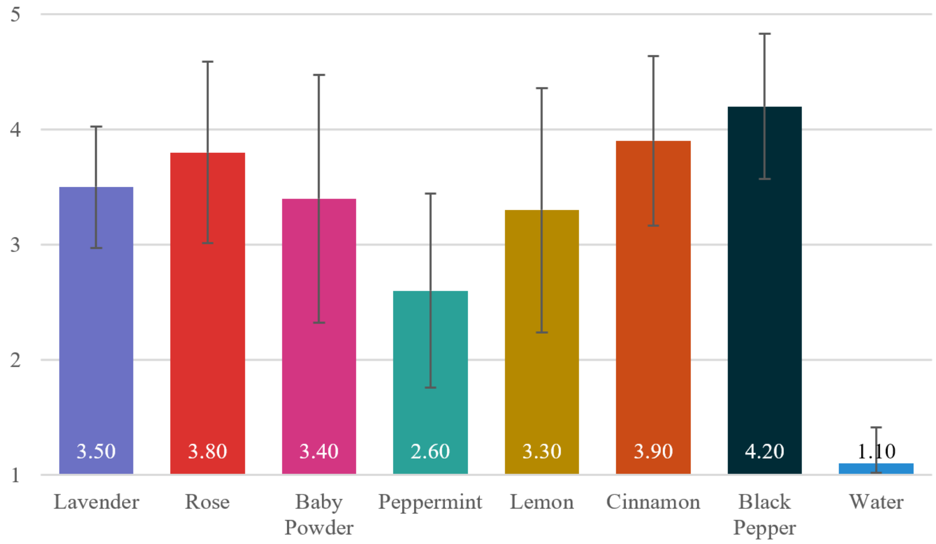


Figure 8.2: Mean response scores to the Odour Selection Questionnaire (OSQ) item: 'This scent's intensity is...'. Responses were given on a 5-point ordinal scale with endpoints 1 - 'Low intensity' to 5 - 'High intensity'.

Figure 8.3 shows the mean response scores to the OSQ item: 'I liked this scent...'. As with all items on the OSQ, responses had a possible score ranging from 1 - 'Not at all' (lowest) to 5 'Very much' (highest). The lemon odour had the highest mean pleasantness score with 4.10, while black pepper had the lowest mean pleasantness score with 2.10. Any mean scores below the midpoint of 3.00 were considered as unpleasant, while all scores above 3.00 were considered as pleasant. The black pepper odour was therefore the only odour that had a mean score that was considered as unpleasant.

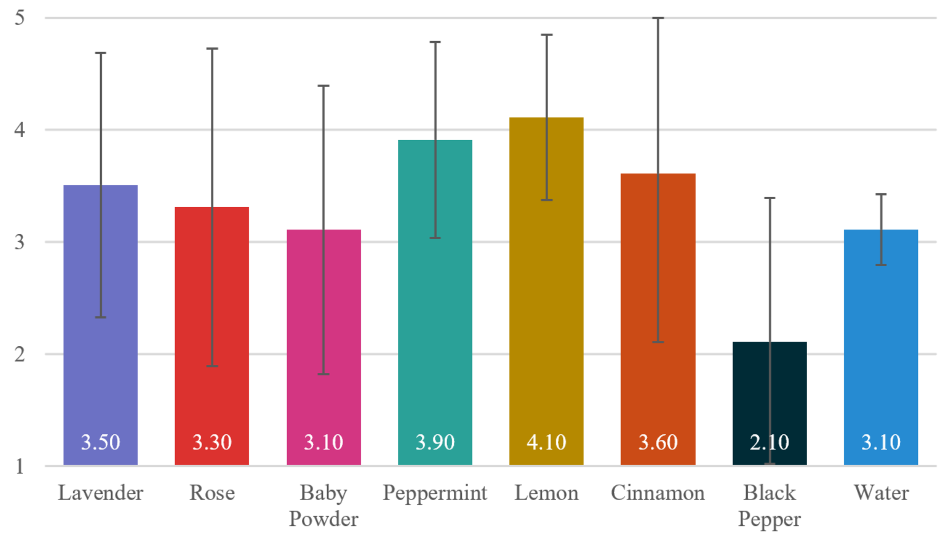


Figure 8.3: Mean response scores to the Odour Selection Questionnaire item: 'I like this scent...'. Responses were given on a 5-point ordinal scale with endpoints 1 - 'Not at all' to 5 - 'Very much'.

The full results from the odour selection task with scores for individual participants can be found in Appendix D.1.

8.3.5.2 Determining the Congruence of the Odours and the Notifications.

To determine the perceived congruence of the odours and notifications, the scores in response to the question 'How much do you think this scent represents the message from this storyline?' were examined for the chalk hands and the flower in vicinity storylines.

The black pepper odour had the highest mean score (4.50) for the chalk hands storyline. Water had the lowest mean score (1.40) for the chalk hands storyline. Both of the floral odours, lavender and rose, also showed low scores for representing the chalk hands storyline (lavender odour mean = 1.90, rose odour mean = 1.70). A full list of mean scores for the responses in regards to the chalk hands storyline in response to the the question 'How much do you think this scent represents the message from this storyline' can be seen in Figure 8.4

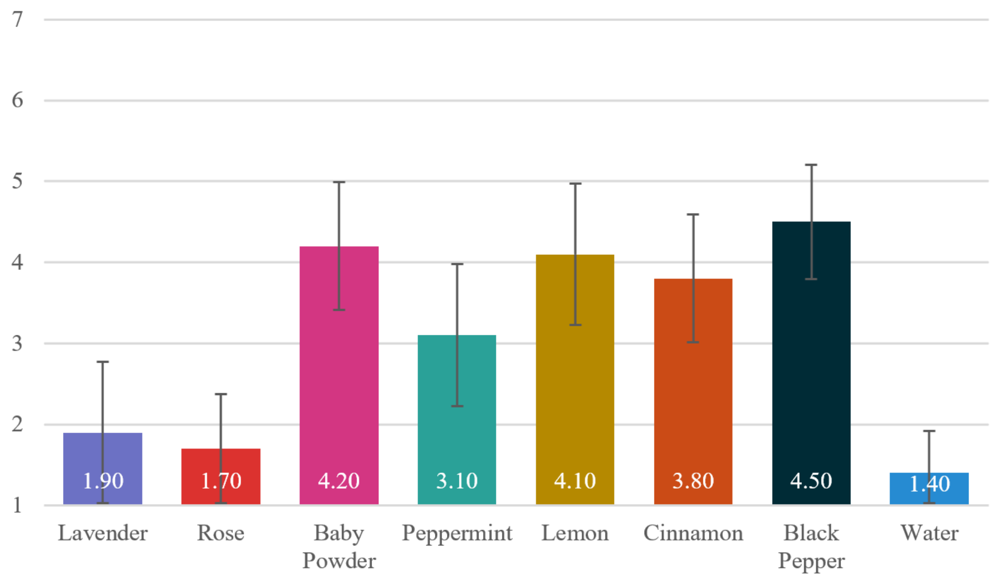


Figure 8.4: Mean response scores to the Odour Selection Questionnaire (OSQ) item: 'How much do you think this scent represents the message from this storyline' for the 'Chalk your hands' storyline. Responses were given on a 7-point ordinal scale with endpoints 1 - 'Not at all' to 7 - 'Very much'.

For the flower in vicinity storyline, both of the floral odours, lavender and rose, had high scores in response to the question 'How much do you think this scent represents the message from this storyline'. The lavender odour had a mean score of 6.5 while the rose odour produced a mean score of 6.1. The lowest scores were found for the black pepper odour with a mean score of 1.3. However, both the water odour and cinnamon odour produced similarly low mean scores of 1.4. A full list of mean scores for the responses in regards to the flower in vicinity storyline in response to the the question 'How much do you think this scent represents the message from this storyline' can be seen in Figure 8.5.

The results of a Wilcoxon Signed Rank test, conducted on the the response scores to the question 'How much do you think this scent represents the message from this storyline' for both storylines, showed that several odours were perceived to be congruent with both storylines. This was the case for the baby powder odour, which produced high scores for both storylines (chalk hands mean = 4.20, flower in vicinity mean = 4.80, Z = 1.20, $p = 0.313$), the peppermint odour, which also produced high scores for both storylines (chalk hands mean = 3.10, flower in vicinity mean = 3.30, Z = 0.347, $p = 0.813$), the lemon odour, which also produced high scores for both storylines (chalk hands mean = 4.10, flower in vicinity mean = 3.70, Z = 1.06, $p = 0.313$), and the water odour which produced low scores (chalk hands mean = 1.4,

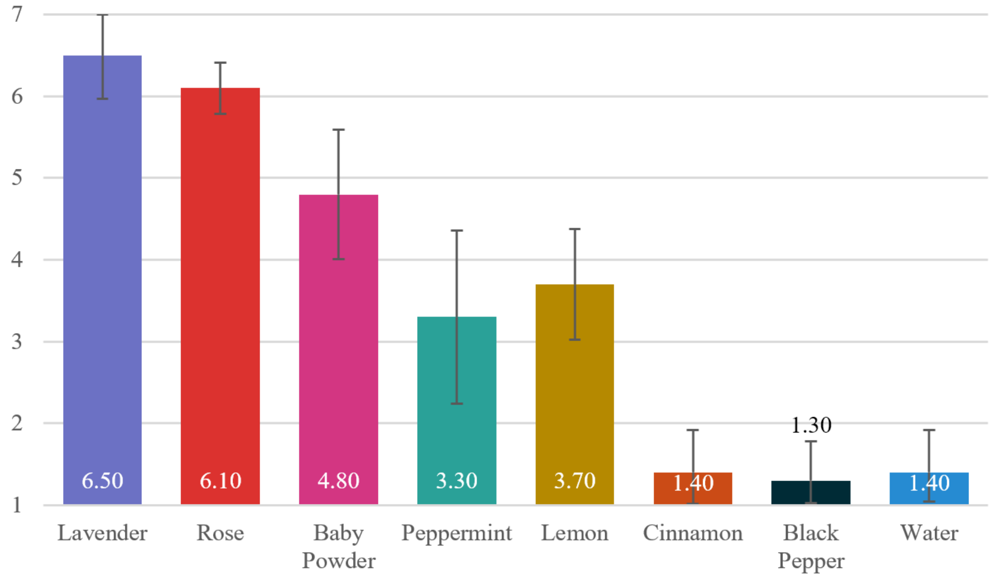


Figure 8.5: Mean response scores to the Odour Selection Questionnaire (OSQ) item: 'How much do you think this scent represents the message from this storyline' for the 'There's a flower in your vicinity' storyline. Responses were given on a 7-point ordinal scale with endpoints 1 - 'Not at all' to 7 - 'Very much'.

flower in vicinity mean = 1.4, Z = 0.00, $p = 1.000$).

Significant differences were found for the floral odours lavender (chalk hands mean = 1.90, flower in vicinity mean = 6.50, Z = 2.83, $p = 0.002$) and rose (chalk hands mean = 1.7, flower in vicinity mean = 6.1, Z = 2.85, $p = 0.002$), which both produced significantly higher scores for the flower in vicinity storyline. Both the cinnamon (chalk hands mean = 3.80, flower in vicinity mean = 1.40, Z = 2.71, $p = 0.004$) and the black pepper (chalk hands mean = 4.50, flower in vicinity mean = 1.30, Z = 2.84, $p = 0.002$) odours on the other hand, produced significantly higher scores for the chalk hands storyline.

Table 8.4 shows the mean response scores to the questionnaire item 'How much do you think this scent represents the message from this storyline' for the chalk hands and flower in vicinity storylines.

Table 8.5 shows the results of the VE based task, where participants were asked to state whether they felt that an odour better represented the chalk hands or flower in vicinity notification. Following the method of Dmitrenko et al. (2017), participants were asked to make an explicit choice between the two notifications, so that an odour could only be associated with one notification. The results show that all 10 participants associated the cinnamon and black pepper odours with the chalk hands notification. All 10 participants also associated the laven-

Odour	**'Chalk your hands' (mean)**	**'There's a flower in your vicinity' (mean)**	***p***
Lavender	1.90	6.50	0.002
Rose	1.70	6.10	0.002
Baby Powder	4.20	4.80	0.313
Peppermint	3.10	3.30	0.813
Lemon	4.10	3.70	0.313
Cinnamon	3.80	1.40	0.004
Black Pepper	4.50	1.30	0.002
Water	1.40	1.40	1.000

Table 8.4: Mean response score to the question 'How much do you think this scent represents the message from this storyline'. Storylines are shown as column headings. The p column shows the results of a Wilcoxon Signed-Rank test between the scores for the different storylines. Underlined values in the p column denote a significant difference $p < 0.05$.

der and rose odour with the flower notification, showing that there were clear preferences in terms of associating certain odours with notifications. These results from the VE based task reflect the determined congruence of the odours from the OSQ, where participants associated the black pepper and cinnamon odours with the chalk hands notification and the lavender and rose odours with the flower in vicinity notification.

Odour	**'Chalk your hands' (%)**	**'There's a flower in your vicinity' (%)**
Lavender	0	100
Rose	0	100
Baby Powder	70	30
Peppermint	30	70
Lemon	30	60
Cinnamon	100	0
Black Pepper	100	0
Water	60	40

Table 8.5: Combined responses to the question 'Which message does the scent convey? 1. There's a flower in your vicinity, or 2. You should chalk your hands?' as determined in the virtual environment. Notifications (messages) are shown as column headings.

8.3.5.3 Evaluating the Combined Results to Determine the Odours That Best Convey the Notifications in the Virtual Environment

The results from Step 2 of the odour selection task showed that participants had clear preferences in terms of associating an odour with a notification, both inside and outside the VE. Participants felt that the cinnamon and black pepper odours were congruent with the chalk hands notification, and that the rose and lavender odour were congruent with the flower in vicinity notification. Table 8.6 shows the responses in terms of the congruence between these odours and the notifications as assessed inside and outside the VE during Step 2 of the odour selection task (see Section 8.3.5.2). The baby powder, peppermint, lemon, and water odours on the other hand were perceived as congruent with both of the notifications and could not be associated with a single notification. For this reason, only the lavender, rose, cinnamon and black pepper odours were considered for further analysis.

	'Chalk your hands'		**'There's a flower in your vicinity'**	
Odour	**Inside VE (%)**	**Outside VE (mean)**	**Inside VE (%)**	**Outside VE (mean)**
Lavender	0	1.90	100	6.50
Rose	0	1.70	100	6.10
Cinnamon	100	3.80	0	1.40
Black Pepper	100	4.50	0	1.30

Table 8.6: Congruence scores of odours and notifications assessed inside and outside the virtual environment. Mean scores are on a scale from 1 (lowest) to 7 (highest).

From these results alone, the black pepper odour would appear to be the best match for the chalk hands notification, while the lavender odour would be the best match for the flower in vicinity notification. However, the suitability for the VE is also determined by the basic perceptual properties of the odours that were collected in Step 1 using the OSQ, the results of which can be seen in Table 8.3. The suitability for the VE was defined as follows. Odours had to have a medium intensity level, defined as a mean intensity response of $2 \le i \le 4$, to ensure that they were perceived by the participants and that they were not too intense, potentially distracting participants. Odours also had to have a mean pleasantness score of 3.5 or higher, to ensure that the odours were generally perceived as pleasant.

While the black pepper odour was perceived as more congruent with the chalk hands notification, with a high intensity score of 4.20 and a low pleasantness score of 2.10, the odour fell outside the defined limits for intensity and pleasantness. The second most congruent odour was the cinnamon odour, which met the criteria for intensity and pleasantness, with mean scores of 3.90 and 3.60 respectively. The mean intensity and pleasantness ratings for the lavender odour met the criteria, with a score of 3.50 for both items.

The selected odours for the odour selection tasks were therefore the cinnamon odour, which was used for the chalk hands notification, while the lavender odour was used for the flower in vicinity notification.

8.4 Part B: Main Study

The purpose of the main study was to evaluate RQ_3 of this thesis: *Are olfactory notifications effective in virtual reality?* by testing the three main hypotheses:

H_1: *Participants can understand olfactory notifications.*

H_2: *Olfactory notifications increase performance in virtual reality.*

H_3: *Congruent pleasant odours when delivered as notifications increase the sense of presence in virtual reality.*

To test H_1, during game-play, participants had to be able to perceive and differentiate between the two odours that were selected during the odour selection task and had to be able to understand the meaning of the chalk hands notification and flower notification, while playing the game. This was measured by assessing participant QoE ratings and task performance and was supplemented by qualitative results from observations and unsolicited remarks. To test H_2, participant task performance was assessed in terms of the number of flower interactions, how often participants chalked their hands, the number of falls and the number of savepoints reached. H_3 was tested by assessing presence scores, which were collected using the Jennet et al. Presence Questionnaire (JPQ) and Igroup Presence Questionnaire (IPQ), an extended version of the Witmer and Singer Presence Questionnaire used in Study Two and Study Three. Presence questionnaire results were also supplemented by qualitative results from observations and unsolicited remarks.

For the main study, a within-subjects design with repeated measures was used to minimise individual differences and to provide a control condition for each participant. There was one independent variable IV_1, which was the display of odours vs no display of odours.

There were six dependent variables, DV_1: The number of flowers participants interacted with; DV_2: How often participants chalked their hands; DV_3: How often participants fell in the

VE; DV_4: How many checkpoints participants reached; DV_5: QoE responses, and DV_6: Presence questionnaire responses. The order of exposure to IV_1 was randomised and counterbalanced. The experimental sessions lasted approximately 45 minutes to 1 hour.

8.4.1 Odour Display

As a result of Part A, lavender was selected as the odour for the flower notification, while cinnamon was selected for the chalk hands notification.

The odours were delivered to the participants using two Aroflora Keylias, one attached to the right side of the *Oculus Rift* headset, while the other was attached to the left, as described in Section 5.4.1. Odours were displayed manually by the experimenter using switches in the USB cables running from the ODs to the power source.

In order to determine when the olfactory notifications should be triggered, the two olfactory notifications were paired with in-game events. 5 seconds after the visual indicator on the hand indicated that chalking is necessary (see Figure 5.6), the experimenter triggered two puffs of cinnamon odour, by flipping the switch twice, with a two second pause in between the puffs:

1. The experimenter flipped the switch to the 'on' position.
2. After 1 second, the experimenter flipped the switch to the 'off' position.
3. After 2 seconds, the experimenter flipped the switch to the 'on' position.
4. After 1 second, the experimenter flipped the switch to the 'off' position.

The odour display was not repeated until the participant had chalked their hands and the chalk indicator had disappeared.

As soon as a flower entered a participant's field of view, the experimenter triggered two puffs of odour, by flipping the switch twice, with an approximate two second pause in between the puffs. As the odours were triggered manually, slight fluctuations in terms of the timings of triggering the odours will have occurred. These timings were not recorded. The odour display was not repeated unless the flower left the field of view of the participant and re-entered (either by moving their head or by climbing away from the flower), and only if 10 seconds had elapsed since the last puff, to prevent olfactory fatigue. The experimenter read the times from the watch used to measure the elapsed time that the participant had spent in the VE and triggered the display of odours manually. Small fluctuations in terms of when odours were triggered will therefore have occurred, for example the experimenter may have triggered the odour 10.5 seconds after the last puff, rather than after 10 seconds.

8.4.2 Post-Game Questionnaire

The PGQ of Study Four consisted of 4 sub-questionnaires. A QoE questionnaire (see Table 5.3) which participants completed twice, once for each notification, but only after the Odour condition, and two presence questionnaires (see Tables 5.4 and 5.5) which participants completed twice, once after both the Odour and No-Odour condition. The full PGQ can be found in Appendix D.3.

In order to test H_1, which stated that participants can understand olfactory notifications, two questions were added to the QoE questionnaire, that had been used in Study Two and Study Three. These were 'Do you think that you changed your behaviour when you perceived the smell?', and 'How effective was the smell at indicating that [notification storyline]', where the notification storyline could either be 'a flower was in your vicinity' or ' you should chalk your hands'. These questions were added to the QoE questionnaire as items 7 and 8 respectively. The full list of questionnaire items can be seen in Figure 8.7 (with the flower notification) and in Figure 8.6 (with the chalk hands notification).

In this study, presence was assessed using the Jennet et al. Presence Questionnaire (JPQ) (see 5.4) and the Igroup Presence Questionnaire (IPQ) (Schubert, Friedmann, et al., 2001), which captures a more complete range of presence related measures. The Igroup Presence Questionnaire (IPQ) is a 14 item (see Table 8.7) presence questionnaire that was developed by combining previous presence questionnaires, including items from Witmer and Singer (1998) and Slater, Usoh, and Steed (1994) (see Section 3.4.4.1), and by adding adding 9 new items relating to the experience of presence (items 2 to 6, 8 to 10, and 14). The questionnaire has been tested and statistically validated (Schubert, Friedmann, et al., 1999, 2001) and is widely used in presence related research (Hein and Mai, 2018). The questionnaire contains 3 subscales: spatial presence (items 2 to 6), involvement (items 7 to 10), and experienced realism (items 11 to 14) (see Section 3.4.4.1 for a description of the presence factors of spatial presence, involvement, and realism). Furthermore the authors included one item on the general experience of presence (item 1 - 'In the computer generated world I had a sense of 'being there''). The IPQ is the second most common presence related questionnaire in use (Hein and Mai, 2018), and includes several of the measurements used by the Witmer and Singer Presence Questionnaire, which was used to assess the sense of presence in Studies Two and Three. The reason that a switch was made to the IPQ was because the questionnaire allows the calculation of an overall score for the sense of presence and includes several items pertaining to an overall sense of 'being there'. The Witmer and Singer Presence Questionnaire was lacking in this regard, and while it was possible to determine whether certain aspects that can lead to a sense of presence in VR were affected by the olfaction, an overall presence score may give further clarity. As was noted in Section 5.6, an overall presence score should still be placed in the context of supplementary data from e.g. observations so that the results can be interpreted in the wider context of the user's experience of the VE.

Questionnaire items are rated on 7-point Likert scales. The labels for the different points of the scale vary depending on the implementation of the IPQ, e.g. from 0 to 6 (Regenbrecht and Schubert, 2002), from -3 to +3 (igroup, 2018) and from 1 to 7 (Brown et al., 2003). As the scales are ordinal, responses give an indication of rank order, rather than measurable quantity and therefore numerical values assigned to the points of the scale are for participant guidance. As I use a scale ranging from 1 to 7 for the JPQ, I also used this scale for the IPQ, thereby following Brown et al. (2003)'s implementation of the IPQ.

Each point is labelled numerically (1 to 7), with 1 indicating a low sense of presence and 7 indicating a high sense of presence. However, the IPQ gives three items with reversed scales. These items are item 3 - 'I felt like I was just perceiving pictures.' with anchors 1 - 'fully disagree' and 7 - 'fully agree', item 9 - 'I still paid attention to the real environment.' with anchors 1 - 'fully disagree' and 7 - 'fully agree', and item 11 - 'How real did the virtual world seem to you?' with anchors 1 - 'completely real' and 7 - 'not real at all'.

While the IPQ can be evaluated in terms of the three subscales, it can also be used to determine an overall presence score, indicating a participant's general sense of presence in the VE. According to Brown et al. (2003), the score is calculated by summing a participant's scores for all questionnaire items of a condition. With 14 items in the questionnaire, and a maximum score of 7 for each item, a total score of $4 \cdot 7 = 98$ was obtainable. However, as three questionnaire items were given in reversed scales, the responses had to be reversed to fit in line with the remaining questionnaire items, where a 1 indicates a low sense of presence and a 7 indicates a high sense of presence. The scores for items 3, 7, and 9 were reversed with the equation: $S_{\text{reverse}} = -1 \cdot S + 8$.

In terms of the questionnaire items, it should be noted that item 11 and item 13 both read 'How real did the virtual world seem to you?', item 11 however uses the anchors 1 - 'Fully disagree' and 7 - 'Fully agree', while item 13 uses the anchors 1 - 'About as real as an imagined world', 7 - 'Indistinguishable from the real world'. See Table 8.7 for the 14 items contained in the questionnaire.

ID	Statement	Rating 1	 7
1	In the computer generated world I had a sense of 'being there'.	Not at all	Very much
2	Somehow I felt that the virtual world surrounded me.	Fully disagree	Fully agree
3 *	I felt like I was just perceiving pictures.	Fully disagree	Fully agree
4	I did not feel present in the virtual space.	Did not feel present	Felt present
5	I had a sense of acting in the virtual space, rather than operating something from outside.	Fully disagree	Fully agree
6	I felt present in the virtual space.	Fully disagree	Fully agree
7	How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)?	Extremely aware	Not aware at all
8	I was not aware of my real environment.	Fully disagree	Fully agree
9 *	I still paid attention to the real environment.	Fully disagree	Fully agree
10	I was completely captivated by the virtual world.	Fully disagree	Fully agree
11 *	How real did the virtual world seem to you?	Completely real	Not real at all
12	How much did your experience in the virtual environment seem consistent with your real world experience?	Not consistent	Very consistent
13	How real did the virtual world seem to you?	About as real as an imagined world	Indistinguishable from the real world
14	The virtual world seemed more realistic than the real world.	Fully disagree	Fully agree

Table 8.7: Igroup Presence Questionnaire (IPQ) (Schubert, Friedmann, et al., 2001). Responses are given on ordinal scales ranging from 1 (low presence) to 7 (high presence). Each point is labelled numerically while the shown labels are only given for endpoints (1 and 7). * indicates that the questionnaire item is anchored in reverse and a rating of 1 indicates a high sense of presence, and 7 indicates a low sense presence.

8.4.3 Procedure

The main study took place at the City, University of London Interaction Lab, a large open space that only contained one desk towards the rear end of the room, allowing for an approximately 5m x 5m open area that could be used for the VR environment. A Post-Game Questionnaire (PGQ) (see Section 8.4.3) was issued to participants after each of the VR conditions i.e. Odour or No-Odour, for which they were asked to remove the headset and to be seated at a second desk with a computer, which was placed by the wall opposite the VR desk. A detailed description of the room setup can be found in Section 6.4.1.

A total of 20 participants took part in this study 10 male (mean age = 30.20 years, SD = 6.01) and 10 female (mean age = 30.30 years, SD = 4.29), which were recruited via university mailing lists and noticeboards across the university. Several inclusion and exclusion criteria applied. Participants were required to have normal or corrected to normal vision and a functioning sense of smell. Participants who required corrective vision aids were asked to wear contact lenses, as not all glasses fit inside the Oculus Rift headset. Participants were screened for olfactory dysfunction using the three-item Q-SIT (Jackman and Doty, 2005) (see Section 6.3). No participants were excluded as a result of the test for olfactory function. Additionally, the participants were asked to refrain from wearing any fragrances on the day of the sessions and not to have any meal, coffee, or to smoke for one hour before the experimental session and were asked to report any smell related allergies or concerns in advance. No compensation was given to participants. Participants were not allowed to have previously taken part in either Study One or Study Two, but had to have had prior experience with VR.

Upon arrival, participants were given the information sheet (see Appendix B.7) and a consent form (see Appendix B.8) to sign. Participants were then screened for olfactory dysfunction using the three item Quick Smell Identification Test (Q-SIT) (Jackman and Doty, 2005) as described in Section 6.3. Participants were then introduced to the VR equipment and the experimenter explained the button placement of the touch controllers as well as how to adjust the HMD. The setup of the *Oculus Rift* VR headset was the same as that of Study Two (see Section 6.4) and Study Three (see Section 7.3). Participants entered their height in the *Oculus Rift* device management settings to ensure that the floor position was set appropriately and then completed the *Oculus Rift* touch tutorial, which introduced them to the use of the touch controllers and allowed them to familiarise themselves with interactions in VR. Upon completing the touch tutorial, the experimenter started the basic tutorial of *The Climb*. During the tutorial, participants are familiarised with the various game mechanics. A large focus of the tutorial is to understand how the chalking mechanic works. Section 5.3.3 gives a detailed description of the various game mechanics that are covered in the tutorial. Once participants had completed the tutorial, they were asked to remove the headset and to take a short break while the experimenter started the Old Mine level in the *The Alps* environment and positioned the player avatar at the starting point in the level. This completed the preparation for the main study and marked the point from which data was collected.

Participants were assigned to one of two groups, according to a pre-determined randomised order. The groups differed in terms of the order in which participants experienced the Odour and No-Odour condition. The groups were designated the 'No-Odour, Odour' group (NO-O), which was exposed to odours during their second run, and the 'Odour, No-Odour' group (O-NO), which was exposed to odours during their first run. The order in which participants were exposed to the conditions can be seen in Table 8.8.

Group	Run	Condition
NO-O	1	No-Odour
No-Odour, Odour	2	Odour
O-NO	1	Odour
Odour, No-Odour	2	No-Odour

Table 8.8: Experimental groups and orders in which they were exposed to the conditions.

For both conditions, the experimenter explained the task of finding purple flowers (from now on simply referred to as flowers) throughout the level and demonstrated how participants should interact with the flowers to be awarded a point, i.e. by touching the flower with one of their hands. To demonstrate this to participants, the experimenter climbed to a flower in the VE, while participants were watching the in-game monitor (see Figure 6.2), showing participants what the flower looked like and how they should interact with it to receive a point. The experimenter also verbally reminded the participants that they should not forget to chalk their hands by saying: "Don't forget to chalk your hands". The experimenter then placed the player avatar at the starting position in the level, removed the headset and helped the participant to put it on. Participants were then instructed to start climbing and to find as many flowers as possible until requested to stop by the experimenter. The participants were allowed to climb for a period of ten minutes, as recorded by a stopwatch placed adjacent to the control PC monitor. During the ten minutes the experimenter recorded the number of times the participants chalked their hands, how often they fell, how many flowers they interacted with, the number of savepoints reached, and any unsolicited remarks concerning their experience of the VE and the odours. A flower point was only given the first time a participant interacted with a flower, subsequent interactions were not scored. During these ten minutes, the experimenter did not interact or speak with the participant. After the ten minutes had elapsed, participants were asked to remove the headset and to proceed to the second desk to fill out the Post-Game Questionnaire (PGQ) (see Section 8.4.2). After completing the PGQ, participants were returned to the VE and were exposed to the second condition. The only difference between the conditions was if odours were displayed or not. In the next section I describe in details the questions used in the PGQ.

While participants were filling out the PGQ, the experimenter placed the player avatar back at the starting position. After completing the PGQ, participants were asked to return to the VE, where they were exposed to the second condition. If this was the odour condition, the experimenter prepared two cotton buds, one with 0.1ml of the lavender odour applied to the tip and the other with 0.1ml of the cinnamon odour applied. Participants were then instructed by the experimenter that they would be receiving two notifications conveyed via smell. The participants were told "When you smell this scent, this means that you should chalk your hands" and were handed and asked to smell the cinnamon cotton bud. Once the participants had familiarised themselves with the odour, the cotton bud was handed back to the experimenter who then handed the participants the other cotton bud, containing the lavender odour, with the accompanying instruction "When you smell this scent, this means that there is a flower in your vicinity", and once the participants had familiarised themselves with the odour, the cotton bud was handed back to the experimenter. As these instructions were only given to participants during the Odour condition, it is possible that this caused participants to pay more attention to both flowers and chalking when compared to the No-Odour condition. However, in order to minimise this effect, both groups were given extensive instructions in terms of interacting with flowers and chalking their hands.

The cotton buds were then discarded outside of the lab, in order to prevent any odour contamination or false positives during the study e.g. a participant thinking there was a flower in the vicinity when this was actually not the case. Participants were then instructed to put on the HMD and were told that the two odours would now be presented again. They were once again told 'When you smell this scent, this means that you should chalk your hands' and the experimenter then actuated the OD containing the cinnamon odour. This was repeated once to ensure that the participant was able to perceive the odour. This familiarisation procedure was then repeated for the lavender odour. Participants were then instructed to climb once again and to interact with as many flowers as possible. The experimenter then displayed the odours, according to the method described above in Section 8.4.1 and recorded the same data as in the previous condition (see Section 8.4). After 10 minutes, participants were once again asked to stop climbing and were instructed to fill out the PGQ, concluding the experimental session.

8.5 Results

In the following section I describe the results of Part B: Main Study. QoE scores were collected using the QoE questionnaire (Table 5.3) and the results are described in Section 8.5.1; performance was measured in terms of flower interactions (see Section 8.5.2.1), how often hands were chalked (see Section 8.5.2.2), the number of falls (see Section 8.5.2.3), and savepoints reached (see Section 8.5.2.3); presence scores were collected using the IPQ (Table 8.7), the JPQ (Table 5.4), and the results are described in Sections 8.5.3.1, and 8.5.3.2 respectively. Finally, qualitative results were collected in terms of observations and unsolicited comments and are described in Section 8.5.4.

8.5.1 Quality of Experience Questionnaire and Odour Effectiveness

Participants were asked to rate the chalk notification odour and flower notification odour using the QoE questionnaire. Overall participants reported similar scores for both odours. Participants stated that they felt that the odours made them change their behaviour (chalk hands mean = 4.50, flower in vicinity mean = 4.40), that the odours were effective at indicating the meaning of the notification (chalk hands mean = 3.85, flower in vicinity mean = 4.50), that the odours were neither annoying (chalk hands mean = 1.40, flower in vicinity mean = 1.35) nor distracting (chalk hands mean = 1.90, flower in vicinity mean = 1.55), made them feel more present in the VE (chalk hands mean = 3.60, flower in vicinity mean = 4.10), that the odours heightened a sense of reality in the VE (chalk hands mean = 3.90, flower in vicinity mean = 4.15), and that they were relevant to what they were seeing (chalk hands mean = 3.60, flower in vicinity mean = 4.40). The mean results of the chalk hands notification can be seen in Figure 8.6, while the mean results for the flower in vicinity notification can be seen in Figure 8.7.

As participants were asked to rate their response to the statement 'I enjoyed the virtual environment.' for both the Odour and No-Odour condition in this study, a Wilcoxon Signed Rank Test was conducted to compare the scores from these conditions. No significant difference between the Odour and No-Odour condition was observed (No-Odour mean = 4.15, SD = 0.85, Odour mean = 4.60, SD = 0.49, Z = 2.19, $p = 0.032$).

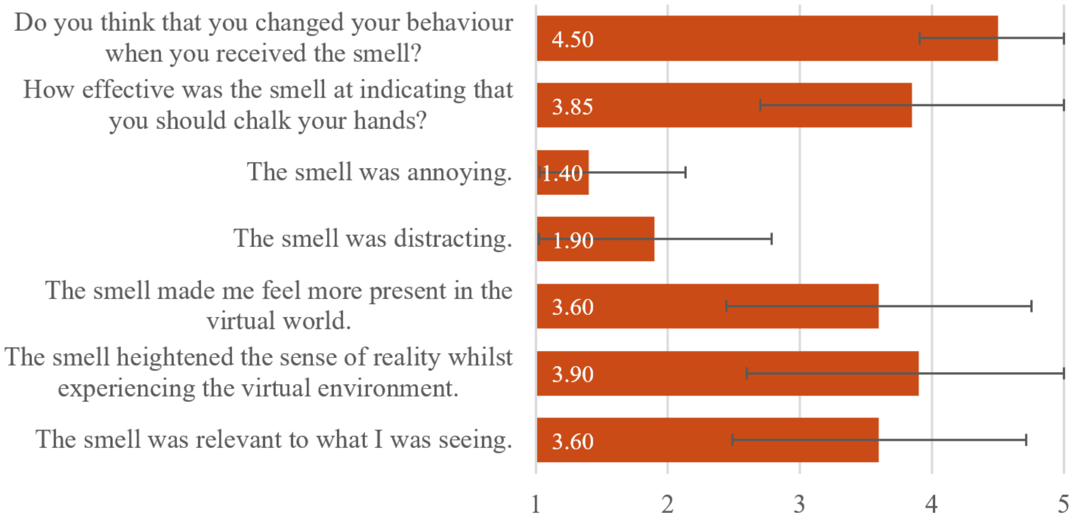


Figure 8.6: Mean responses to the Quality of Experience related factors of the 'Chalk your hands' notification.

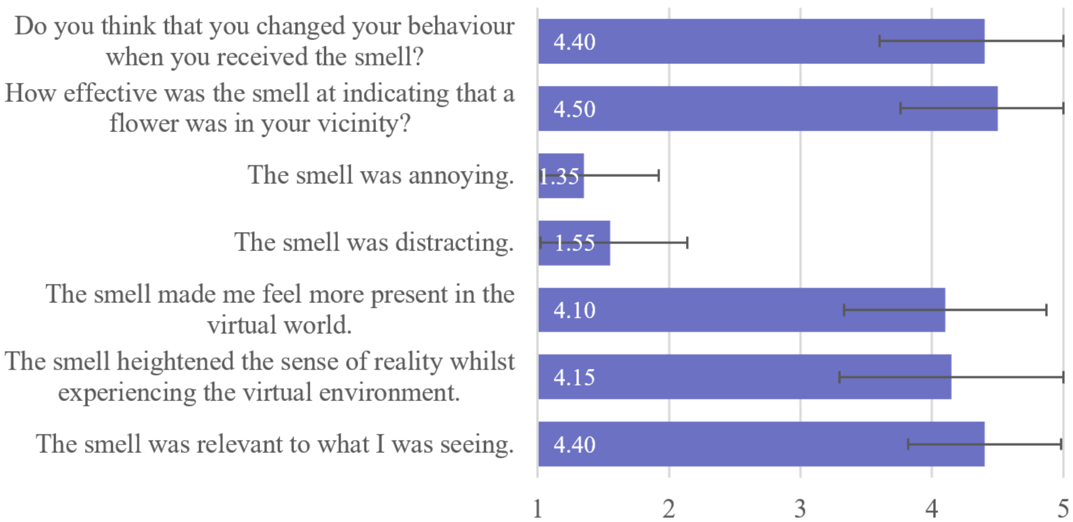


Figure 8.7: Mean responses to the Quality of Experience related factors of the 'There's a flower in your vicinity' notification.

8.5.2 Performance

In this section, performance related results are presented. Overall, olfactory notifications led to a significant improvement in the participants' performance. Participants' performance was assessed by examining: i)the number of flowers they interacted with (see Section 8.5.2.1); ii) the number of times they chalked their hands (see Section 8.5.2.2); iii) the number of times they fell (see Section 8.5.2.3); and iv) the number of save points they reached (see Section 8.5.2.4).

The data from each of the performance metrics was statistically analysed to determine if olfactory notifications improved their performance. I will now outline the statistical tests that were conducted on the data and report on the results of these tests in the subsequent sections.

To determine if participants of a group performed better in the Odour condition compared to the No-Odour condition, for each performance metric, a Wilcoxon Signed Rank test was conducted, comparing the first run against the second run of the same group. The groups were the 'No-Odour Odour' (NO-O) group, who were exposed to the odours during their second run only, and the 'Odour No-Odour' (O-NO) group, who experienced odours during their first run only.

To determine whether there were any ordering effects, I conducted, Mann-Whitney U-Tests for Independent Samples, comparing the data of the No-Odour condition of both groups, i.e. the first run for the NO-O group and the second run for the O-NO group, followed by a comparison of the Odour condition of both groups.

Depending on the outcome of this analysis, further statistical tests were carried out, the details of which are given in the appropriate sections for each performance metrics below.

As an overview of results, the mean scores of the 4 different performance metrics were calculated and can be seen in Figure 8.8.

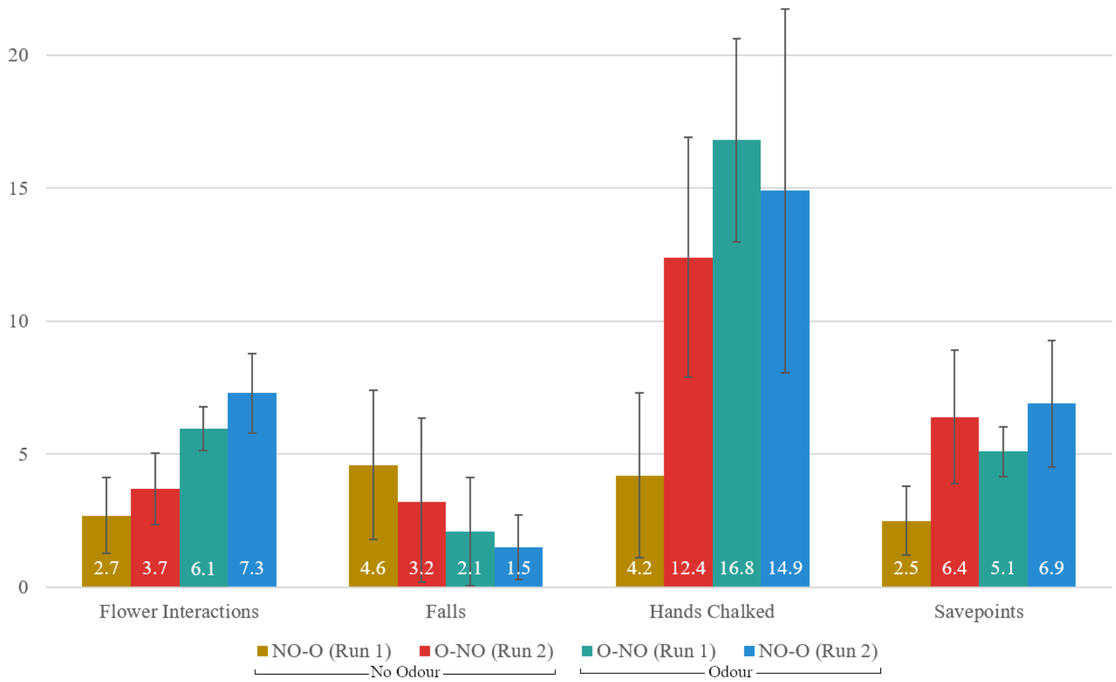


Figure 8.8: Comparison of the mean performance metric scores for the 'No-Odour Odour' group and the 'Odour No-Odour' group.

8.5.2.1 Flower Interaction Scores

Participants were awarded one point for the first interaction with every purple flower they encountered while playing the game (see Figure 6.1).

A Wilcoxon Signed Rank test was conducted to compare the first and second runs for both groups to see if the olfactory flower notification improved performance. A comparison between the first and second run of the NO-O group showed that participants scored significantly higher during the second run, when they had the olfactory flower notification (1^{st} run mean = 2.70, 2^{nd} run mean = 7.30, Z = 2.85, $p = 0.0019$).

A comparison between the first and second run of the O-NO group showed that participants scored significantly higher during the first run, when they had the olfactory flower notification (1^{st} run mean = 6.10, 2^{nd} run mean = 3.70, Z = 2.85, $p = 0.002$).

To determine if there were any ordering effects, a Mann-Whitney U-Test was conducted between the Odour conditions of both groups. There were no significant differences between the runs (NO-O 2^{nd} run mean = 7.30, O-NO 1^{st} run mean = 6.10, U = 27, $p = 0.089$), indicating that there was no ordering effect. A Mann-Whitney U-Test was conducted between the No-Odour conditions of both groups. No significant difference was found between the scores (NO-O 1^{st} run mean = 2.70, O-NO 2^{nd} run mean = 3.70, U = 29, $p = 0.043$), once again indicating that the order of the conditions did not affect ratings.

To determine if the olfactory had an overall effect on flower interaction scores, the scores of the Odour condition (scores from the first run of the O-NO group and from the second run of the NO-O condition) were compared with the scores from the combined No-Odour condition (scores from the second run of the O-NO group and from the first run of the NO-O condition). A Wilcoxon Signed Rank test revealed that participants in the Odour condition scored significantly higher than those in the No-Odour condition (No-Odour mean = 3.20, Odour mean = 6.70, Z = 3.89, $p < 0.000$).

Table 8.9 shows the mean flower scores and associated standard deviations for both groups during the first and second run.

8.5.2.2 Chalking

This section details the results of the number of times that participants fully chalked a single hand. While participants nearly exclusively chalked both hands, this was scored as two individual instances.

A comparison between the first and second run of the NO-O group using a Wilcoxon

		1^{st} Run	2^{nd} Run
NO-O	**Mean**	2.70	7.30
	SD	1.42	1.49
O-NO	**Mean**	5.90	3.70
	SD	0.54	1.35

Table 8.9: Comparison of mean flower scores between first and second runs of each group.

Signed Rank test, showed that participants chalked their hands significantly more often during the second run (1^{st} run mean = 4.20, 2^{nd} run mean = 14.90, Z = 2.81, $p = 0.0019$). A comparison between the first and second run of the O-NO group using a Wilcoxon Signed Rank test, showed that participants chalked their hands significantly more often during the first run ((1^{st} run mean = 16.80, 2^{nd} run mean = 12.40, Z = 2.09, $p = 0.0371$).

To determine if there were any ordering effects, a Mann-Whitney U-Test was conducted between the Odour conditions of both groups. There were no significant differences between the runs (NO-O 2^{nd} run mean = 7.30, O-NO 1^{st} run mean = 6.10, U = 40.5, $p = 0.481$), indicating that there was no ordering effect. A Mann-Whitney U-Test was conducted between the No-Odour conditions of both groups. Scores for the O-NO group were found to be significantly higher (NO-O 1^{st} run mean = 2.70, O-NO 2^{nd} run mean = 3.70, U = 6, $p < 0.000$). Indicating that there was an ordering effect.

I then conducted a Mann Whitney U test, comparing the first runs of the NO-O and O-NO group, which revealed that the group which received odour notifications during the run (O-NO) chalked their hands significantly more often during this run (No-Odour median = 16.50, mean = 4.20, Odour median = 3.00, mean = 16.80, U = 1.00, $p < 0.0000$).

A comparison using a Mann Whitney U test between the second runs of the two groups showed that although the NO-O group chalked their hands more often, however there was no significant difference (No-Odour median = 10.50, mean = 12.40, Odour median = 11.50, mean = 14.90, U = 41.00, $p = 0.528$).

Table 8.10 shows the mean number of times participants chalked their hands and associated standard deviations for both groups during the first and second run.

8.5.2.3 Falls

This section details the results of the number of times that participants fell, causing them to re-start at the last savepoint.

A comparison between the first and second run of the NO-O group showed that partici-

		1st Run	2nd Run
NO-O	**Mean**	4.20	14.90
	SD	3.09	6.85
O-NO	**Mean**	16.80	12.40
	SD	3.82	4.50

Table 8.10: Comparison of mean number of times participants performed the 'Chalk your hands' action between first and second runs of each group.

pants fell significantly more often during the first run (1^{st} run mean = 4.60, 2^{nd} run mean = 1.50, Z = 2.54, $p = 0.0078$). A comparison between the first and second run of the O-NO group showed that participants fell more often during the second run, although not significantly more often (1^{st} run mean = 2.10, 2^{nd} run mean = 3.20, Z = 1.55, $p = 0.148$).

To determine if there were any ordering effects, a Mann-Whitney U-Test was conducted between the Odour conditions of both groups. There were no significant differences between the runs (NO-O 2^{nd} run mean = 1.50, O-NO 1^{st} run mean = 2.10, U = 45.50, $p = 0.739$), indicating that there was no ordering effect. A Mann-Whitney U-Test was conducted between the No-Odour conditions of both groups. No significant difference was found between the scores (NO-O 1^{st} run mean = 4.60, O-NO 2^{nd} run mean = 3.20, U = 34, $p < 0.247$). Indicating that there was no ordering effect.

Comparing the first runs of the NO-O and O-NO group showed that the group which received odour notifications during the run (O-NO) fell significantly less often (No-Odour median = 5.50, mean = 4.60, Odour median = 1.50, mean = 2.10, U = 23.00, $p = 0.0432$).

A comparison between the second runs of the two groups showed that the NO-O group fell less often, although not significantly so (No-Odour median = 2.50, mean = 3.20, Odour median = 1.50, mean = 1.50, U = 36.00, $p = 0.315$).

To determine if the olfactory had an overall effect on the number of falls, the scores of the Odour condition (scores from the first run of the O-NO group and from the second run of the NO-O condition) were compared with the scores from the combined No-Odour condition (scores from the second run of the O-NO group and from the first run of the NO-O condition). A Wilcoxon Signed Rank test revealed that participants in the Odour condition scored significantly higher than those in the No-Odour condition (No-Odour mean = 3.29, Odour mean = 1.80, Z = 2.89, $p = 0.002$).

Table 8.11 shows the mean number of times participants fell and re-started at the last save-point, and associated standard deviations for both groups during the first and second run.

		1st Run	2nd Run
NO-O	**Mean**	4.60	1.50
	SD	2.80	1.20
O-NO	**Mean**	2.10	3.20
	SD	2.02	3.16

Table 8.11: Comparison of mean number of times participants fell and re-spawned at the last savepoint, between first and second runs of each group.

8.5.2.4 Savepoints Reached

This section details the results of the number of savepoints that a participant reached during the 10 minutes of play of each run. The number of checkpoints reached indicates how far a participant has progressed through the level. While there was no set task to climb as far as possible in a level, the number of flowers that can be found directly correlates to the number of checkpoints reached: the further a participant climbed, the more flowers that they encountered.

A comparison between the first and second run of the NO-O group showed that participants reached significantly more savepoints during the second run (1^{st} run mean = 2.50, 2^{nd} run mean = 6.90, Z = 2.82, $p = 0.002$). A comparison between the first and second run of the O-NO group showed that participants reached more savepoints during the second run; this difference however was not significant. (1^{st} run mean = 5.10, 2^{nd} run mean = 6.40, Z = 1.41, $p = 0.195$).

To determine if there were any ordering effects, a Mann-Whitney U-Test was conducted between the Odour conditions of both groups. There were no significant differences between the runs (NO-O 2^{nd} run mean = 6.90, O-NO 1^{st} run mean = 5.10, U = 31.50, $p = 0.165$), indicating that there was no ordering effect. A Mann-Whitney U-Test was conducted between the No-Odour conditions of both groups. Scores for the O-NO group were found to be significantly higher (NO-O 1^{st} run mean = 2.50, O-NO 2^{nd} run mean = 6.40, U = 7.50, $p < 0.000$). Indicating that there was an ordering effect.

Comparing the first runs of the NO-O and O-NO group showed that the group which received odour cues during the run (O-NO) reached significantly more savepoints (No-Odour median = 2.50, mean = 2.50, Odour median = 5.50, mean = 5.10, U = 6.50, $p = 0.0005$).

A comparison between the second runs of the two groups showed that the NO-O group progressed further in the level, however this difference was not significant (No-Odour median = 5.50, mean = 6.40, Odour median = 7.00, mean = 6.90, U = 45.00, $p = 0.73$).

Table 8.12 shows the mean number of savepoints participants reached, and associated standard deviations for both groups during the first and second run.

		1st Run	2nd Run
NO-O	**Mean**	2.50	6.90
	SD	1.28	2.39
O-NO	**Mean**	5.10	6.40
	SD	0.94	2.50

Table 8.12: Comparison of mean number of savepoints reached, between first and second runs of each group.

8.5.3 Presence Results

In this section I present the results of the data collected for the presence metrics. Data was collected using the IPQ (Table 8.7) and the JPQ (Table 5.4). Section 8.5.3.1 gives details of the IPQ results and Section 8.10 gives details of the JPQ results.

As the conditions of the two groups had been counterbalanced, participants of the different groups experienced the conditions in the opposite order. I therefore wanted to determine whether an ordering effect could be observed and conducted a Mann-Whitney U Test for Independent Samples on the Odour condition of the NO-O group, which was their 2nd run, against the Odour condition of the O-NO group, which was their 1st run. This was followed by Mann-Whitney U Tests for Independent Samples between the scores of the No-Odour conditions of the groups. A significant difference in results would indicate that there is a possible ordering effect.

If no such ordering effect could be observed for a questionnaire item, I conducted a Wilcoxon Signed Rank test between the Odour and No-Odour conditions of the groups to be able to determine if the exposure to odours caused significant differences in terms of sense of presence. As a clarification, Table 8.13 details how the data were analysed. The statistics of this analysis for the IPQ can be found in Section 8.5.3.1, while the statistics of the analysis of the JPQ can be found in Section 8.10.

8.5.3.1 Igroup Presence Questionnaire

In this section, I present the results of the IPQ. Each questionnaire item was analysed according to the order shown in Table 8.13.

I begin my analysis of each questionnaire by comparing the compound presence scores of the Odour condition against the No-Odour condition to determine if olfactory notifications had an overall effect on the sense of presence. The IPQ is specifically set out to determine an

No-Odour Condition	Statistical Test	Odour Condition	Reason
Run 1 (NO-O)	Mann-Whitney U-Test	Run 2 (O-NO)	Is there an ordering effect?
Run 2 (O-NO)	Mann-Whitney U-Test	Run 1 (NO-O)	
Run 1 (NO-O) + Run 2 (O-NO)	Wilcoxon Signed-Rank Test	Run 2 (NO-O) + Run 1 (O-NO)	Did odours affect the responses?

Table 8.13: Overview of the statistical analysis of the Igroup Presence Questionnaire and Jennet et al. Presence Questionnaire.

overall presence effect (see Section 8.4.2), by comparing the sums of participants' scores for all questionnaire items of a condition. As a reminder, questionnaire items 3, 7, and 9 had to be reversed for this analysis in order to match the direction of the anchors of the remaining items, which was 1 - low sense of presence, to 7 - high sense of presence (see Section 8.4.2), which was done with the equation: $S_{\text{reverse}} = -1 \cdot S + 8$.

A comparison of the mean compound scores of the No-Odour condition and the Odour condition of the IPQ, using a Wilcoxon Signed Rank test, showed that the scores of the Odour condition were significantly higher (No-Odour mean = 60.40, Odour mean = 67.40, Z = 2.70, p = 0.005), showing that olfactory notifications significantly increased the sense of presence in the VE.

To determine if the responses to any of the questionnaire items showed signs of an ordering effect, I compared the scores of the No-Odour conditions of the two groups using Mann-Whitney U-Tests for Independent Samples. The results of this analysis can be found in Table 8.14. This was followed by a comparison of the Odour conditions of the two groups using a Mann-Whitney U-Tests for Independent Samples. The results of this analysis can also be found in Table 8.14. The results in the table show that responses to the statement 'Somehow I felt that the virtual world surrounded me.' were significantly different between the groups for the No-Odour condition (NO-O mean = 5.30, O-NO mean = 4.30, U = 21.50, p = 0.029). The results also show that responses to the statement 'I felt present in the virtual space.' were significantly different between the groups for the No-Odour condition (NO-O mean = 5.20, O-NO mean = 3.90, U = 19.50, p = 0.019). The results for the remaining questionnaire items were not significantly different when comparing the groups for both the Odour and No-Odour condition.

IPQ Questionnaire Item	**Condition**	**Group**	**Mean Score**	***p***
In the computer generated world I had a sense of 'being there'.	No-Odour	NO-O	5.00	0.353
		O-NO	4.60	
	Odour	NO-O	5.20	0.125
		O-NO	5.90	
Somehow I felt that the virtual world surrounded me.	No-Odour	NO-O	5.30	0.029
		O-NO	4.30	
	Odour	NO-O	5.50	0.75
		O-NO	5.40	
* I felt like I was just perceiving pictures.	No-Odour	NO-O	2.70	0.579
		O-NO	2.30	
	Odour	NO-O	2.90	0.089
		O-NO	1.90	
I did not feel present in the virtual space.	No-Odour	NO-O	5.50	0.075
		O-NO	4.40	
	Odour	NO-O	5.30	0.195
		O-NO	3.90	
I had a sense of acting in the virtual space, rather than operating something from outside.	No-Odour	NO-O	5.00	0.393
		O-NO	4.40	
	Odour	NO-O	5.40	0.971
		O-NO	5.40	
I felt present in the virtual space.	No-Odour	NO-O	5.20	0.019
		O-NO	3.90	
	Odour	NO-O	5.60	0.684
		O-NO	5.80	
How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)?	No-Odour	NO-O	4.70	0.123
		O-NO	3.50	
	Odour	NO-O	4.30	0.089
		O-NO	5.30	

Table 8.14 continued from previous page

Questionnaire Item	**Condition**	**Group**	**Mean Score**	***p***
I was not aware of my real environment.	No-Odour	NO-O	2.90	0.166
		O-NO	4.00	
	Odour	NO-O	3.20	0.970
		O-NO	3.30	
* I still paid attention to the real environment.	No-Odour	NO-O	2.10	0.089
		O-NO	2.70	
	Odour	NO-O	1.60	0.052
		O-NO	2.30	
I was completely captivated by the virtual world.	No-Odour	NO-O	4.80	0.971
		O-NO	4.80	
	Odour	NO-O	5.70	0.436
		O-NO	5.30	
* ◇ How real did the virtual world seem to you?	No-Odour	NO-O	2.90	0.190
		O-NO	3.60	
	Odour	NO-O	2.80	0.218
		O-NO	2.30	
How much did your experience in the virtual environment seem consistent with your real world experience?	No-Odour	NO-O	3.90	0.353
		O-NO	3.40	
	Odour	NO-O	4.70	0.393
		O-NO	4.30	
⋆ How real did the virtual world seem to you?	No-Odour	NO-O	3.80	0.166
		O-NO	3.20	
	Odour	NO-O	4.20	0.218
		O-NO	4.70	

Table 8.14 continued from previous page

Questionnaire Item	Condition	Group	Mean Score	*p*
The virtual world seemed more realistic than the real world.	No-Odour	NO-O	1.30	0.7394
		O-NO	1.20	
	Odour	NO-O	1.60	0.631
		O-NO	1.40	

Table 8.14: Results of Mann-Whitney U-Tests for Independent Samples on Igroup Presence Questionnaire items comparing the scores of the participants groups for both conditions. Emphasised text indicates significant difference between mean scores.
* Anchored in reverse with 1 - high sense of presence and 7 - low sense of presence.
◇ Anchors for this item are 1 - Completely real, and 7 - Not real at all.
★ Anchors for this item are 1 - About as real as an imagined world, and 7 - Indistinguishable from the real world.

Figure 8.9 gives an overview of the mean differences between each of the groups for all questions from the presence questionnaire.

For each of the questionnaire items that did not show an ordering effect, I then conducted a Wilcoxon Signed Rank tests on the scores of the Odour condition (combined scores of the first run of the O-NO group and the second run of the NO-O group) against the scores of the No-Odour condition (combined scores of the second run of the O-NO group and the first run of the NO-O group). The results for each of the questionnaire items can be found below.

'In the computer generated world I had a sense of "being there".' Responses to this question were significantly higher for the Odour condition. (No-Odour mean = 4.80, Odour mean = 5.55, Z = 2.34, $p = 0.02$)

'I felt like I was just perceiving pictures.' No significant difference was found between the Odour and No-Odour condition (Odour mean = 2.40, SD = 1.02, No-Odour mean = 2.50, SD = 1.11, Z = 0.45, $p = 0.733$), this difference was very small.

'I did not feel present in the virtual space.' There was no significant difference between the No-Odour and Odour condition (No-Odour mean = 4.95, SD = 1.28, Odour mean = 4.60, SD = 1.69, Z = 0.52, $p = 0.640$).

'I had a sense of acting in the virtual space, rather than operating something from outside.' Responses to this question were significantly higher for the Odour condition. (No-Odour mean = 4.70, Odour mean = 5.40, Z = 2.26, $p = 0.026$).

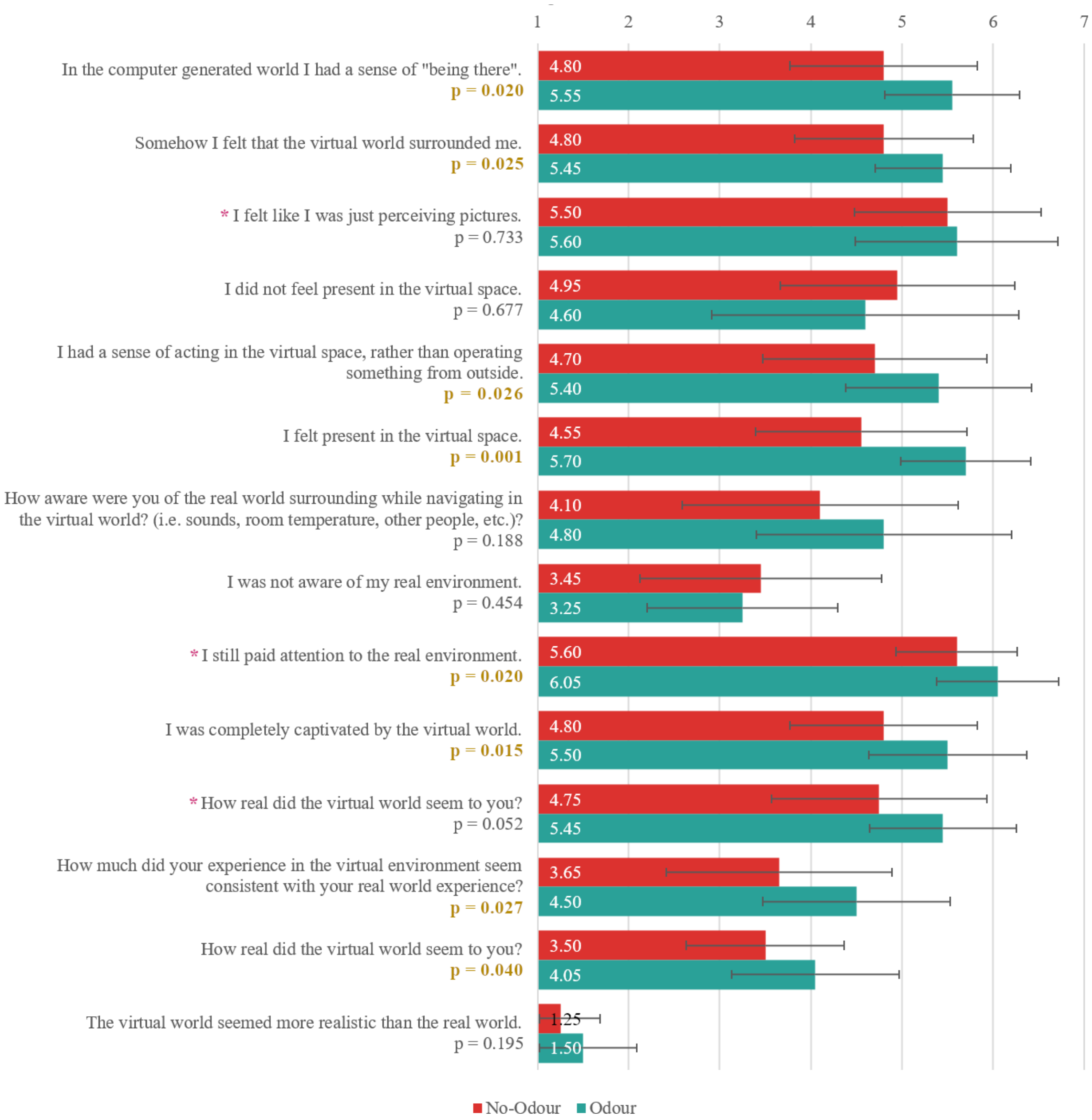


Figure 8.9: Mean responses to the Igroup Presence Questionnaire (IPQ). * indicates that the scores of the item were reversed (as the questionnaire item was anchored in reverse) so that a score of 1 now indicates a low sense of presence and a 7 indicates a high sense of presence, in line with the remaining questionnaire items. Emphasised scores indicate a significant difference between the conditions $p < 0.05$.

'I felt present in the virtual space.' Responses to this question were significantly higher for the Odour condition. (No-Odour mean = 4.55, Odour mean = 5.70, Z = 3.05, $p = 0.001$).

'How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)?' No significant difference was found between the No-Odour and the Odour condition (No-Odour mean = 4.10, SD = 1.51, Odour mean = 4.80, SD = 1.40, Z = 1.34, $p = 0.188$) .

'I was not aware of my real environment.' No significant difference was found between the No-Odour and the Odour condition (No-Odour mean = 3.45, SD = 1.32, Odour mean = 3.25, SD = 1.04, Z = 0.78, $p = 0.454$).

'I still paid attention to the real environment.' Responses to this question were significantly higher for the No-Odour condition (No-Odour mean = 2.30, Odour mean = 1.85, Z = 2.44, $p = 0.011$). As the anchors for this item were reversed, this result indicates that the Odour condition resulted in a significantly higher sense of presence.

'I was completely captivated by the virtual world.' Responses to this question were significantly higher for the Odour condition (No-Odour mean = 4.80, Odour mean = 5.50, Z = 2.44, $p = 0.015$).

'How real did the virtual world seem to you?' Responses to this question were significantly higher for the No-Odour condition. (No-Odour mean = 4.25, Odour mean = 3.55, Z = 1.99, $p = 0.052$). As the anchors for this item were reversed, this result indicates that the Odour condition resulted in a significantly higher sense of presence.

'How much did your experience in the virtual environment seem consistent with your real world experience?' Responses to this question were significantly higher for the Odour condition. (No-Odour mean = 3.65, Odour mean = 4.50, Z = 2.29, $p = 0.027$).

'How real did the virtual world seem to you?' A significant difference between the Odour and No-Odour condition was observed. Responses for the odour condition were significantly higher (No-Odour mean = 3.50, Odour mean = 4.05, Z = 2.12, $p = 0.039$).

item['The virtual world seemed more realistic than the real world.'] No significant difference was found between the No-Odour and the Odour condition (No-Odour mean = 1.25, SD = 0.43, Odour mean = 1.50, SD = 0.59, Z = 1.43, $p = 0.232$).

8.5.3.2 Jennet et al. Presence Questionnaire

In this section I present the results of the JPQ. The scores from the JPQ were analysed with the same methods as the IPQ as described in Section 8.5.3.1 and therefore followed the statistical analysis as detailed in 8.13.

To determine if the responses to any of the questionnaire items showed signs of an ordering effect, I compared the scores of the No-Odour conditions of the two groups using Mann-Whitney U-Tests for Independent Samples. The results of this analysis can be found in Table

JPQ Questionnaire Item	**Condition**	**Group**	**Mean Score**	***p***
To what extent did you feel you were emotionally attached the game?	No-Odour	NO-O	4.80	0.063
		O-NO	3.80	
	Odour	NO-O	5.20	0.436
		O-NO	4.80	
Were there any times during the game in which you just wanted to give up?	No-Odour	NO-O	2.90	0.739
		O-NO	3.30	
	Odour	NO-O	2.30	0.393
		O-NO	2.80	
At any point did you find yourself become so involved that you were unaware you were even using controls?	No-Odour	NO-O	3.70	0.529
		O-NO	3.40	
	Odour	NO-O	4.80	0.436
		O-NO	3.80	
To what extent were you aware of yourself in your surroundings?	No-Odour	NO-O	5.10	0.353
		O-NO	4.50	
	Odour	NO-O	4.10	0.631
		O-NO	3.80	
To what extent did you feel you were focused on the game?	No-Odour	NO-O	4.70	0.853
		O-NO	4.70	
	Odour	NO-O	6.10	0.853
		O-NO	6.10	

Table 8.15: Results of Mann-Whitney U-Tests for Independent Samples on Jennet et al. Presence Questionnaire items comparing the scores of the participants groups for both conditions. Emphasised text indicates significant difference between mean scores.

8.15. This was followed by a comparison of the Odour conditions of the two groups using a Mann-Whitney U-Tests for Independent Samples. The results of this analysis can also be found in Table 8.14. The results in the table show that there were no significant differences for any of the questionnaire items between the scores of the No-Odour condition, nor between the scores of the Odour condition. Figure 8.10 gives an overview of the mean differences between each of the groups for all questions from the JPQ. The detailed results and statistics for each question are now discussed in detail.

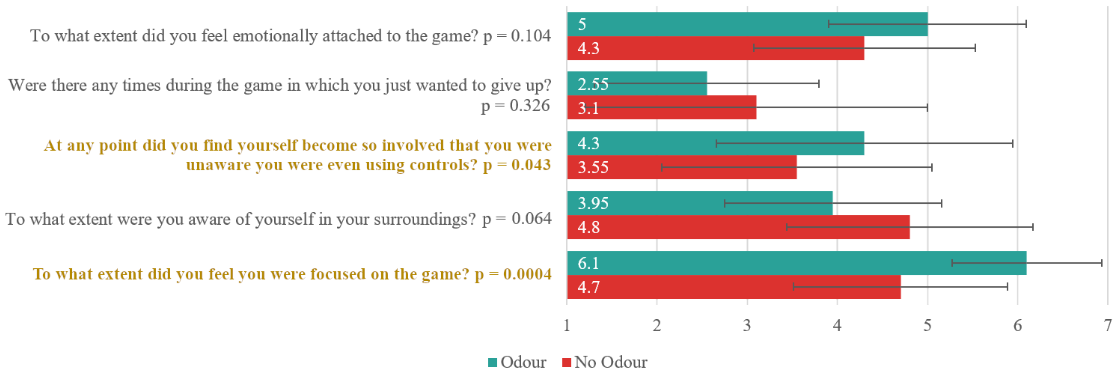


Figure 8.10: A comparison of the mean responses to the Jennet et al. Presence Questionnaire in the odour and non-odour conditions. Emphasised text indicates significant difference between mean scores.

To determine whether the olfactory notifications significantly affected the responses of the JPQ, I then conducted a Wilcoxon Signed Rank tests on the scores of the Odour condition (combined scores of the first run of the O-NO group and the second run of the NO-O group) against the scores of the No-Odour condition (combined scores of the second run of the O-NO group and the first run of the NO-O group). The results for each of the questionnaire items can be found below under the respective headings below.

'To what extent did you feel emotionally attached to the game?' No significant difference was found between the No-Odour and the Odour condition (No-Odour mean = 4.30, SD = 1.23, Odour mean = 5.00, SD = 1.10, Z = 1.66, $p = 0.105$).

'Were there any times during the game in which you just wanted to give up?' No significant difference was found between the No-Odour and the Odour condition (No-Odour mean = 3.10, SD = 1.89, Odour mean = 2.55, SD = 1.24, Z = 1.02, $p = 0.326$).

'At any point did you find yourself become so involved that you were unaware you were even using controls?' Responses to this question were significantly higher for the Odour condition (No-Odour mean = 3.55, Odour mean = 4.30, Z = 2.04, $p = 0.043$).

'To what extent were you aware of yourself in your surroundings?' No significant difference was found between the No-Odour and the Odour condition (No-Odour mean = 4.80, Odour mean = 3.95, Z = 1.95, $p = 0.064$).

'To what extent did you feel you were focused on the game?' Responses to this question were significantly higher for the Odour condition. (No-Odour mean = 4.70, Odour mean =

6.10, Z = 3.25, $p = 0.0004$).

8.5.4 Qualitative Results

In this study, noting down observations and unsolicited comments by the experimenter was impeded by the demanding and continuous task of triggering the OD whenever a flower came into participants' field of view, and when the visual chalk hands notification was displayed on their virtual hands. As the sessions were not recorded, only a limited number of observations and comments could be noted down.

Qualitative results were recorded in terms of unsolicited comments that participants made regarding the use of the odours in the VE, as well as in terms of observations that were made regarding the use of the olfactory notifications while in the VE.

All 20 participants, upon receiving the flower in vicinity notification paused climbing to look for any flowers in their vicinity. One participant (O-NO6, Male, 27 years old), was adept at climbing very quickly and was able to climb at high speeds. When receiving the flower notification, the participant would react by stopping and looking around in the environment, but because he had been climbing so fast, the flowers had sometimes already left his field of view (the exact number of times that this happened was not recorded). This seemed to confuse the participant, who on two occasions started to backtrack his path to find the flowers that had been the source of the notifications, but was unable to find the flowers and gave up shortly. The exact times of how long the participant spent backtracking was not recorded, but this appeared to have been around 5 to 10 seconds each time. In an informal conversation after the participant had completed the final PGQ, the participant stated: "I realised that the smell was coming from a flower but I couldn't find it.", adding "I really just wanted to get to the end of the level and didn't want to spend a lot of time finding those flowers. I still found a lot of flowers on the path.".

Participant NO-O3 stated: "The flower smell was easy to understand because it was kind of natural but I had to think a couple of times what the other smell meant. After a couple of times I remembered it.".

8.6 Discussion

Study Four investigated the use of odours as notifications in virtual reality. The results showed that congruent pleasant odours were effective as notifications and resulted in increased task performance, in terms of the number of flowers participants interacted with, the number of times they chalked their hands, the number of savepoints participants were able to reach, and the number of times they fell in the VE.

There were two types of olfactory notifications in the VE. The first was as a unimodal notification, which was only delivered via olfactory stimulation (a lavender odour), which alerted participants that a flower was in their vicinity, which was relevant to participants as they were told to interact with as many flowers as possible by touching them. The second was as a multimodal notification, delivered through both visual and olfactory cues. For this multimodal notification, the smell of cinnamon was used to represent chalk, and this was delivered together with a visual notification on a person's virtual wrist prompting participants to chalk their hands (the visual component of the multimodal notification can be seen in Figure 5.6). Both the flower notification and the chalk hands notification were effective and resulted in a change of behaviour that increased task performance, indicating that the olfactory notifications were noticed, correctly identified and understood by the users.

In this section, I will now discuss in more details the results in regards to RQ_3 of this PhD thesis: *Are olfactory notifications effective in virtual reality?*, and the three hypotheses of this study:

H_1: *Participants can understand olfactory notifications.* (Section 8.6.1).

H_2: *Olfactory notifications increase performance in virtual reality.* (Section 8.6.2).

H_3: *Congruent pleasant odours when delivered as notifications increase the sense of presence in virtual reality.* (Section 8.6.3).

8.6.1 H_1: Participants Can Understand Olfactory Notifications.

The results of Study Four showed that participants were able to understand olfactory notifications. QoE related results (see Section 8.5.1), which were collected for both the lavender essential oil odour, which was used for the flower notification, and for the cinnamon essential oil odour, which was used for the chalk hands notification, showed that both odours were perceived as neither annoying, nor distracting, that they heightened participants' sense of reality in the VE, and that they made the participants feel more present in the virtual world. Importantly in regard do H_1, participants reported that both of the odours made them change their behaviour (QoE questionnaire item 7) and that they were effective at indicating the different types of events (that there is a flower in the vicinity / that chalk levels are low) (QoE questionnaire item 8), indicating that participants did indeed understand the olfactory notifications.

This could also be observed during the experimental sessions where participants would often pause climbing to look for any flowers in their vicinity, when they perceived the lavender odour.

One reason why participants were able to understand the notifications may have been that both odours were also given a high congruence rating with the notification that they represent. This is perhaps unsurprising for the lavender odour, which has a direct semantic relationship with the notification (There's a flower in your vicinity) and therefore very little processing of the odour is necessary to understand what the notification means. In the case of the chalk notification, there is no direct semantic relationship between the odour and the notification, given that chalk is both devoid of both colour (white) and devoid of strong odour. It is therefore likely that participants took into consideration further properties such as the shape or texture of chalk, properties which have also been shown to influence the perception of congruence (Hanson-Vaux et al., 2013; Spence and Ngo, 2012). Perhaps the dry or dusty texture of chalk, which is somewhat similar to cinnamon powder, was perceived as congruent. The precise reasons for the perceived congruence of the cinnamon odour and the chalk hands notification however remain unknown and further research will need to determine which factors influence perceived congruence.

Performance scores provided supplementary information that supports the claim of H_1. Participants interacted with significantly more flowers when they were exposed to odours, compared to when they were not. Similarly, participants chalked their hands significantly more often during their first run, when they received olfactory notifications. Further performance related results are discussed in detail in Section 8.6.2.

8.6.2 H_2: Olfactory Notifications Increase Performance in Virtual Reality.

As in Studies Three and Four, objective metrics were collected about participant performance. These metrics included the number of flowers a participant interacted with, the number of times a participant chalked their hands, the number of falls, and the number of savepoints that were reached (the latter two of which are related to how regularly participants chalk their hands). These performance related results were able to show that olfactory notifications could significantly increase performance of the VE.

First and foremost, participants interacted with significantly more flowers when they received the flower notification. As indicated by the QoE results (see Section 8.5.1), participants had no issues understanding the flower notification. While the flower notification was understood by all participants, the timing of when the flower notification was displayed, was key to its effectiveness. One participant became adept at climbing very quickly and was able to navigate the environment at high speeds. In some instances, this meant that the flower notification was noticed too late as the participant had already climbed past the flower and was not able to find the flower as it was no longer in the immediate field of view. In unsolicited comments after the experimental session the participant stated that he had realised that the source of the lavender odour was flowers in his vicinity but that finding the flowers was difficult as he did not want to travel backwards to interact with the flower and preferred to climb towards the end of the level. The use of a *smell space* as suggested by Huang et al. (2012b)(see Section 3.4.2) could have allowed for a better timing of notifications, making them appropriate for faster climbers. Huang et al. (2012b) determine the timing of odour delivery using the speed at which a virtual object moves towards a user and the time it takes for odours to be perceived by the user after delivery. This in essence creates an odour bubble or *smell space* around the virtual object in which odours are displayed, and which grows and shrinks with the speed of the user. However, Huang et al. (2012b)'s implementation is based on desktop environments in which the user's position is static in relation to the virtual world and the implementation would have to be adapted to be applicable for a VE.

While the effects of the flower notification were easily observable via higher flower interaction scores, the effects of the chalk hands notification were more complex. While participants chalked their hands significantly more often in the first run when they received olfactory notifications compared to when they did not, this was not the case for the second run, where there was no significant difference between the Odour and the No-Odour condition. This is an interesting effect and appears counter-intuitive as one would expect participants to chalk their hands more often when they received the olfactory notification reminding them to do so. Looking at the results in Table 8.10 shows that the first run of the O-NO group chalked their hands the highest number of times out of all runs (mean = 16.80). This is four times as often as the first run of the NO-O group (mean = 4.20), indicating that the participants of the O-NO group clearly noticed the chalk hands notification and changed their behaviour accordingly, increasing task performance. When comparing the second runs of the groups, the difference however is far less pronounced and not significant (NO-O second run chalk mean = 14.90, O-NO second run chalk mean = 12.40), however importantly, both scores are very high when compared to run 1 of the No-Odour condition. To understand the reason for these results it is necessary to examine how chalking affects participants' performance in the game.

The in-game chalking notification, which is displayed visually on the player's virtual wrists by displaying the text 'Re-Chalk' (see Figure 5.6), is visible when the player's chalk levels fall below a certain threshold while climbing. Chalk levels control how long one can hold on to the wall with only one hand without falling. It is possible to continue climbing even when chalk levels have been completely depleted, but one needs to be very quick to be able to grab on to the next hold with one hand before the stamina on the other hand depletes and one therefore falls. The chalking notification is especially important when learning the game as players do not yet understand how quickly chalk depletes and need to be reminded to re-chalk, while they learn how to use the controls of the game and begin to understand how to navigate the virtual world efficiently without falling. The notification becomes less useful as players become better at climbing, which is when they have learned to judge when to chalk their hands, based on their previous experiences. However, as the attention of novice players is nearly entirely focused on understanding the climbing controls and navigating through the level, a notification to chalk ones' hands is very important. However, as the visual notification is placed on the wrists of the players, and player attention is generally on the available holds on the walls, or where to place one's hand next (and not on their hands or wrists), as would be the case in a real-world climbing scenario, the visual notification to chalking hands is rarely noticed by novice players. This also explains the very low chalking rates for the first run of the NO-O group, where participants only chalked a mean 4.20 times. Comparing this result to the mean 16.80 times that participants of the first run of the O-NO group chalked their hands reveals that the olfactory notification was very successful in drawing attention to the task of chalking one's hands. This is an interesting result when revisiting the available literature on olfactory notifications, which has been divided on the view of whether olfaction is an effective notification modality (Arroyo et al., 2002; Bodnar et al., 2004) see Section 3.4.6. These contradicting results suggest that the effectiveness of olfactory notifications is application specific and can outperform visual notifications depending on the scenario.

Why then, did participants during the second run not chalk their hands more often when they received the olfactory notification compared to when they did not? First of all, it must be noted that participants chalked their hands significantly more often when they were in the second run of the O-NO group (mean 12.40) compared to the first run of the NO-O group (mean 4.20), which were both in the No-Odour condition, showing that participants in the NO-Odour condition of the O-NO group chalked unusually often, rather in line with what was observed for the Odour condition (NO-O Odour condition mean = 14.90, O-NO Odour condition mean = 16.80). It is possible that because the second run of the O-NO group followed the Odour condition, that participants were more aware of the importance of chalking due to the olfactory chalk hands notification during their first run, and therefore chalked their hands mote often than had they not received the olfactory chalk hands notification at all.

The number of savepoints reached as well as the number of falls mirror those of the number of times participants chalked their hands. This is not surprising as both falling and progressing further in the level (indicated by the number of savepoints reached) are directly related to successfully and repeatedly chalking one's hands. A player who is more aware of the need to chalk one's hands will fall less often and will therefore be able to progress further in the level in a shorter amount of time.

8.6.3 H_3: Congruent Pleasant Odours When Delivered as Notifications Increase the Sense of Presence in Virtual Reality.

The results from the IPQ and JPQ showed that the participants reported a significantly higher sense of presence when they received olfactory notifications.

Foremost, the combined presence scores of the IPQ were significantly higher when participants were exposed to odours (No-Odour mean = 60.40, Odour mean = 67.40). This finding was supported by the result of the general indicator for the sense of presence (item 1 IPQ) which showed that the 'sense of "being there"' was significantly higher in the Odour condition. It was further supported by the responses to the statement that 'I felt present in the virtual space', which were also significantly higher for the Odour condition, indicating that the olfactory notifications increased the sense of presence in VR. This finding is supported by the individual questionnaire items of the IPQ and JPQ, which give better understanding of the finer-grained effects of the olfactory notifications.

The IPQ item 8: 'I was not aware of my real environment' showed some of the lowest mean scores (No-Odour 3.45, Odour 3.25), and participants actually reported a lower score in the Odour condition compared to the No-Odour condition (though not significantly). A possible explanation may be that the question was asked in the form of a double negative, as the anchors were given as '1 - fully disagree' and '7 fully agree', which may have confused participants. It would seem advisable to rephrase the statement as a positive: 'I was aware of my real environment' and to reverse the anchors, as was done with items 3, 9, and 11. In regard to item 11 however, which read 'How real did the virtual world seem to you' with anchors '1 - completely real' and '7 - not real at all', the reasons for the reversal of the anchors are not clear. As noted previously in Section 8.4.2, the question 'How real did the virtual world seem to you?' was used both for items 11 and 13 of the IPQ, however with different anchors. The responses to item 13, which used the (non-reversed) anchors of '1 - about as real as an imagined world' and '7 - indistinguishable from the real world' were significantly higher for the odour condition, while responses to the reversed item 11 were not significantly different between the groups. It is not clear whether this difference was due to the different concepts of presence that the anchors aimed to elucidate, or simply due to the fact that item 11 uses reversed anchors in a questionnaire that predominantly rated a low agreement to a statement or response to a question with a 1 (the left endpoint of the scale) and a high agreement or response with a 7 (the right endpoint of the scale).

Further questionnaire items showed that participants felt a significantly higher sense of presence. For example, the fact that participants stated that their experience in the VE seemed more consistent with their real world experience (IPQ item 12) when they perceived odours, once again, when put in relation with the overall sense of presence score, support the claim that a consistent set of sensory is necessary for a high degree of perceived presence (Steuer, 1992).

Results from the JPQ (see Section 8.5.3.2) showed that participants felt that they were significantly more focused on the game (JPQ item 5) when they were in the Odour condition. Focus, as stated previously in this thesis (Section 3.4.4.1), and in relevant research (Fontaine, 1992; Slater, Lotto, et al., 2009; Witmer and Singer, 1998), has been directly related to the sense of presence in VR, supporting the findings of the IPQ. Participants also reported that they became so involved that they felt significantly less aware that they were using controls (JPQ item 3) when they were exposed to odours. This is perhaps a supporting result for the chalk hands notification, which drew attention to the fact that participants should chalk their hands to be able to continue climbing without falling. In combination with the visual chalk hands notification displayed on participants' virtual hands (see Figure 5.6), the olfactory chalk hands notification enabled participants to focus on the climbing, being less distracted by interruptions from falling.

Overall, these results showed that olfactory notifications had a significant effect on the sense of presence in the VE *The Climb*. Given that this shows that odours could affect the sense of presence in the VE and that the display of olfactory notifications increased the perceived sense of presence, it would seem appropriate to consider the display of odours as an immersive factor of a VE (see Section 3.4.4.1). While the number of sensory modalities that are incorporated in a VE have been considered as part of its quantifiable immersivity, there has been little supporting evidence in terms of the inclusion of olfactory stimuli, with previous research demonstrating only that unpleasant odours affect the sense of presence, as shown by Baus and Bouchard (2017). The results of Study Four in regard to the effect of olfactory notifications on the sense of presence however give further empirical evidence that olfaction is indeed an immersive factor of a VE.

8.6.4 RQ$_3$ and General Discussion

Both the performance related and QoE results shed new light on prior research on olfactory notifications in VR, which had produced mixed results about their effectiveness, and showed that olfactory notifications could be very effective (Arroyo et al., 2002) and not effective at all (Bodnar et al., 2004) of notifying users of an event. The results from Study Four demonstrate that olfactory notifications can be very effective in terms of being noticeable and informing participants of important events which lead them to change their behaviour in comparison to when they do not receive the notifications. Furthermore the notifications did not disrupt participants' from their main activity of climbing. Overall, the results from Study Four provide evidence for each of the hypotheses, that participants can understand olfactory notifications (H$_1$), that olfactory notifications increase performance in virtual reality (H$_2$), and that congruent pleasant odours when delivered as notifications increase the sense of presence in virtual reality (H$_3$), and thereby give an indication of how olfactory notifications can be used effectively in VR. Furthermore, this study as well as my two previous studies on object-odour congruence in VR have demonstrated a method with which odours can be selected successfully for their congruence with both objects, as well as notifications in VR, which will be useful for future research into olfaction in virtual reality.

8.7 Conclusions

This study set out to answer RQ$_3$ of this PhD thesis: *Are olfactory notifications effective in virtual reality?*. To do so, three hypothesis were tested:

H$_1$: *Participants can understand olfactory notifications.*

H$_2$: *Olfactory notifications increase performance in virtual reality.*

H_3: *Congruent pleasant odours when delivered as notifications increase the sense of presence in virtual reality.*

The results from the data collected during the main part of this study were not able to disprove these hypotheses, thereby demonstrating how olfactory notifications can be used effectively in VR.

Two types of olfactory notifications were developed for the VR mountain-climbing game *The Climb*, which was also used in Study One and Two. The first was to notify participants of a flower in their vicinity, the second was to notify participants to chalk their hands, an essential game-mechanic for successful climbing. In a odour selection task based on the method from Study One and Study Two, two odours were selected that were perceived as congruent with the notifications. Participants showed a preference for a lavender essential oil to represent the flower notification and chose a cinnamon essential oil to represent the chalk hands notification.

The two notifications were used in the main part of the study, where participants were given the task to interact with as many flowers as possible while climbing as far as possible through the VE. The results showed that participant task performance was significantly higher when they received olfactory notifications, measured in terms of the number of purple flowers participants interacted with, the number of times they chalked their hands, the number of falls, and the number of checkpoints reached. In the case of the number of times that participant chalked their hands, the olfactory notifications brought on a learning effect, as participants became more aware of the importance of the chalking mechanic, which resulted in increased chalking in the No-Odour condition, when this followed the Odour condition.

QoE results showed that participants understood the olfactory notifications. Participants stated that they changed their behaviour due to the olfactory notifications and that these were effective at indicating that a flower was in the vicinity and that hands should be chalked.

The results further showed that the sense of presence was significantly increased when participants received olfactory notifications. This was both in terms of evidence provided by individual questionnaire items, where scores were significantly higher in the Odour condition compared to the No-Odour condition, e.g. item 1 - 'In the computer generated world I had a sense of 'being there'.', item 6 - 'I felt present in the virtual space.', and item 10 - 'I was completely captivated by the virtual world.', as well as the overall combined presence score of the IPQ.

The contributions from this study therefore are:

1. To demonstrate that odours are effective as VR notifications i.e. change participants' behaviour, and do not divert attention from the main task.
2. To provide further evidence for the effectiveness of the novel odour selection method that was developed as part of this thesis (see Section 5.5).
3. To provide supporting evidence for the successful use of the novel OD which was developed as part of this thesis (see Section 5.4.1).

Chapter 9

Discussion

9.1 Summary of the Research

The main driver behind this doctoral project was the existing knowledge gap regarding the use of olfaction as a sensory modality in VR and a broader interest in the use of olfaction in HCI. The opportunities were defined and discussed in Chapters 1 and 3 with regard to related work in the respective fields. To bridge this gap, I examined the perception of odours and how they may affect our behaviour and sense of presence in a VE to enhance user experience in VR. I address this by developing a method for odour selection that is suitable for research studies in HCI, by developing a novel OD for VEs, and by providing further empirical findings that may inform future work with the olfactory sense in an HCI setting. These include confirmation that odours can impact emotional perception, the sense of presence as well as QoE, and that they can improve task performance and facilitate quicker learning in VR.

This PhD research has contributed to the knowledge of how olfaction can affect user experiences in VR. To do so, it investigated three research objectives, reported in Section 1.1, in four empirical studies. The individual contributions are summarised below with regard to the overall research objectives.

$\mathbf{OBJ_1}$ To develop and test a method for odour selection.

1. A contribution of this thesis is the development of a method for odour selection for HCI studies. This is the first systematic method for odour selection in HCI and takes into consideration the basic factors of odour perception, such as, valence, intensity, and familiarity, to ensure consistency and reproducibility of the odours.

OBJ_2 To develop an olfactory display for VEs.

1. Currently, commercially available ODs for VR systems are both expensive and limited in their delivery of odours. The developed system tackles current shortcomings and is based on an off-the shelf piezoelectric atomizer. The atomizer can vaporise liquid based odorants in minute quantities; <0.01 ml of odorant is vaporised in a single puff. This mostly prevents the odours from lingering in the environment. The OD delivers odorants directly to a person's nose, even with swift head-motions. The OD costs less than £20, reducing the cost barrier and providing an easy solution to add odours to any headset-based VR system.

OBJ_3 To investigate how olfaction can affect the user experience in VR.

1. **Congruent pleasant odours increase a sense of presence in VR:**
   One of the main contributions of this thesis is novel empirical evidence which adds support to the argument that congruent pleasant odours can increase the sense of presence in VR. The addition of odours to VR should potentially enhance the sense of presence by increasing the spectrum of sensory stimulation, thereby providing a more realistic experience that is more consistent with our real-world experiences. In three studies that examine the congruence of odours and VR content, the results indicate that congruent, pleasant odours appear to increase the sense of presence in VR. and that incongruent pleasant odours do not affect the sense of presence in VR. The contributions are thus additional empirical evidence that:
   (a) Incongruent pleasant odours do not increase presence in VR.
   (b) Congruent pleasant odours do increase presence in VR.

2. **Pleasant odours can increase interactions with virtual objects:**
   In my studies, pleasant odours emitted by virtual objects can increase interaction with the object, regardless of congruence with the object. If virtual objects are associated with the release of pleasant odours, then participants interact with them significantly more than they do with non-odour emitting virtual objects. In two empirical studies, participants were given the task to find as many flowers as possible in a game based VE and to touch them to gain points. In one condition, the virtual flowers released an odour upon being touched. The results of these studies show

that when the flowers emitted an odour, regardless of if this odour was perceived as congruent or incongruent with the flower, participants interacted with the flowers significantly more often compared to when the flowers did not release an odour.

3. **Odours can be effective VR notifications:**
Odour perception mostly occurs on a subconscious level, meaning that we do not have to shift our attention to process the perception of an odour. A further contribution of the thesis is the finding that odours can be effective as VR notification tools and do not divert attention from the main task. In Study Three I demonstrate that odours can be used as notifications in two ways. First, as a direct notification - users were notified of the presence of an object in their vicinity. Second, to reinforce a primary notification delivered in a different sensory modality - to reinforce a visual notification on a person's virtual wrist that they had to perform a certain sequence of movements. Both types of olfactory notifications were effective and resulted in a change of behaviour that increased task performance, indicating that the odour notifications were noticed, correctly identified and understood by the users.

4. **Odours can affect the emotional perception of digital images:** This thesis also makes a contribution of knowledge about the effect of odours on emotional responses, namely that they appear capable of altering them. Odours have the ability to affect a person's emotions, for example, to change a person's judgement of the attractiveness of human faces (Dematte et al., 2007). In a study on the effects of valence of odour on the emotional perception of digital images, I demonstrate that negative odours affect a person's perception of an image, changing how they rate the valence and arousal of the images.

In this final chapter I will discuss in more detail the results of my project with direct reference to the research questions it set out to address. I will then discuss the limitations of the presented work and finally give directions for future research for the use of olfaction as a sensory modality in HCI, based on the conducted work.

9.2 Discussion of the Research Questions

In this section I discuss the results of Studies One, Two, Three, and Four in light of the main research questions that I had set to answer as part of this PhD thesis. The section begins with

9.2.1 Overarching Research Question

RQ_0 *In what ways can odours be used to enhance user experience in VR?*

The main research question of this PhD project was based on bridging prior knowledge from the field of psychology (see Section 3.2) and HCI (see Section 3.4) to gain an understanding of how olfactory perception could be used in a VR setting to enhance user experience. Existing psychology-based research showed that olfaction could be used to affect human behaviour, for example through its close relation to memories, which are often directly associated with an odour, and emotions (see Section 3.3). While the field of HCI has made attempts to make use of these properties, researchers have struggled with issues mainly relating to odour display and lack of odour selection methodology (Section 3.4 and 3.5), omitting to take into consideration the basic dimensions of odour perception (see Section 3.3.1).

Due to such lack of odour selection methodology and in order to answer RQ_0, it first became necessary to develop such a method, to ensure that the selected odours were perceived with the desired properties by participants. Second, it was necessary to develop an OD for VR HMDs as these currently do not exist and prior ODs for VR suffer from a range of undesirable properties (see Section 3.5) that make them unfit for purpose. A new type of OD that used an ultrasonic atomiser to disperse odours was tested in Study One, to determine if this type of technology would show advantages over existing ODs. The results showed that the OD produced odours that did not linger and which were noticed by participants in a short amount of time, overcoming certain limitations present with previous ODs (see Section 4.9). However, the OD suffered from several issues, such as clogging up when used with viscous odorants, difficulties in refilling the device with a new odorant, and by being only compatible with mobile devices (see Section 4.10). To tackle these limitations, a new OD was developed, which targeted these flaws, and which was subsequently used for studies Two, Three and Four (see Section 5.4).

To determine whether odours could enhance user experience in VR, RQ_0 was broken down into three main research questions, each addressing a separate research gap in the field of HCI, relating to the use of olfaction (see Section 3.6). The research questions were:

$RQ_{exploratory}$ *Do odours affect the emotional perception of digital images?*

RQ_1 *How does congruence of odour affect presence in virtual reality?*

RQ_2 *How do odours affect task performance in virtual reality?*

RQ_3 *Are olfactory notifications effective in virtual reality?*

9.2.2 Exploratory Research Question

Do odours affect the emotional perception of digital images?

This research question was addressed in Study One (Chapter 4), which examined how a set of 5 odours of different valences affected the emotional perception of 12 images of different valences. This study found that odours caused a significant change in participant's emotional perception of the images and this change was related to congruence in terms of synaesthetic correspondences between the valences of odours and images. If both image and odour were perceived with a positive valence, i.e. pleasant, they were considered congruent. Emotional responses were captured using the activation evaluation wheel (see Section 4.3) and were translated to numerical valence and arousal values according to literature (see Section 4.4).

The results showed that odours were able to significantly affect the emotional perception of the images both in terms of valence and arousal. Different effects were observed depending on the congruence of image and odour valence. Overall odours were able to shift valence responses in the direction of their associated valence. Positive valence odours were able to shift responses towards a positive score, while negative valence odours shifted responses towards a negative score. When examining absolute changes, incongruent odours produced a greater change than the congruent odours. This was perhaps due to the surprising nature of the contradicting valences of the odours and images, however the exact reasons remain unknown and future research will have to determine why this was the case, as there were exceptions to the norm.

As opposed to the results with positive odours and images, negative odours produced more varied responses from the participants. It is possible that the negative odours were perceived quite differently and that this was an issue of odour selection. For example, throughout the experiment it was observed that the faecal odour triggered a concomitant avoidance response as is the case with odours that irritate the trigeminal nerve. There are two possible conclusions to draw from this observation. First of all, that odours which trigger the trigeminal nerve may be perceived completely differently from odours that do not do so. Second, it is possible that another of the selected negative odours was simply not perceived as very unpleasant by participants, or that they simply did not notice it due to a lack of intensity. In either case, it would be necessary to have a more systematic odour selection process, to prevent these uncertainties in future research. Such a methodology can be found in Section 5.5 and was used in the subsequent studies.

Arousal responses were not as clear cut as valence responses, possibly due to the selection methodology, which was primarily focused on valence, rather than arousal. However, both positive and negative valence odours were able to affect arousal responses significantly. When negative odours significantly affected responses, this usually resulted in a decrease of arousal, while positive odours conversely showed an increase in arousal responses. While this kind of shift may be expected in terms of valence responses (an unpleasant odour causes an image to be perceived with a more negative valence), there should not be a direct connection between negative valence odours and negative arousal responses.

It is possible that these trends are due to the emotion descriptors of the activation-evaluation wheel (see Figure 4.2). For example, a faecal odour in combination with any of the images may have produced a response of 'disgust' (arousal of -1) rather than a reduction of 'joy'. Similarly, the odour of oranges may have caused 'surprise' rather than a reduction of 'sadness' when viewing the image of a person lying in trash. This is perhaps also a critique of the use of the activation-evaluation wheel in HCI studies. The interpretation of the results is subject to a degree of uncertainty as the intent behind emotion responses are not always clear. For example, when a participant gives a response of 'anger', one cannot always tell which stimulus they are responding to. Does the participant feel anger at the content of the image as modulated by the odour, at the semantic incongruence between image and odour, or does the participant simply not like the smell. However, while it is possible that participants mis-attributed their responses to the incorrect sensory stimuli (Spence, Obrist, et al., 2017), this may not be important, as the fact remains that the experience altogether was affected by the odours and that odours were able to affect the participant's emotional perception. Synaesthetic congruence in terms of valence played an important part in determining the magnitude of the degree to which odours were able to affect responses, with incongruent combinations producing a greater change than congruent combinations. While this provided a response to $RQ_{exploratory}$ by confirming that odours could alter emotional responses to digital images, Study One brought forth several other significant if not more important results worth mentioning in relation to odour selection and the OD.

Such as insights for the use of a novel OD technology as well as for an odour selection methodology, as the results showed that the act of displaying odours may have affected the emotional perception of images. Several shortcomings with regard to the OD were identified as discussed in 4.9 that led to a less than desirable performance. These included a restriction to the use of low-viscosity odorants only, difficulties in refilling the device with new odorant, and a restriction to use with *Apple* hand-held devices running *iOS*. However, despite these shortcomings, the underlying technology, based on a piezoelectric atomiser, which is responsible for dispersing the odours, proved to be useful in several areas and was able to overcome issues of existing systems, such as by preventing odours from lingering in the vicinity. These properties make the technology very attractive to the use in olfaction-based research. I therefore used a similar OD for my remaining studies, also based on a piezoelectric atomiser, but with a removable odorant reservoir and more robust motor, which also worked with more viscous liquids.

Finally, insights were gained into the selection of odours. A large number of studies that examined olfaction as a sensory modality in HCI encountered issues with their selected odours, which in large part was due to a lack of systematic odour selection methodology (e.g. Baus and Bouchard, 2017; Bodnar et al., 2004; Brewster et al., 2006; J. N. Kaye, 2001, see Section 3.4 for a complete review). Issues included unpleasant mixing of odours, varying and changing intensities, and unforeseen associations between odours and memories. Several of these issues were also encountered in response to $RQ_{exploratory}$. First of all, odour intensity may have played a large role in the differences observed between the two negative valence odours. Second, semantic congruence of odours and images was not taken into consideration. It is therefore possible that participants drew semantic connections between certain odours and images that affected their responses. Third, unexpected interactions may have occurred due to prior experiences with the odours and associated memories. It is clear that individual differences can have a significant impact on the perception of an odour as well as the effects of said odour on a user's experience. The effect of memories linked to odours on user experience can pose a considerable difficulty in olfactory research in HCI and while their effects have been noted anecdotally (e.g. Bodnar et al., 2004; Ranasinghe, Eason Wai Tung, et al., 2018), in terms of odour selection they have been overlooked. However, the practicability of controlling for odours that do not invoke memories is questionable, as virtually all odours may form odour memories, considering the physiology of olfaction and how closely tied olfaction and memory centres are on a neurological level (Herz and Engen, 1996). It seems more reasonable to be aware and to keep in mind the individual variability of participants and to supplement empirical research with qualitative data gathering, such as by questioning participants about their past exposures to an odour and associated memories.

From the results that were collected as part of $RQ_{exploratory}$, it is difficult to make blanket claims concerning the general effect of odours on a user's experience. While odours were able to affect the emotional perception of some images, responses to others were not affected and the precise reasons for these differences are not easily apparent. While congruence of valence played a role in the effect, the results led to further questions, first and foremost how semantic congruence between olfactory stimuli and other sensory modalities affects user experience, which was explored through research questions RQ_1, in studies Two, Three, and Four.

9.2.3 Research Question 1

How does congruence of odour affect presence in virtual reality?

The perceived congruence between odour and secondary sensory stimulus was identified as a promising area of research from a HCI perspective. Prior work in the field of psychology demonstrated that olfaction exhibits strong crossmodal correspondences with other sensory modalities and that this could be used to affect participants' perception and behaviours (see Section 3.3.2). These crossmodal correspondences have been shown to occur on the basis of both semantic congruence as well as synaesthetic congruence (see Section 3.4.3). From an HCI perspective, congruence in relation to olfaction has been largely under-explored. Many, but not all, studies used olfactory cues that were both semantically and synaesthetically unrelated with the study setup or a given task, and rarely gave a rationale for the selected odours. One of the main aspects that can affect the perception of presence in VR is the vividness of sensory information and with this, a consistency of information displayed across sensory modalities. It is therefore likely that olfactory congruence can play an important role in terms of defining if a person perceives a sense of presence in VR or not.

As congruence is defined both in terms of a synaesthetic and semantic relationship of sensory modalities, RQ_1 was split into two sub-research question:

RQ_{1a} *How do pleasant, congruent odours affect perceived presence in virtual reality?*

RQ_{1b} *How do pleasant, incongruent odours affect perceived presence in virtual reality?*

9.2.3.1 Research Question 1a

How do pleasant, congruent odours affect perceived presence in virtual reality?

Results from Studies Two and Four addressed RQ_{1a}. Both studies examined the effect of pleasant, semantically congruent odours on the degree of perceived presence in the VR game

The Climb. The results showed that the odours were able to significantly increase perceived presence in VR.

Study Two introduced a novel method for odour selection, which was developed based on the results of Study One, while taking into consideration insights from prior research involving olfaction in HCI as well as the basic properties of odour perception and is described in Section 5.5. Odour selection poses an ongoing challenge in olfaction-related research in HCI, and has been a concern for nearly two decades (J. N. Kaye, 2001). Researchers to date have encountered issues associated with odour intensity (with low intensity causing low detection rates as well as high intensity causing odours to be perceived as unpleasant (Baus and Bouchard, 2017)), associated with odours that were difficult to differentiate (Bodnar et al., 2004), or issues associated with unwanted effects caused by individual differences in terms of previous experiences and memories associated with the odours (Arroyo et al., 2002).

The main purpose of the method was to select a set of odours, which are perceived with the intended intensity, valence, and congruence; which captures if participants are able to identify the odour, and if the odour evokes similar associations across participants. An odour selection task was conducted to select two odours which were perceived as pleasant (positive valence) with a similar intensity and which were congruent with a yellow and a purple flower (see Figure 6.1) in the virtual mountain climbing game *The Climb*. The results showed that participants were able to agree on two odours in terms of the above-mentioned variables, which were subsequently used in the main experiment of Study Two. In terms of valence, participants rated odours they identified correctly as significantly more pleasant than those that they had not smelled previously or which they were not able to identify. Participants generally had trouble naming fragrance oils, which are produced synthetically, but were able to identify them as generally floral. However, the product names given to the odours by the manufacturer did not match any of the names given by the participants, highlighting once again the difficulty of selecting odours as noted by Brewster et al. (2006) and emphasising the need for an odour selection methodology that captures participant perception of the odours, rather than relying on product names.

The selected odours were validated in the main part of Study Two by measuring how participants perceived the QoE of the VE. The results showed that the odours' qualities were perceived as intended, as participants stated that they were pleasant, congruent with the virtual flowers, relevant to what they were seeing, that they were not annoying nor distracting, and that participants could perceive them.

Results from the presence related questionnaires showed that pleasant, semantically congruent odours that were displayed by interaction with virtual flowers were able to significantly increase the degree of focus on the game, the emotional attachment to the game, and the degree to which their senses were completely engaged, when they were exposed to the odours. While the questionnaire does not give an overall presence score, all three of these items have been directly linked to the perception of presence (Fontaine, 1992; Jennett et al., 2008; Slater, Lotto, et al., 2009; Witmer and Singer, 1998). Furthermore, participants responded that the odours had heightened their sense of reality whilst experiencing the VE, another factor influencing the perception of presence (Schubert, Friedmann, et al., 1999).

There were certain factors which were not affected by the display of odours. Participants felt that odours did not affect their awareness of the controls (i.e. HMD and *Oculus Touch* controllers), did not feel more aware of their (real-world) surroundings, felt that the odours did not add to the consistency between their real-world experiences and the VE, and did not feel that that the information was less inconsistent or disconnected when exposed to the odours. However, several of these factors (consistency between real world and VE; disconnectedness of information) already showed very high responses when the VE was experienced without odours, indicating a possible ceiling effect.

The main aim of Study Four was to investigate the use of congruent pleasant odours as notifications in VR, however, presence related results were also collected to supplement those gained in studies Two and Three. Study Four used the same odour selection methodology as Study Two, to produce two odours that were perceived as congruent with two types of notifications. The odours were used in the main experiment of Study Four, where participants were given the task to collect as many flowers as possible in the VE. The results showed that the odours were able to significantly increase the sense of presence, both in terms of evidence from individual questionnaire items as well as overall presence scores.

Overall, the results from Study Two and Study Four show that pleasant congruent odours can increase the sense of presence in VR. However, these results stand in direct contrast to Baus and Bouchard's 2017 study on the effect of odour valence on perceived presence in VR. Their study showed that while unpleasant odours were able to affect the sense of presence significantly, pleasant odours had no such effect. The main differences between Baus and Bouchard's study and studies Two and Four are that Baus and Bouchard used incongruent odours (though unverified) while Studies Two and Four used odours which were perceived as congruent with the VE, demonstrating that valence alone is not a sufficient determinant for the effect of an odour on the perception of presence in a VE, and that congruence must be considered when using odours to enhance the sense of presence in VR.

In conclusion, the results from Studies Two and Four in regard to RQ_{1a} have shown that pleasant congruent odours can positively impact the user experience of a VE by increasing a variety of measures including an overall sense of presence - the defining feature of VR. While these results give an indication for the usefulness of olfaction in a VR context, previous research produced less promising results for the use of olfaction as a sensory modality in VR, drawing attention to the difficulties associated with the sense and highlighting the need for a systematic odour selection process, which was also part of this PhD project.

9.2.3.2 Research Question 1b

How do pleasant, incongruent odours affect perceived presence in virtual reality?

Results from Study Three addressed this research question and showed that odours which were perceived as incongruent with the VE did not affect perceived presence in VR. The only significant difference between when participants were or were not exposed to an odour was in response to the question 'How completely were all of your senses engaged?'. This is perhaps unsurprising as it states that participants were able to perceive the odours and were consciously aware of the fact that they had perceived an odour and therefore felt their senses were more engaged. While an increase in the perception of how completely the senses were engaged could indicate that there was an increase in presence, there was only little supporting evidence to corroborate this interpretation and hence it seems more likely that the sense of presence was not affected overall.

The only supporting evidence for an increase in perceived presence is that participants felt that the odours increased their sense of reality in the VE. This however is one of the main factors which have been shown to lead to a sense of presence (Schubert, Friedmann, et al., 1999). To understand why such contrasting results were found it was necessary to take into consideration qualitative results from observations, and unsolicited comments from participants. Participants generally felt confused about the display of the odours, and the perception of the odours varied wildly. There were several key areas where participant perception diverged. Firstly, participants were not clear in terms of the origin of the odours. While some perceived the origin from within the VE and even as originating from the flowers (as with congruent odours in Study Two), others thought that the odours came from other objects in the VE, e.g. another climber eating chocolate-chip cookies in the vicinity, or even from outside the VE e.g. one person thought thought that the experimenter might be eating cookies. In the latter case it is clear that the odours did not add to a sense of presence but rather may have even produced a break in presence by reminding participants of their real-world surroundings. For those participants who believed that the source of the odours was inside the VE, there were further differences in terms of the qualities of the odours. While some identified the odours correctly as cherry and chocolate-chip cookies, others identified the odours simply as sweet or even floral, even congruent with the flowers that triggered the odour display.

Similar to the real world, we have expectations about what objects should smell like in the virtual world. If objects do not smell as expected this can cause unexpected reactions, which may or may not be positive. In the domain of food design, where experiments were carried out to determine if congruence of colour and taste affected enjoyment of the food, for example, it was demonstrated that congruent colour/taste combinations were always perceived as pleasant, while incongruent combinations were sometimes perceived as unpleasant. Those cases in which participants enjoyed the incongruent combinations were often because participants enjoyed being surprised by the unconventional taste and colour combinations, however, overall enjoyment was still lower than for any of the congruent combinations (Velasco, Michel, et al., 2016). It appears that incongruent odours caused similar reactions from participants in Study Three, where there was confusion and surprise when they were displayed. However, some participants still felt that the odours were congruent with the VE, perhaps due to a general preference and expectation of congruence (Piqueras-Fiszman and Spence, 2012). It is further clear that incongruent odours have starkly different effects on participants and further amplify individual differences in terms of odour perception. Unless the intent is to surprise participants, based on my research it is therefore not recommendable to expose participants to incongruent odours when aiming to enhance user experience in VR.

A comparison between the results of Studies Two and Three (see Section 7.6.2) gave further insights into the differences between the effects of congruent and incongruent odours on the sense of presence and QoE. The results showed that there were significant differences both metrics. Incongruent odours made participants significantly more aware of their real-world surroundings and participants felt that the information coming from their various senses was significantly more inconsistent and disconnected than with the congruent odours, indicating that the incongruent odours were detrimental to the virtual experience and to the sense of presence in the VE, and highlighting the importance of selecting odours that are perceived as congruent with objects in the VE. This interpretation was supported by QoE results, which showed that the incongruent odours were perceived as less relevant to the VE, heightened the sense of reality significantly less than the congruent odours, and were seen as significantly more distracting and annoying than the congruent odours, demonstrating once again that the incongruent odours were detrimental to the experience of the VE. These results again highlighted the importance of selecting odours that are congruent with objects in the VE, thereby adding to an experience that is consistent across all sensory modalities.

9.2.4 Research Question 2

How do odours affect task performance in virtual reality?

Task performance was assessed as part of Study Two, Study Three and Study Four, where participants were given the task to find and interact with as many virtual flowers as possible. In studies Two and Three, task performance was recorded in terms of the number of flowers that participants interacted with while playing the VR game *The Climb*. Study Four expanded on performance related measurements and also recorded the number of falls, the number of times participants chalked their hands, and the number of savepoints participants reached.

The results from studies Two and Three showed that participants interacted with significantly more flowers when these were perceived to release an odour upon being touched. This was true for both odours that were congruent with the flowers (Study Two) and odours that were incongruent with the flowers (Study Three). It is possible that the odours acted as a form of gratification mechanism, rewarding participants for having found a flower and motivating them to continue with the task. It is also possible that the odours acted as a reminder for the primary task of interacting with the flowers, which participants did not receive when they were in the condition that did not display odours.

Results from Study Four confirm the finding that odours can improve task performance, while giving evidence for different types of tasks beyond flower interaction. In terms of flower interactions, participants performed significantly better when they were exposed to odours. This occurred both when odours were delivered during the first run and the second run and mirrors the results from studies Two and Three. These results from Study Four are perhaps less surprising, as the odour display in this study was triggered when a flower entered a participant's field of view, notifying them of a flower close-by and giving them an advantage compared to when no odours were displayed.

The results on falls, savepoints reached, and number of times participants chalked their hands, showed that the participants appeared to gain a quicker understanding of the game mechanics when they received odour notifications. In their first run, participants fell less often, reached more savepoints and chalked their hands significantly more often when compared to those participants that were not exposed to the odours. This learning effect carried over into the second run, and there were no significant differences in terms of falls, checkpoints reached, and number of times participants chalked their hands between those that received odour notifications and those that did not.

Overall the results from studies Two, Three and Four show that odours were able to significantly increase task performance in VR. This was both the case for odours that were displayed as notifications as well as for odours that were triggered by interacting with virtual objects, showing that olfaction can be a beneficial asset to enhance user experience in a VE.

9.2.5 Research Question 3

Are olfactory notifications effective in virtual reality?

Previous research, which compared odour notification to those delivered in other sensory modalities in a desktop setting, had produced contradictory results, stating that odours were both very disruptive and not disruptive at all (Arroyo et al., 2002; Bodnar et al., 2004). The reasons for this were determined as issues with odour selection, as well as issues in terms of the OD which caused odours to linger. Both odour selection and OD issues had negative effects on participant performance, who had trouble understanding the odour notifications, if they were noticed at all. The authors suggest that with improved odour selection and delivery, odour notifications could be used successfully. In a recent study Dmitrenko et al. (2017) demonstrated that participants could successfully understand odour notifications, however their effectiveness was not assessed.

Hence there were several parts to answering RQ_3. First of all, a set of notifications that were meaningful in the context of VR were determined. Second of all, a set of odours was selected and evaluated in a pilot study, which were perceived as congruent with the notifications. Third, the odour notifications were assessed within a VE, determining if participants were able to understand the odour notifications and secondly if the notifications proved effective at changing participant behaviour and improving task performance.

As opposed to desktop notifications such as in Bodnar et al. (2004) and Arroyo et al. (2002), notifications in VR should not be as disruptive as possible, which would constitute a deterioration of user experience, as this may have negative effects on presence and should be congruent with the VE to provide a display of information that is consistent across all sensory modalities. Two types of notifications were therefore selected, which were relevant to the primary task of interacting with or 'collecting' flowers in the VE. The first was to notify participants of flowers in their vicinity. The second was to notify and remind participants to chalk their hands, an action directly related to the ease of climbing by allowing players to hold on to the wall for longer without falling, and thereby improve progression through the game. The latter notification is already present in-game in the form of a visual indicator that displays "Chalk Hands" on participant's wrists (see Figure 5.5). From observations during Study Two and Three it was clear that participants often did not notice the visual notification and hence missed the fact that they had to chalk their hands.

A pilot study was conducted to determine a set of odours which were perceived as being congruent with the notifications. The results showed that participants preferred a lavender essential oil to represent the 'flower in vicinity' notification, while a cinnamon essential oil was chosen to represent the 'chalk hands' notification. The chosen odours were evaluated during the main study, where QoE related responses were collected for both types of notifications. The results showed that both odours were perceived as neither annoying, nor distracting, that they heightened participants' sense of reality in the VE, and that they made the participants feel more present in the virtual world. These results show that the odours were appropriate for the use with the VE, as they were not detrimental to the user experience but actually enhanced key areas of the user experience of VR, such as the sense of reality in the VE and the sense of presence. When evaluating the odours as notifications in VR, participants also reported that the odours made them change their behaviour and that the odours were effective at indicating the different types of events, showing that the odour notifications were generally understood and that participants felt that the odours impacted their gameplay. This is an important distinction to previous research on olfactory notifications, such as by Bodnar et al. (2004) and Arroyo et al. (2002), where participants had problems in remembering the meaning of an odour notification and in distinguishing between different odour notifications. Furthermore, Bodnar et al. (2004) specifically state that participants felt that they would be able to improve their performance with the olfactory stimuli with further practice, implying a difficulty inherent with odours. The results from Study Four however show that participants were generally able to understand the odour notifications and that this took no extended training, highlighting the importance of choice of odours.

To assess whether participants not only felt like they had understood the notifications but also to determine whether the notifications had a measurable effect on gameplay performance, several task performance related measurements were taken, relating to the two notifications, namely the number of flowers collected as well as the number of times participants chalked their hands. Participants performed significantly better during the first run when they perceived odours when compared to those that did not. In the second run however, no significant differences were found between the two groups in terms of hands chalked. This was most likely due to a learning effect brought on by the exposure to odour notifications during the first run. Those participants who received odour notifications to chalk their hands during their first run quickly learned to chalk their hands, an effect which lasted into their second run, where they did not receive odour notifications, but continued to chalk their hands regularly. These results show that olfactory notifications could be used to reduce the learning curves in VR, especially in VEs that require players to learn new and complex game mechanics. Furthermore, the evidence brought forward in this study strongly suggests that olfactory cues could be integrated into VR user interfaces to improve user experiences and should be considered to enhance VR experiences.

As the VR game was very demanding in terms of attention (especially visual and tactile) and exerted a high degree of stress on participants, odour notifications also proved very successful for this particular scenario as they were able to communicate information in a modality that did not distract from the main activity (climbing) or interfere with other sensory information. In comparison to the visual-only notification to chalk hands, which required participants to halt climbing and to focus their attention on their wrist and away from the next rock hold, participants did not need to halt or shift their visual attention away from their main activity while perceiving the odour notification.

Overall, the results from Study Four demonstrate that odour notifications can be very effective in terms of being noticed, in informing of an event, and in changing participant behaviour. Furthermore, this was possible without disrupting a participant's primary task, giving clear enhancements of the user experience of the VE.

9.3 Limitations

The research reported in this PhD thesis provides evidence that the use of olfaction can enhance user experience in VR; however, certain limitations apply. As with any user-based study, the results are directly dependent on the sample of the population that takes part in the study. The samples for all the parts of the main study as well as the exploratory study were arguably limited to a degree from the outset by the selection of participants (mostly WEIRD (Henrich et al., 2010)) which cannot reflect the general population as well as by the number of participants questioned. This is something common to academic studies and particularly studies in this field and many of the ones reviewed in the literature review. Sample size however may have been a factor that influenced results. This was specifically apparent in Study One, where the Earthworm odour was perceived with the intended negative valence in a pilot study but produced results similar to the neutral odour in the main experiment. The refined method for odour selection in studies Two, Three, and Four however produced odours that were perceived as intended, indicating that the method for odour selection was suitable for a low sample size. Nevertheless, these studies made use of a select number of odours. While their results give examples for how olfaction can be used in a VR setting and the effect it may have on user experience, their scope is limited by the extent of the number and types of odours that were used. Because of this it is not possible to generalise these results for all odours without reservation, as has been made clear in the various chapters, which drew attention to individual differences in odour perception, as well as the different properties of the odours such as their intensity, valence, and congruence. The results must therefore be taken as an indication for what is possible with the use of olfaction as a sensory modality in VR and not as a general given and will hopefully lead to future research that completes our understanding of the olfactory sense.

Certain inaccuracies may have also arisen due to the need to manually trigger the OD at appropriate timings while participants were in the VE. For studies Two and Three, it was easy to observe participants and to determine when to trigger the OD consistently - every time when a participant touched a flower. For Study Four however this was not as straightforward. Here the release of the floral odour was triggered when a flower entered a participant's field of view. As participants had unique approaches to climbing and head movement, this could mean that for some participants, flowers entered their field of view when they were far away, while for others the flowers entered the field of view when they were in their close proximity. This meant that there were certain inconsistencies in terms of how close or far a flower was to the participant when they perceived the floral odour. A better approach is discussed in Section 9.4.

Lastly, the VR environment used in studies Two, Three and Four may have been a limiting factor. These three VR studies were carried out in the same game and level, creating a bias for the specific game. However, as stated in Section 5.2 at the time of determining which VR game would be most suitable for the use with odours, *The Climb* offered distinct advantages over the other evaluated games.

9.4 Future Work

Throughout this PhD thesis, several areas of future work were identified, which are discussed in this section.

As throughout the studies it became clear that the participant selection was limited in that it involved mostly students or University-affiliated groups with a WEIRD background (Henrich et al., 2010), an obvious avenue for future research would be to revisit and strengthen the current study experiments with a larger and more varied pool of test subjects, something that very few studies in this field can account for. Similarly, all three of the main studies of this PhD project were set in the VR game *The Climb* and the results may have been different in another VE. *The Climb* was chosen specifically as it had identifiable odour emitting objects (flowers) spread throughout the environment, the intent of which was to make it easy for participants to identify the source of the odours and therefore to integrate them believably into the virtual world. This raises the question how participants would have perceived the odours in a different game, where odour objects are not as easily identifiable or do not have a real-world counterpart, such as in a fantasy or science fiction game, or in a non-game VE.

Using odours with non-game VEs raises another avenue for future work, such as posed by VR-based E-Learning. The use of olfaction with (non-VR) serious games for example, has already shown to be beneficial to knowledge acquisition and retention, as well as engagement (Covaci et al., 2018). The results from this thesis, namely that odours can increase the sense of presence and task performance, and that odour notifications can affect behaviour, could potentially benefit an E-Learning application. If smells can increase presence they may increase concentration; and if smells can draw attention to objects or tasks within the VR environment then they can likely help participants focus on important aspects of the learning experience. A future study on the topic could examine if an increase in sense of presence and focus through odours could lead to an improvement in knowledge acquisition and retention for example.

Another future research task could be to sharpen the focus on individual differences and how they influence the effects of olfaction in a VE. Study Three (Chapter 7) which examined the effect of incongruent pleasant odours on presence, task performance and QoE in VR, showed that participants could have wildly different perceptions of the odours and this caused a variety of reactions that ranged from perceiving the odours as congruent with the in-game objects, as well as originating from outside the VE entirely, potentially creating a break in presence. By paying attention to different reactions by different participants and aiming to gauge what caused them through select groups or more in depth post experiment interviews. As discussed in the previous chapters, olfaction is a very subjective sensory modality and trying to connect it to personal factors may bring much stronger results but also help in understanding more about the sense and how it can affect us.

As discussed in Section 6.6, my results showed that odours were able to significantly increase the sense of presence in VR, however other researchers have found contradicting results, where odours did not affect the sense of presence (Dinh et al., 1999), or only unpleasant odours were able to affect the sense of presence (Baus and Bouchard, 2017). One main difference between these studies and mine was the use of congruent odours, which may have been responsible for the differences. However, another difference lies in the mechanism of how the odours were displayed. Both Dinh et al. (1999) and Baus and Bouchard (2017) used ambient odours in their studies, which were displayed for the entire duration of the experience in the VE. In my studies, odours were displayed when participants interacted with virtual objects, and as notifications, and only for brief periods of time in the form of short bursts. Future research could therefore determine how different modes of displaying odours affect QoE and sense of presence. Similarly, the type of notifications and the tasks associated with their odours could be expanded on. In Study Four, odours were used to notify participants of objects in their vicinity and to remember to perform an action. The latter of these notification was delivered in two sensory modalities, through olfaction and vision (as the reminder to chalk hands was also displayed on the virtual wrists of the participants). Future research could therefore examine how notifications delivered as odours only would affect participants and if this would have affected their ability to understand the meaning of the notification. Furthermore, the combination of odours and other sensory modalities could be explored, adding heat or sound for example to form multisensory notifications, to explore if these could further increase measures such as task performance, and how these would affect how disruptive or distracting these notifications are.

On a more technical note, while the novel OD used for Studies Two, Three, and Four showed promising results for the use of piezoelectric atomisers with VR HMDs, these devices are limited to one odour per OD at the current time. This was not an issue in my studies, where the number of odours was limited to 2, however this also severely limits the fidelity and spectrum of odours that can be used to enhance a VE. While the results of my research showed that odours can increase the sense of presence in VR, researchers may want to explore how participants react to an increased number of odours, perhaps increasing the perceived realism of the VE. However, any such attempts will eventually run into the issue that olfaction is a chemical sense which relies on direct contact between the odorant and the olfactory bulb to register an odour perception. As opposed to the senses of vision and audition, where the entire perceptive spectrum can be represented digitally, olfaction requires a physical medium, the odorant, and the breadth of olfactory stimulation in a VE is therefore limited by the number of odours selected by the researchers. It would be valuable therefore for any future work in this area to come up with a solution to the issue of how to include more and different odours within a single VR environment, while avoiding the aforementioned issues of mixing and lingering odours. A different improvement that would make the current OD more versatile would be to turn it into a wireless device, in order to limit any obtrusive factors.

As was mentioned in Section 9.3, by triggering the release of the floral odour when a flower entered a participant's field of view, the distance of the flower to the participant was not consistent and a better approach to when odours are released by the OD will have to be determined. One approach might be to trigger the OD based on the in-game distance between the player avatar and the flowers. However, this would have required access to the in-game data such as player position and flower positions, either through the source-code of the game or an Application Programming Interface (API), which was not available. The accurate timing of odour display in relation to other sensory information has been studied in terms of the use of ODs with video content. Ademoye and Ghinea (2009) and Murray, Lee, et al. (2014) showed that the perceived QoE of olfaction-enhanced videos was the highest when odour display and semantically related video content were in sync (e.g. smoke odour and video of a burning fire) and that QoE decreased the greater the temporal offset between odour display and semantically related video content (see Section 3.4.2 for details). Similarly, such an in-sync period may exist in VR. While there are no immediate cuts in between semantically related and unrelated content as one may encounter in a video (e.g. one scene is set in a lush forest, while the next is set in a chemical plant), it seems likely that the timing of odour display is an important factor influencing QoE as well as a sense of presence. While a time-based in-sync period is appropriate for olfaction-enhanced videos which are displayed as a continuum in time from the beginning to end, players in VR can move back and forth through the game at different speeds and the distance between their virtual position and the odour emitting object. It is very likely that an in-sync period exists in VR, but this will have to be determined in future research, such as by applying the research of Huang et al. (2012b) to a VR setting.

A further field for future work became apparent when selecting a measure for the sense of presence. As was discussed in Section 3.4.4.1, there currently is no unanimously accepted definition for the term presence beyond the sense of "being there" (Witmer and Singer, 1998) in the virtual world. This has led to a vast variety of approaches to how the sense of presence could be measured. Questionnaires have been the most common type of measure used to assess the subjective sense of presence, however, a plethora of questionnaires exist (at least 32 by 2003 (Youngblut, 2003)), with at least 11 different presence questionnaires being used between 2016 and 2017 alone (Hein and Mai, 2018), which was when I began my research on the effect of olfaction on the sense of presence in VR. While several of these questionnaires are more commonly used, such as the Witmer and Singer Presence Questionnaire, and the IPQ, which I used in my studies, neither of these were entirely satisfactory, as discussed in Sections 6.6, 7.5, and 8.6. Furthermore, currently no presence questionnaire addresses the effect of the inclusion of sensory modalities in VR that go beyond vision and audition, and very rarely haptic, and these are usually kept very general. As an example, the most commonly used presence questionnaire, the Witmer and Singer Presence Questionnaire includes three sound-specific questions that probe the perception of a sound ("6. How much did the auditory aspects of the environment involve you?", "15. How well could you identify sounds?" and "16. How well could you localize sounds?" (Witmer and Singer, 1998, p. 232)). Because of this lack for sensory-specific questions, researchers have resorted to modifying existing questionnaires and swapping out references of one sensory modality to another one (Ranasinghe, Eason Wai Tung, et al., 2018; Ranasinghe, Jain, et al., 2017). This approach however, does not capture the finer-grained details of how the sensory modalities affect the sense of presence. For example, had questions 15. and 16. of the Witmer and Singer Presence Questionnaire been amended for the use with olfaction (15. How well could you identify *odours*? and 16. How well could you localize *odours*?), a response agreeing with question 15 ("Very well"), would not necessarily indicate a high sense of presence, as was demonstrated by the results of Study Three, which showed that even though participants believed that they had identified an odour, they were often incorrect, and that this could have actually reduced their sense of presence. Similarly, some participants in this study were sure that the odour originated from outside the VE, which would have also resulted in a high presence score according to the amended question 16 (How well could you localize *odours*?), even though this in reality may have reduced the sense of presence. With emerging technologies that enable the inclusion of different sensory modalities to VEs, it is clear that new tools for the assessment of their effects on presence are necessary. For olfaction especially, where the addition of odours has had mixed results in terms of being able to affect the sense of presence, new forms of measurement could broaden our understanding of why this was the case and how the sense can be integrated into VEs to enhance the sense of presence.

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Appendix A

Study One

A.1 Full Size Images

Figure A.1: Neutral Image 1: Toolbox

Figure A.2: Neutral Image 2: Fire Extinguisher

Figure A.3: Neutral Image 3: Door

Figure A.4: Neutral Image 4: Refrigerator

Figure A.5: Positive Image 1: Smiling Child

Figure A.6: Positive Image 2: Panorama of Historical Town

Figure A.7: Positive Image 3: Couple in Nature

Figure A.8: Positive Image 4: Festive Dinner

Figure A.9: Negative Image 1: Zombie Head

Figure A.10: Negative Image 2: Child in War Zone

Figure A.11: Negative Image 3: Person in Trash

Figure A.12: Negative Image 4: Pig's Heads

A.2 Pilot Study Raw Results

Table A.1: Pilot Study Neutral Images Raw Results
[1] P. Age = Participant Age

Image	**Neutral 1** Toolbox		**Neutral 2** Fire Extinguisher		**Neutral 3** Door		**Neutral 4** Refrigerator	
P. Age [1]	Strength	Emotion	Strength	Emotion	Strength	Emotion	Strength	Emotion
26	0	Neutral	0	Neutral	0	Neutral	1	Disgust
26	0	Neutral	1	Fear	2	Anticipation	0	Neutral
28	0	Neutral	0	Neutral	0	Neutral	1	Disgust
29	0	Neutral	0	Neutral	0	Neutral	1	Surprise
62	0	Neutral	0	Neutral	0	Neutral	0	Neutral
61	1	Joy	1	Fear	0	Neutral	0	Neutral

Table A.2: Pilot Study Positive Images Raw Results
[1] P. Age = Participant Age

Image	**Positive 1** Smiling Child		**Positive 2** Historical Town		**Positive 3** Couple in Nature		**Positive 4** Festive Dinner	
P. Age [1]	Strength	Emotion	Strength	Emotion	Strength	Emotion	Strength	Emotion
26	6	Joy	3	Anticipation	4	Trust	6	Anticipation
26	4	Joy	4	Joy	3	Joy	4	Anticipation
28	1	Surprise	2	Anticipation	3	Joy	2	Joy
29	3	Joy	2	Joy	5	Joy	3	Anticipation
62	4	Joy	2	Joy	2	Joy	4	Joy
61	4	Joy	3	Joy	4	Joy	5	Joy

Table A.3: Pilot Study Negative Images Raw Results
[1] P. Age = Participant Age

Image	**Negative 1** Zombie Head		**Negative 2** Child in War Zone		**Negative 3** Person in Trash		**Negative 4** Pig's Heads	
P. Age [1]	Strength	Emotion	Strength	Emotion	Strength	Emotion	Strength	Emotion
26	2	Disgust	3	Anger	7	Disgust	6	Disgust
26	4	Disgust	4	Sadness	4	Disgust	4	Sadness
28	3	Fear	2	Sadness	2	Disgust	5	Disgust
29	4	Disgust	2	Anger	1	Sadness	1	Anger
62	3	Fear	6	Sadness	1	Disgust	2	Trust
61	2	Fear	4	Sadness	2	Disgust	3	Disgust

A.3 Main Study Raw Results

Table A.4: Study One: Main Study Raw Results
[1] Part. # = Participant Number

Part. #[1]	Emotion	Strength	Odour	Image	ID	Group
1	disgust	4	Earthworm	Negative 1	A27	A
3	surprise	3	Earthworm	Negative 1	A27	A
5	disgust	5	Earthworm	Negative 1	A27	A
7	fear	6	Earthworm	Negative 1	A27	A
9	anger	3	Earthworm	Negative 1	A27	A
11	disgust	7	Earthworm	Negative 1	A27	A
13	fear	3	Earthworm	Negative 1	A27	A
15	fear	6	Earthworm	Negative 1	A27	A
17	disgust	2	Earthworm	Negative 1	A27	A
19	anticipation	4	Earthworm	Negative 1	A27	A
21	disgust	2	Earthworm	Negative 1	A27	A
22	neutral	0	Earthworm	Negative 1	A27	A
1	sadness	4	Earthworm	Negative 2	A30	A
3	neutral	0	Earthworm	Negative 2	A30	A
5	sadness	5	Earthworm	Negative 2	A30	A
7	fear	7	Earthworm	Negative 2	A30	A
9	sadness	5	Earthworm	Negative 2	A30	A
11	sadness	1	Earthworm	Negative 2	A30	A
13	sadness	3	Earthworm	Negative 2	A30	A
15	sadness	6	Earthworm	Negative 2	A30	A
17	sadness	2	Earthworm	Negative 2	A30	A
19	fear	4	Earthworm	Negative 2	A30	A
21	sadness	4	Earthworm	Negative 2	A30	A
22	trust	6	Earthworm	Negative 2	A30	A
2	disgust	5	Earthworm	Negative 3	B27	B
4	surprise	3	Earthworm	Negative 3	B27	B
6	surprise	5	Earthworm	Negative 3	B27	B
8	disgust	2	Earthworm	Negative 3	B27	B

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
10	neutral	0	Earthworm	Negative 3	B27	B
12	disgust	3	Earthworm	Negative 3	B27	B
14	disgust	4	Earthworm	Negative 3	B27	B
16	disgust	6	Earthworm	Negative 3	B27	B
18	disgust	2	Earthworm	Negative 3	B27	B
20	surprise	3	Earthworm	Negative 3	B27	B
2	disgust	7	Earthworm	Negative 4	B30	B
4	disgust	5	Earthworm	Negative 4	B30	B
6	disgust	4	Earthworm	Negative 4	B30	B
8	disgust	2	Earthworm	Negative 4	B30	B
10	disgust	4	Earthworm	Negative 4	B30	B
12	disgust	4	Earthworm	Negative 4	B30	B
14	disgust	3	Earthworm	Negative 4	B30	B
16	surprise	3	Earthworm	Negative 4	B30	B
18	anger	4	Earthworm	Negative 4	B30	B
20	disgust	4	Earthworm	Negative 4	B30	B
1	neutral	0	Earthworm	Neutral 1	A25	A
3	trust	1	Earthworm	Neutral 1	A25	A
5	trust	3	Earthworm	Neutral 1	A25	A
7	sadness	4	Earthworm	Neutral 1	A25	A
9	neutral	0	Earthworm	Neutral 1	A25	A
11	trust	2	Earthworm	Neutral 1	A25	A
13	neutral	0	Earthworm	Neutral 1	A25	A
15	neutral	0	Earthworm	Neutral 1	A25	A
17	neutral	0	Earthworm	Neutral 1	A25	A
19	anticipation	4	Earthworm	Neutral 1	A25	A
21	disgust	4	Earthworm	Neutral 1	A25	A
22	surprise	6	Earthworm	Neutral 1	A25	A
1	neutral	0	Earthworm	Neutral 2	A28	A
3	surprise	3	Earthworm	Neutral 2	A28	A

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
5	neutral	0	Earthworm	Neutral 2	A28	A
7	neutral	0	Earthworm	Neutral 2	A28	A
9	disgust	1	Earthworm	Neutral 2	A28	A
11	neutral	0	Earthworm	Neutral 2	A28	A
13	neutral	0	Earthworm	Neutral 2	A28	A
15	fear	3	Earthworm	Neutral 2	A28	A
17	neutral	0	Earthworm	Neutral 2	A28	A
19	neutral	0	Earthworm	Neutral 2	A28	A
21	disgust	2	Earthworm	Neutral 2	A28	A
22	trust	6	Earthworm	Neutral 2	A28	A
2	neutral	0	Earthworm	Neutral 3	B25	B
4	surprise	3	Earthworm	Neutral 3	B25	B
6	sadness	5	Earthworm	Neutral 3	B25	B
8	neutral	0	Earthworm	Neutral 3	B25	B
10	trust	2	Earthworm	Neutral 3	B25	B
12	neutral	0	Earthworm	Neutral 3	B25	B
14	anticipation	3	Earthworm	Neutral 3	B25	B
16	disgust	4	Earthworm	Neutral 3	B25	B
18	neutral	0	Earthworm	Neutral 3	B25	B
20	disgust	5	Earthworm	Neutral 3	B25	B
2	disgust	7	Earthworm	Neutral 4	B28	B
4	joy	6	Earthworm	Neutral 4	B28	B
6	disgust	4	Earthworm	Neutral 4	B28	B
8	anticipation	4	Earthworm	Neutral 4	B28	B
10	neutral	0	Earthworm	Neutral 4	B28	B
12	anticipation	5	Earthworm	Neutral 4	B28	B
14	neutral	0	Earthworm	Neutral 4	B28	B
16	disgust	5	Earthworm	Neutral 4	B28	B
18	neutral	0	Earthworm	Neutral 4	B28	B
20	disgust	2	Earthworm	Neutral 4	B28	B

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
1	anticipation	3	Earthworm	Positive 1	A26	A
3	trust	3	Earthworm	Positive 1	A26	A
5	joy	3	Earthworm	Positive 1	A26	A
7	disgust	2	Earthworm	Positive 1	A26	A
9	neutral	0	Earthworm	Positive 1	A26	A
11	joy	7	Earthworm	Positive 1	A26	A
13	surprise	2	Earthworm	Positive 1	A26	A
15	trust	3	Earthworm	Positive 1	A26	A
17	neutral	0	Earthworm	Positive 1	A26	A
19	anticipation	4	Earthworm	Positive 1	A26	A
21	disgust	2	Earthworm	Positive 1	A26	A
22	trust	6	Earthworm	Positive 1	A26	A
1	anticipation	5	Earthworm	Positive 2	A29	A
3	joy	1	Earthworm	Positive 2	A29	A
5	joy	5	Earthworm	Positive 2	A29	A
7	sadness	6	Earthworm	Positive 2	A29	A
9	sadness	4	Earthworm	Positive 2	A29	A
11	neutral	0	Earthworm	Positive 2	A29	A
13	neutral	0	Earthworm	Positive 2	A29	A
15	joy	3	Earthworm	Positive 2	A29	A
17	neutral	0	Earthworm	Positive 2	A29	A
19	trust	3	Earthworm	Positive 2	A29	A
21	disgust	2	Earthworm	Positive 2	A29	A
22	neutral	0	Earthworm	Positive 2	A29	A
2	joy	2	Earthworm	Positive 3	B26	B
4	surprise	2	Earthworm	Positive 3	B26	B
6	disgust	5	Earthworm	Positive 3	B26	B
8	anticipation	3	Earthworm	Positive 3	B26	B
10	joy	2	Earthworm	Positive 3	B26	B
12	neutral	0	Earthworm	Positive 3	B26	B

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
14	joy	5	Earthworm	Positive 3	B26	B
16	joy	3	Earthworm	Positive 3	B26	B
18	trust	1	Earthworm	Positive 3	B26	B
20	trust	3	Earthworm	Positive 3	B26	B
2	surprise	4	Earthworm	Positive 4	B29	B
4	surprise	3	Earthworm	Positive 4	B29	B
6	anticipation	5	Earthworm	Positive 4	B29	B
8	joy	3	Earthworm	Positive 4	B29	B
10	joy	5	Earthworm	Positive 4	B29	B
12	neutral	0	Earthworm	Positive 4	B29	B
14	joy	2	Earthworm	Positive 4	B29	B
16	surprise	5	Earthworm	Positive 4	B29	B
18	anticipation	5	Earthworm	Positive 4	B29	B
20	anticipation	4	Earthworm	Positive 4	B29	B
1	disgust	4	Excrement	Negative 1	A33	A
3	disgust	7	Excrement	Negative 1	A33	A
5	disgust	7	Excrement	Negative 1	A33	A
7	anger	7	Excrement	Negative 1	A33	A
9	disgust	7	Excrement	Negative 1	A33	A
11	disgust	7	Excrement	Negative 1	A33	A
13	disgust	5	Excrement	Negative 1	A33	A
15	disgust	7	Excrement	Negative 1	A33	A
17	disgust	4	Excrement	Negative 1	A33	A
19	disgust	5	Excrement	Negative 1	A33	A
21	anger	7	Excrement	Negative 1	A33	A
22	disgust	7	Excrement	Negative 1	A33	A
1	anger	6	Excrement	Negative 2	A36	A
3	disgust	6	Excrement	Negative 2	A36	A
5	sadness	5	Excrement	Negative 2	A36	A
7	anger	7	Excrement	Negative 2	A36	A

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
9	anger	7	Excrement	Negative 2	A36	A
11	disgust	7	Excrement	Negative 2	A36	A
13	disgust	7	Excrement	Negative 2	A36	A
15	disgust	5	Excrement	Negative 2	A36	A
17	disgust	3	Excrement	Negative 2	A36	A
19	disgust	5	Excrement	Negative 2	A36	A
21	disgust	5	Excrement	Negative 2	A36	A
22	anger	7	Excrement	Negative 2	A36	A
2	disgust	7	Excrement	Negative 3	B33	B
4	disgust	5	Excrement	Negative 3	B33	B
6	disgust	5	Excrement	Negative 3	B33	B
8	disgust	6	Excrement	Negative 3	B33	B
10	disgust	7	Excrement	Negative 3	B33	B
12	disgust	7	Excrement	Negative 3	B33	B
14	disgust	7	Excrement	Negative 3	B33	B
16	disgust	6	Excrement	Negative 3	B33	B
18	disgust	7	Excrement	Negative 3	B33	B
20	anger	6	Excrement	Negative 3	B33	B
2	disgust	7	Excrement	Negative 4	B36	B
4	anger	3	Excrement	Negative 4	B36	B
6	disgust	7	Excrement	Negative 4	B36	B
8	disgust	7	Excrement	Negative 4	B36	B
10	anger	6	Excrement	Negative 4	B36	B
12	disgust	7	Excrement	Negative 4	B36	B
14	disgust	6	Excrement	Negative 4	B36	B
16	disgust	3	Excrement	Negative 4	B36	B
18	disgust	7	Excrement	Negative 4	B36	B
20	disgust	5	Excrement	Negative 4	B36	B
1	surprise	5	Excrement	Neutral 1	A31	A
3	disgust	3	Excrement	Neutral 1	A31	A

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
5	disgust	4	Excrement	Neutral 1	A31	A
7	disgust	6	Excrement	Neutral 1	A31	A
9	disgust	7	Excrement	Neutral 1	A31	A
11	disgust	7	Excrement	Neutral 1	A31	A
13	anger	4	Excrement	Neutral 1	A31	A
15	disgust	3	Excrement	Neutral 1	A31	A
17	disgust	2	Excrement	Neutral 1	A31	A
19	disgust	5	Excrement	Neutral 1	A31	A
21	disgust	6	Excrement	Neutral 1	A31	A
22	neutral	0	Excrement	Neutral 1	A31	A
1	disgust	5	Excrement	Neutral 2	A34	A
3	disgust	7	Excrement	Neutral 2	A34	A
5	disgust	4	Excrement	Neutral 2	A34	A
7	disgust	7	Excrement	Neutral 2	A34	A
9	anger	5	Excrement	Neutral 2	A34	A
11	disgust	7	Excrement	Neutral 2	A34	A
13	disgust	6	Excrement	Neutral 2	A34	A
15	sadness	3	Excrement	Neutral 2	A34	A
17	disgust	2	Excrement	Neutral 2	A34	A
19	disgust	4	Excrement	Neutral 2	A34	A
21	disgust	7	Excrement	Neutral 2	A34	A
22	anger	6	Excrement	Neutral 2	A34	A
2	disgust	7	Excrement	Neutral 3	B31	B
4	disgust	4	Excrement	Neutral 3	B31	B
6	disgust	7	Excrement	Neutral 3	B31	B
8	disgust	4	Excrement	Neutral 3	B31	B
10	surprise	6	Excrement	Neutral 3	B31	B
12	disgust	7	Excrement	Neutral 3	B31	B
14	anticipation	7	Excrement	Neutral 3	B31	B
16	disgust	5	Excrement	Neutral 3	B31	B

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
18	disgust	7	Excrement	Neutral 3	B31	B
20	disgust	4	Excrement	Neutral 3	B31	B
2	disgust	7	Excrement	Neutral 4	B34	B
4	anger	3	Excrement	Neutral 4	B34	B
6	disgust	7	Excrement	Neutral 4	B34	B
8	disgust	3	Excrement	Neutral 4	B34	B
10	disgust	7	Excrement	Neutral 4	B34	B
12	anger	6	Excrement	Neutral 4	B34	B
14	surprise	7	Excrement	Neutral 4	B34	B
16	disgust	6	Excrement	Neutral 4	B34	B
18	trust	1	Excrement	Neutral 4	B34	B
20	disgust	6	Excrement	Neutral 4	B34	B
1	sadness	4	Excrement	Positive 1	A32	A
3	disgust	5	Excrement	Positive 1	A32	A
5	surprise	3	Excrement	Positive 1	A32	A
7	anger	5	Excrement	Positive 1	A32	A
9	disgust	6	Excrement	Positive 1	A32	A
11	disgust	6	Excrement	Positive 1	A32	A
13	disgust	6	Excrement	Positive 1	A32	A
15	joy	3	Excrement	Positive 1	A32	A
17	disgust	2	Excrement	Positive 1	A32	A
19	sadness	5	Excrement	Positive 1	A32	A
21	disgust	7	Excrement	Positive 1	A32	A
22	surprise	7	Excrement	Positive 1	A32	A
1	disgust	5	Excrement	Positive 2	A35	A
3	disgust	6	Excrement	Positive 2	A35	A
5	disgust	4	Excrement	Positive 2	A35	A
7	anger	7	Excrement	Positive 2	A35	A
9	disgust	7	Excrement	Positive 2	A35	A
11	disgust	4	Excrement	Positive 2	A35	A

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
13	disgust	7	Excrement	Positive 2	A35	A
15	anticipation	2	Excrement	Positive 2	A35	A
17	disgust	1	Excrement	Positive 2	A35	A
19	disgust	4	Excrement	Positive 2	A35	A
21	disgust	7	Excrement	Positive 2	A35	A
22	disgust	6	Excrement	Positive 2	A35	A
2	disgust	4	Excrement	Positive 3	B32	B
4	disgust	6	Excrement	Positive 3	B32	B
6	disgust	6	Excrement	Positive 3	B32	B
8	disgust	5	Excrement	Positive 3	B32	B
10	disgust	7	Excrement	Positive 3	B32	B
12	anger	7	Excrement	Positive 3	B32	B
14	surprise	7	Excrement	Positive 3	B32	B
16	disgust	4	Excrement	Positive 3	B32	B
18	disgust	4	Excrement	Positive 3	B32	B
20	disgust	2	Excrement	Positive 3	B32	B
2	disgust	7	Excrement	Positive 4	B35	B
4	disgust	6	Excrement	Positive 4	B35	B
6	disgust	6	Excrement	Positive 4	B35	B
8	disgust	5	Excrement	Positive 4	B35	B
10	disgust	5	Excrement	Positive 4	B35	B
12	disgust	7	Excrement	Positive 4	B35	B
14	joy	4	Excrement	Positive 4	B35	B
16	disgust	4	Excrement	Positive 4	B35	B
18	disgust	1	Excrement	Positive 4	B35	B
20	disgust	2	Excrement	Positive 4	B35	B
2	fear	3	No Odorant	Negative 1	A3	B
4	fear	4	No Odorant	Negative 1	A3	B
6	fear	3	No Odorant	Negative 1	A3	B
8	disgust	3	No Odorant	Negative 1	A3	B

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
10	surprise	2	No Odorant	Negative 1	A3	B
12	fear	4	No Odorant	Negative 1	A3	B
14	fear	7	No Odorant	Negative 1	A3	B
16	disgust	5	No Odorant	Negative 1	A3	B
18	fear	5	No Odorant	Negative 1	A3	B
20	disgust	2	No Odorant	Negative 1	A3	B
2	sadness	2	No Odorant	Negative 2	A6	B
4	sadness	2	No Odorant	Negative 2	A6	B
6	anger	3	No Odorant	Negative 2	A6	B
8	sadness	4	No Odorant	Negative 2	A6	B
10	sadness	6	No Odorant	Negative 2	A6	B
12	anger	5	No Odorant	Negative 2	A6	B
14	sadness	3	No Odorant	Negative 2	A6	B
16	sadness	7	No Odorant	Negative 2	A6	B
18	sadness	5	No Odorant	Negative 2	A6	B
20	anger	4	No Odorant	Negative 2	A6	B
1	disgust	5	No Odorant	Negative 3	B3	A
3	disgust	4	No Odorant	Negative 3	B3	A
5	disgust	1	No Odorant	Negative 3	B3	A
7	disgust	4	No Odorant	Negative 3	B3	A
9	disgust	4	No Odorant	Negative 3	B3	A
11	disgust	2	No Odorant	Negative 3	B3	A
13	surprise	3	No Odorant	Negative 3	B3	A
15	disgust	6	No Odorant	Negative 3	B3	A
17	disgust	2	No Odorant	Negative 3	B3	A
19	disgust	1	No Odorant	Negative 3	B3	A
21	disgust	5	No Odorant	Negative 3	B3	A
22	disgust	6	No Odorant	Negative 3	B3	A
1	fear	7	No Odorant	Negative 4	B6	A
3	disgust	4	No Odorant	Negative 4	B6	A

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
5	disgust	2	No Odorant	Negative 4	B6	A
7	disgust	3	No Odorant	Negative 4	B6	A
9	surprise	3	No Odorant	Negative 4	B6	A
11	disgust	2	No Odorant	Negative 4	B6	A
13	disgust	5	No Odorant	Negative 4	B6	A
15	disgust	4	No Odorant	Negative 4	B6	A
17	disgust	6	No Odorant	Negative 4	B6	A
19	disgust	1	No Odorant	Negative 4	B6	A
21	disgust	5	No Odorant	Negative 4	B6	A
22	surprise	7	No Odorant	Negative 4	B6	A
2	neutral	0	No Odorant	Neutral 1	A1	B
4	neutral	0	No Odorant	Neutral 1	A1	B
6	neutral	0	No Odorant	Neutral 1	A1	B
8	neutral	0	No Odorant	Neutral 1	A1	B
10	neutral	0	No Odorant	Neutral 1	A1	B
12	neutral	0	No Odorant	Neutral 1	A1	B
14	neutral	0	No Odorant	Neutral 1	A1	B
16	anticipation	2	No Odorant	Neutral 1	A1	B
18	neutral	0	No Odorant	Neutral 1	A1	B
20	joy	2	No Odorant	Neutral 1	A1	B
2	neutral	0	No Odorant	Neutral 2	A4	B
4	neutral	0	No Odorant	Neutral 2	A4	B
6	neutral	0	No Odorant	Neutral 2	A4	B
8	neutral	0	No Odorant	Neutral 2	A4	B
10	joy	1	No Odorant	Neutral 2	A4	B
12	neutral	0	No Odorant	Neutral 2	A4	B
14	neutral	0	No Odorant	Neutral 2	A4	B
16	neutral	0	No Odorant	Neutral 2	A4	B
18	fear	1	No Odorant	Neutral 2	A4	B
20	fear	1	No Odorant	Neutral 2	A4	B

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
1	neutral	0	No Odorant	Neutral 3	B1	A
3	neutral	0	No Odorant	Neutral 3	B1	A
5	neutral	0	No Odorant	Neutral 3	B1	A
7	anticipation	3	No Odorant	Neutral 3	B1	A
9	neutral	0	No Odorant	Neutral 3	B1	A
11	neutral	0	No Odorant	Neutral 3	B1	A
13	neutral	0	No Odorant	Neutral 3	B1	A
15	neutral	0	No Odorant	Neutral 3	B1	A
17	neutral	0	No Odorant	Neutral 3	B1	A
19	neutral	0	No Odorant	Neutral 3	B1	A
21	anticipation	3	No Odorant	Neutral 3	B1	A
22	sadness	6	No Odorant	Neutral 3	B1	A
1	neutral	0	No Odorant	Neutral 4	B4	A
3	trust	4	No Odorant	Neutral 4	B4	A
5	disgust	1	No Odorant	Neutral 4	B4	A
7	neutral	0	No Odorant	Neutral 4	B4	A
9	anticipation	2	No Odorant	Neutral 4	B4	A
11	neutral	0	No Odorant	Neutral 4	B4	A
13	anger	1	No Odorant	Neutral 4	B4	A
15	anticipation	4	No Odorant	Neutral 4	B4	A
17	neutral	0	No Odorant	Neutral 4	B4	A
19	neutral	0	No Odorant	Neutral 4	B4	A
21	neutral	0	No Odorant	Neutral 4	B4	A
22	surprise	4	No Odorant	Neutral 4	B4	A
2	joy	5	No Odorant	Positive 1	A2	B
4	surprise	3	No Odorant	Positive 1	A2	B
6	joy	2	No Odorant	Positive 1	A2	B
8	joy	4	No Odorant	Positive 1	A2	B
10	joy	4	No Odorant	Positive 1	A2	B
12	joy	6	No Odorant	Positive 1	A2	B

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
14	joy	5	No Odorant	Positive 1	A2	B
16	joy	5	No Odorant	Positive 1	A2	B
18	surprise	3	No Odorant	Positive 1	A2	B
20	neutral	0	No Odorant	Positive 1	A2	B
2	trust	2	No Odorant	Positive 2	A5	B
4	joy	3	No Odorant	Positive 2	A5	B
6	joy	3	No Odorant	Positive 2	A5	B
8	anticipation	4	No Odorant	Positive 2	A5	B
10	trust	2	No Odorant	Positive 2	A5	B
12	trust	5	No Odorant	Positive 2	A5	B
14	joy	4	No Odorant	Positive 2	A5	B
16	anticipation	3	No Odorant	Positive 2	A5	B
18	joy	2	No Odorant	Positive 2	A5	B
20	sadness	2	No Odorant	Positive 2	A5	B
1	joy	3	No Odorant	Positive 3	B2	A
3	joy	5	No Odorant	Positive 3	B2	A
5	joy	3	No Odorant	Positive 3	B2	A
7	joy	4	No Odorant	Positive 3	B2	A
9	joy	2	No Odorant	Positive 3	B2	A
11	joy	2	No Odorant	Positive 3	B2	A
13	joy	4	No Odorant	Positive 3	B2	A
15	joy	3	No Odorant	Positive 3	B2	A
17	joy	2	No Odorant	Positive 3	B2	A
19	joy	3	No Odorant	Positive 3	B2	A
21	joy	4	No Odorant	Positive 3	B2	A
22	trust	7	No Odorant	Positive 3	B2	A
1	joy	6	No Odorant	Positive 4	B5	A
3	joy	4	No Odorant	Positive 4	B5	A
5	trust	3	No Odorant	Positive 4	B5	A
7	joy	4	No Odorant	Positive 4	B5	A

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
9	joy	4	No Odorant	Positive 4	B5	A
11	joy	3	No Odorant	Positive 4	B5	A
13	anticipation	7	No Odorant	Positive 4	B5	A
15	anticipation	6	No Odorant	Positive 4	B5	A
17	joy	4	No Odorant	Positive 4	B5	A
19	anticipation	3	No Odorant	Positive 4	B5	A
21	anticipation	5	No Odorant	Positive 4	B5	A
22	anticipation	7	No Odorant	Positive 4	B5	A
1	sadness	5	Orange	Negative 1	A15	A
3	surprise	5	Orange	Negative 1	A15	A
5	disgust	4	Orange	Negative 1	A15	A
7	neutral	0	Orange	Negative 1	A15	A
9	anger	1	Orange	Negative 1	A15	A
11	disgust	3	Orange	Negative 1	A15	A
13	fear	3	Orange	Negative 1	A15	A
15	fear	4	Orange	Negative 1	A15	A
17	disgust	1	Orange	Negative 1	A15	A
19	anticipation	4	Orange	Negative 1	A15	A
21	fear	2	Orange	Negative 1	A15	A
22	anticipation	4	Orange	Negative 1	A15	A
1	disgust	5	Orange	Negative 2	A18	A
3	neutral	0	Orange	Negative 2	A18	A
5	sadness	5	Orange	Negative 2	A18	A
7	sadness	7	Orange	Negative 2	A18	A
9	anticipation	4	Orange	Negative 2	A18	A
11	sadness	1	Orange	Negative 2	A18	A
13	sadness	3	Orange	Negative 2	A18	A
15	sadness	5	Orange	Negative 2	A18	A
17	neutral	0	Orange	Negative 2	A18	A
19	sadness	5	Orange	Negative 2	A18	A

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
21	sadness	3	Orange	Negative 2	A18	A
22	anticipation	4	Orange	Negative 2	A18	A
2	disgust	3	Orange	Negative 3	B15	B
4	surprise	6	Orange	Negative 3	B15	B
6	disgust	1	Orange	Negative 3	B15	B
8	disgust	2	Orange	Negative 3	B15	B
10	disgust	2	Orange	Negative 3	B15	B
12	surprise	2	Orange	Negative 3	B15	B
14	disgust	4	Orange	Negative 3	B15	B
16	surprise	4	Orange	Negative 3	B15	B
18	surprise	1	Orange	Negative 3	B15	B
20	fear	2	Orange	Negative 3	B15	B
2	neutral	0	Orange	Negative 4	B18	B
4	surprise	6	Orange	Negative 4	B18	B
6	surprise	4	Orange	Negative 4	B18	B
8	surprise	3	Orange	Negative 4	B18	B
10	disgust	6	Orange	Negative 4	B18	B
12	neutral	0	Orange	Negative 4	B18	B
14	disgust	6	Orange	Negative 4	B18	B
16	surprise	3	Orange	Negative 4	B18	B
18	disgust	2	Orange	Negative 4	B18	B
20	disgust	2	Orange	Negative 4	B18	B
1	trust	4	Orange	Neutral 1	A13	A
3	neutral	0	Orange	Neutral 1	A13	A
5	anticipation	5	Orange	Neutral 1	A13	A
7	joy	5	Orange	Neutral 1	A13	A
9	neutral	0	Orange	Neutral 1	A13	A
11	joy	2	Orange	Neutral 1	A13	A
13	neutral	0	Orange	Neutral 1	A13	A
15	anticipation	6	Orange	Neutral 1	A13	A

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
17	neutral	0	Orange	Neutral 1	A13	A
19	anticipation	4	Orange	Neutral 1	A13	A
21	anticipation	3	Orange	Neutral 1	A13	A
22	surprise	5	Orange	Neutral 1	A13	A
1	anticipation	4	Orange	Neutral 2	A16	A
3	surprise	3	Orange	Neutral 2	A16	A
5	neutral	0	Orange	Neutral 2	A16	A
7	joy	5	Orange	Neutral 2	A16	A
9	trust	4	Orange	Neutral 2	A16	A
11	surprise	3	Orange	Neutral 2	A16	A
13	neutral	0	Orange	Neutral 2	A16	A
15	fear	3	Orange	Neutral 2	A16	A
17	neutral	0	Orange	Neutral 2	A16	A
19	anticipation	3	Orange	Neutral 2	A16	A
21	trust	4	Orange	Neutral 2	A16	A
22	trust	5	Orange	Neutral 2	A16	A
2	neutral	0	Orange	Neutral 3	B13	B
4	trust	3	Orange	Neutral 3	B13	B
6	neutral	0	Orange	Neutral 3	B13	B
8	neutral	0	Orange	Neutral 3	B13	B
10	surprise	2	Orange	Neutral 3	B13	B
12	anticipation	3	Orange	Neutral 3	B13	B
14	anticipation	1	Orange	Neutral 3	B13	B
16	joy	5	Orange	Neutral 3	B13	B
18	neutral	0	Orange	Neutral 3	B13	B
20	anticipation	2	Orange	Neutral 3	B13	B
2	surprise	5	Orange	Neutral 4	B16	B
4	surprise	3	Orange	Neutral 4	B16	B
6	neutral	0	Orange	Neutral 4	B16	B
8	anticipation	3	Orange	Neutral 4	B16	B

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
10	neutral	0	Orange	Neutral 4	B16	B
12	anticipation	3	Orange	Neutral 4	B16	B
14	surprise	4	Orange	Neutral 4	B16	B
16	surprise	4	Orange	Neutral 4	B16	B
18	neutral	0	Orange	Neutral 4	B16	B
20	disgust	2	Orange	Neutral 4	B16	B
1	anticipation	4	Orange	Positive 1	A14	A
3	trust	3	Orange	Positive 1	A14	A
5	joy	4	Orange	Positive 1	A14	A
7	joy	7	Orange	Positive 1	A14	A
9	neutral	0	Orange	Positive 1	A14	A
11	joy	4	Orange	Positive 1	A14	A
13	joy	4	Orange	Positive 1	A14	A
15	joy	5	Orange	Positive 1	A14	A
17	joy	2	Orange	Positive 1	A14	A
19	joy	5	Orange	Positive 1	A14	A
21	surprise	3	Orange	Positive 1	A14	A
22	joy	6	Orange	Positive 1	A14	A
1	anticipation	5	Orange	Positive 2	A17	A
3	sadness	2	Orange	Positive 2	A17	A
5	joy	3	Orange	Positive 2	A17	A
7	joy	7	Orange	Positive 2	A17	A
9	anticipation	6	Orange	Positive 2	A17	A
11	joy	4	Orange	Positive 2	A17	A
13	joy	3	Orange	Positive 2	A17	A
15	neutral	0	Orange	Positive 2	A17	A
17	anticipation	2	Orange	Positive 2	A17	A
19	trust	4	Orange	Positive 2	A17	A
21	anticipation	2	Orange	Positive 2	A17	A
22	anticipation	5	Orange	Positive 2	A17	A

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
2	joy	7	Orange	Positive 3	B14	B
4	joy	4	Orange	Positive 3	B14	B
6	trust	5	Orange	Positive 3	B14	B
8	trust	3	Orange	Positive 3	B14	B
10	trust	3	Orange	Positive 3	B14	B
12	joy	4	Orange	Positive 3	B14	B
14	anticipation	5	Orange	Positive 3	B14	B
16	anticipation	5	Orange	Positive 3	B14	B
18	joy	3	Orange	Positive 3	B14	B
20	joy	4	Orange	Positive 3	B14	B
2	surprise	7	Orange	Positive 4	B17	B
4	joy	5	Orange	Positive 4	B17	B
6	joy	5	Orange	Positive 4	B17	B
8	joy	3	Orange	Positive 4	B17	B
10	joy	7	Orange	Positive 4	B17	B
12	joy	4	Orange	Positive 4	B17	B
14	anticipation	5	Orange	Positive 4	B17	B
16	surprise	4	Orange	Positive 4	B17	B
18	joy	4	Orange	Positive 4	B17	B
20	anticipation	2	Orange	Positive 4	B17	B
1	sadness	4	Strawberry	Negative 1	A21	A
3	disgust	2	Strawberry	Negative 1	A21	A
5	surprise	4	Strawberry	Negative 1	A21	A
7	surprise	5	Strawberry	Negative 1	A21	A
9	surprise	4	Strawberry	Negative 1	A21	A
11	disgust	1	Strawberry	Negative 1	A21	A
13	fear	3	Strawberry	Negative 1	A21	A
15	fear	3	Strawberry	Negative 1	A21	A
17	disgust	2	Strawberry	Negative 1	A21	A
19	anticipation	4	Strawberry	Negative 1	A21	A

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
21	fear	3	Strawberry	Negative 1	A21	A
22	surprise	4	Strawberry	Negative 1	A21	A
1	fear	5	Strawberry	Negative 2	A24	A
3	sadness	3	Strawberry	Negative 2	A24	A
5	anger	6	Strawberry	Negative 2	A24	A
7	sadness	7	Strawberry	Negative 2	A24	A
9	surprise	4	Strawberry	Negative 2	A24	A
11	sadness	1	Strawberry	Negative 2	A24	A
13	surprise	5	Strawberry	Negative 2	A24	A
15	sadness	2	Strawberry	Negative 2	A24	A
17	neutral	0	Strawberry	Negative 2	A24	A
19	fear	4	Strawberry	Negative 2	A24	A
21	sadness	2	Strawberry	Negative 2	A24	A
22	surprise	3	Strawberry	Negative 2	A24	A
2	disgust	7	Strawberry	Negative 3	B21	B
4	neutral	0	Strawberry	Negative 3	B21	B
6	disgust	4	Strawberry	Negative 3	B21	B
8	surprise	4	Strawberry	Negative 3	B21	B
10	anticipation	4	Strawberry	Negative 3	B21	B
12	surprise	5	Strawberry	Negative 3	B21	B
14	surprise	6	Strawberry	Negative 3	B21	B
16	surprise	5	Strawberry	Negative 3	B21	B
18	anticipation	3	Strawberry	Negative 3	B21	B
20	neutral	0	Strawberry	Negative 3	B21	B
2	disgust	2	Strawberry	Negative 4	B24	B
4	surprise	3	Strawberry	Negative 4	B24	B
6	disgust	1	Strawberry	Negative 4	B24	B
8	surprise	3	Strawberry	Negative 4	B24	B
10	disgust	6	Strawberry	Negative 4	B24	B
12	disgust	3	Strawberry	Negative 4	B24	B

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
14	fear	3	Strawberry	Negative 4	B24	B
16	surprise	6	Strawberry	Negative 4	B24	B
18	sadness	3	Strawberry	Negative 4	B24	B
20	anticipation	3	Strawberry	Negative 4	B24	B
1	joy	4	Strawberry	Neutral 1	A19	A
3	trust	3	Strawberry	Neutral 1	A19	A
5	anticipation	4	Strawberry	Neutral 1	A19	A
7	anticipation	5	Strawberry	Neutral 1	A19	A
9	neutral	0	Strawberry	Neutral 1	A19	A
11	neutral	0	Strawberry	Neutral 1	A19	A
13	surprise	4	Strawberry	Neutral 1	A19	A
15	surprise	6	Strawberry	Neutral 1	A19	A
17	neutral	0	Strawberry	Neutral 1	A19	A
19	neutral	0	Strawberry	Neutral 1	A19	A
21	anticipation	4	Strawberry	Neutral 1	A19	A
22	surprise	5	Strawberry	Neutral 1	A19	A
1	neutral	0	Strawberry	Neutral 2	A22	A
3	sadness	1	Strawberry	Neutral 2	A22	A
5	neutral	0	Strawberry	Neutral 2	A22	A
7	neutral	0	Strawberry	Neutral 2	A22	A
9	trust	4	Strawberry	Neutral 2	A22	A
11	neutral	0	Strawberry	Neutral 2	A22	A
13	neutral	0	Strawberry	Neutral 2	A22	A
15	fear	1	Strawberry	Neutral 2	A22	A
17	neutral	0	Strawberry	Neutral 2	A22	A
19	anticipation	4	Strawberry	Neutral 2	A22	A
21	anticipation	3	Strawberry	Neutral 2	A22	A
22	trust	5	Strawberry	Neutral 2	A22	A
2	anticipation	2	Strawberry	Neutral 3	B19	B
4	trust	5	Strawberry	Neutral 3	B19	B

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
6	joy	5	Strawberry	Neutral 3	B19	B
8	surprise	3	Strawberry	Neutral 3	B19	B
10	trust	3	Strawberry	Neutral 3	B19	B
12	surprise	4	Strawberry	Neutral 3	B19	B
14	anticipation	4	Strawberry	Neutral 3	B19	B
16	anticipation	4	Strawberry	Neutral 3	B19	B
18	neutral	0	Strawberry	Neutral 3	B19	B
20	surprise	2	Strawberry	Neutral 3	B19	B
2	joy	7	Strawberry	Neutral 4	B22	B
4	surprise	4	Strawberry	Neutral 4	B22	B
6	surprise	5	Strawberry	Neutral 4	B22	B
8	joy	3	Strawberry	Neutral 4	B22	B
10	joy	2	Strawberry	Neutral 4	B22	B
12	trust	3	Strawberry	Neutral 4	B22	B
14	surprise	5	Strawberry	Neutral 4	B22	B
16	joy	5	Strawberry	Neutral 4	B22	B
18	trust	2	Strawberry	Neutral 4	B22	B
20	disgust	1	Strawberry	Neutral 4	B22	B
1	anticipation	3	Strawberry	Positive 1	A20	A
3	anger	2	Strawberry	Positive 1	A20	A
5	joy	4	Strawberry	Positive 1	A20	A
7	trust	6	Strawberry	Positive 1	A20	A
9	trust	5	Strawberry	Positive 1	A20	A
11	joy	7	Strawberry	Positive 1	A20	A
13	joy	4	Strawberry	Positive 1	A20	A
15	joy	6	Strawberry	Positive 1	A20	A
17	joy	4	Strawberry	Positive 1	A20	A
19	joy	6	Strawberry	Positive 1	A20	A
21	joy	5	Strawberry	Positive 1	A20	A
22	trust	6	Strawberry	Positive 1	A20	A

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
1	anticipation	5	Strawberry	Positive 2	A23	A
3	joy	5	Strawberry	Positive 2	A23	A
5	joy	6	Strawberry	Positive 2	A23	A
7	joy	7	Strawberry	Positive 2	A23	A
9	anticipation	5	Strawberry	Positive 2	A23	A
11	surprise	1	Strawberry	Positive 2	A23	A
13	anticipation	5	Strawberry	Positive 2	A23	A
15	joy	6	Strawberry	Positive 2	A23	A
17	anticipation	3	Strawberry	Positive 2	A23	A
19	trust	1	Strawberry	Positive 2	A23	A
21	trust	5	Strawberry	Positive 2	A23	A
22	trust	4	Strawberry	Positive 2	A23	A
2	joy	7	Strawberry	Positive 3	B20	B
4	joy	5	Strawberry	Positive 3	B20	B
6	joy	6	Strawberry	Positive 3	B20	B
8	joy	6	Strawberry	Positive 3	B20	B
10	neutral	0	Strawberry	Positive 3	B20	B
12	joy	7	Strawberry	Positive 3	B20	B
14	joy	6	Strawberry	Positive 3	B20	B
16	trust	4	Strawberry	Positive 3	B20	B
18	joy	5	Strawberry	Positive 3	B20	B
20	surprise	3	Strawberry	Positive 3	B20	B
2	joy	7	Strawberry	Positive 4	B23	B
4	joy	2	Strawberry	Positive 4	B23	B
6	joy	6	Strawberry	Positive 4	B23	B
8	trust	4	Strawberry	Positive 4	B23	B
10	trust	7	Strawberry	Positive 4	B23	B
12	joy	4	Strawberry	Positive 4	B23	B
14	joy	4	Strawberry	Positive 4	B23	B
16	joy	4	Strawberry	Positive 4	B23	B

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
18	joy	7	Strawberry	Positive 4	B23	B
20	joy	5	Strawberry	Positive 4	B23	B
1	fear	3	Water	Negative 1	A9	A
3	surprise	2	Water	Negative 1	A9	A
5	anticipation	3	Water	Negative 1	A9	A
7	disgust	3	Water	Negative 1	A9	A
9	anger	2	Water	Negative 1	A9	A
11	disgust	2	Water	Negative 1	A9	A
13	fear	3	Water	Negative 1	A9	A
15	fear	5	Water	Negative 1	A9	A
17	disgust	3	Water	Negative 1	A9	A
19	neutral	0	Water	Negative 1	A9	A
21	disgust	2	Water	Negative 1	A9	A
22	disgust	7	Water	Negative 1	A9	A
1	disgust	5	Water	Negative 2	A12	A
3	sadness	3	Water	Negative 2	A12	A
5	anticipation	3	Water	Negative 2	A12	A
7	anger	6	Water	Negative 2	A12	A
9	anticipation	1	Water	Negative 2	A12	A
11	sadness	3	Water	Negative 2	A12	A
13	sadness	3	Water	Negative 2	A12	A
15	sadness	5	Water	Negative 2	A12	A
17	sadness	2	Water	Negative 2	A12	A
19	fear	1	Water	Negative 2	A12	A
21	sadness	2	Water	Negative 2	A12	A
22	sadness	5	Water	Negative 2	A12	A
2	disgust	2	Water	Negative 3	B9	B
4	fear	3	Water	Negative 3	B9	B
6	anticipation	3	Water	Negative 3	B9	B
8	neutral	0	Water	Negative 3	B9	B

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
10	disgust	4	Water	Negative 3	B9	B
12	disgust	1	Water	Negative 3	B9	B
14	disgust	1	Water	Negative 3	B9	B
16	anticipation	4	Water	Negative 3	B9	B
18	anticipation	1	Water	Negative 3	B9	B
20	anticipation	2	Water	Negative 3	B9	B
2	sadness	4	Water	Negative 4	B12	B
4	disgust	3	Water	Negative 4	B12	B
6	disgust	4	Water	Negative 4	B12	B
8	disgust	3	Water	Negative 4	B12	B
10	anger	3	Water	Negative 4	B12	B
12	neutral	0	Water	Negative 4	B12	B
14	disgust	5	Water	Negative 4	B12	B
16	disgust	3	Water	Negative 4	B12	B
18	sadness	1	Water	Negative 4	B12	B
20	disgust	1	Water	Negative 4	B12	B
1	anticipation	4	Water	Neutral 1	A7	A
3	neutral	0	Water	Neutral 1	A7	A
5	trust	4	Water	Neutral 1	A7	A
7	disgust	6	Water	Neutral 1	A7	A
9	neutral	0	Water	Neutral 1	A7	A
11	neutral	0	Water	Neutral 1	A7	A
13	neutral	0	Water	Neutral 1	A7	A
15	neutral	0	Water	Neutral 1	A7	A
17	neutral	0	Water	Neutral 1	A7	A
19	neutral	0	Water	Neutral 1	A7	A
21	neutral	0	Water	Neutral 1	A7	A
22	neutral	0	Water	Neutral 1	A7	A
1	neutral	0	Water	Neutral 2	A10	A
3	neutral	0	Water	Neutral 2	A10	A

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
5	neutral	0	Water	Neutral 2	A10	A
7	neutral	0	Water	Neutral 2	A10	A
9	neutral	0	Water	Neutral 2	A10	A
11	neutral	0	Water	Neutral 2	A10	A
13	neutral	0	Water	Neutral 2	A10	A
15	neutral	0	Water	Neutral 2	A10	A
17	neutral	0	Water	Neutral 2	A10	A
19	anger	4	Water	Neutral 2	A10	A
21	neutral	0	Water	Neutral 2	A10	A
22	neutral	0	Water	Neutral 2	A10	A
2	neutral	0	Water	Neutral 3	B7	B
4	anticipation	2	Water	Neutral 3	B7	B
6	neutral	0	Water	Neutral 3	B7	B
8	neutral	0	Water	Neutral 3	B7	B
10	neutral	0	Water	Neutral 3	B7	B
12	neutral	0	Water	Neutral 3	B7	B
14	anticipation	2	Water	Neutral 3	B7	B
16	neutral	0	Water	Neutral 3	B7	B
18	neutral	0	Water	Neutral 3	B7	B
20	neutral	0	Water	Neutral 3	B7	B
2	neutral	0	Water	Neutral 4	B10	B
4	surprise	2	Water	Neutral 4	B10	B
6	surprise	4	Water	Neutral 4	B10	B
8	anticipation	3	Water	Neutral 4	B10	B
10	neutral	0	Water	Neutral 4	B10	B
12	neutral	0	Water	Neutral 4	B10	B
14	neutral	0	Water	Neutral 4	B10	B
16	anticipation	3	Water	Neutral 4	B10	B
18	neutral	0	Water	Neutral 4	B10	B
20	neutral	0	Water	Neutral 4	B10	B

Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
1	anticipation	5	Water	Positive 1	A8	A
3	joy	1	Water	Positive 1	A8	A
5	joy	3	Water	Positive 1	A8	A
7	joy	5	Water	Positive 1	A8	A
9	neutral	0	Water	Positive 1	A8	A
11	joy	4	Water	Positive 1	A8	A
13	joy	3	Water	Positive 1	A8	A
15	joy	5	Water	Positive 1	A8	A
17	neutral	0	Water	Positive 1	A8	A
19	anticipation	4	Water	Positive 1	A8	A
21	joy	4	Water	Positive 1	A8	A
22	neutral	0	Water	Positive 1	A8	A
1	anticipation	5	Water	Positive 2	A11	A
3	disgust	3	Water	Positive 2	A11	A
5	joy	3	Water	Positive 2	A11	A
7	sadness	3	Water	Positive 2	A11	A
9	joy	5	Water	Positive 2	A11	A
11	neutral	0	Water	Positive 2	A11	A
13	anticipation	3	Water	Positive 2	A11	A
15	anticipation	2	Water	Positive 2	A11	A
17	neutral	0	Water	Positive 2	A11	A
19	anticipation	3	Water	Positive 2	A11	A
21	trust	2	Water	Positive 2	A11	A
22	neutral	0	Water	Positive 2	A11	A
2	joy	5	Water	Positive 3	B8	B
4	anticipation	2	Water	Positive 3	B8	B
6	surprise	4	Water	Positive 3	B8	B
8	neutral	0	Water	Positive 3	B8	B
10	trust	3	Water	Positive 3	B8	B
12	joy	1	Water	Positive 3	B8	B

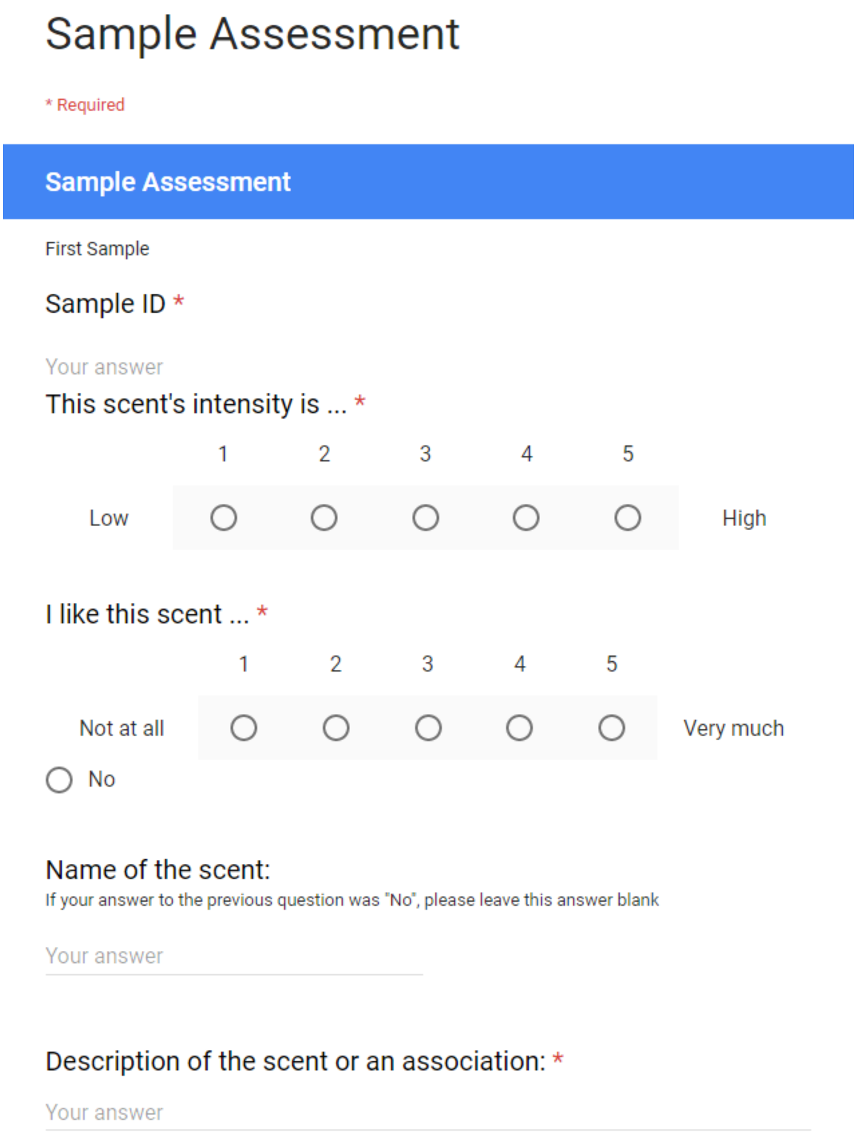
Table A.4 continued from previous page

Part. #	Emotion	Strength	Odour	Image	ID	Group
14	joy	1	Water	Positive 3	B8	B
16	anticipation	5	Water	Positive 3	B8	B
18	disgust	1	Water	Positive 3	B8	B
20	trust	4	Water	Positive 3	B8	B
2	neutral	0	Water	Positive 4	B11	B
4	neutral	0	Water	Positive 4	B11	B
6	sadness	5	Water	Positive 4	B11	B
8	neutral	0	Water	Positive 4	B11	B
10	neutral	0	Water	Positive 4	B11	B
12	joy	3	Water	Positive 4	B11	B
14	joy	5	Water	Positive 4	B11	B
16	anticipation	3	Water	Positive 4	B11	B
18	neutral	0	Water	Positive 4	B11	B
20	anticipation	3	Water	Positive 4	B11	B

Appendix B

Study Two

B.1 Odour Selection Task Questionnaire


Sample Assessment

* Required

Sample Assessment

First Sample

Sample ID *

Your answer

This scent's intensity is ... *

	1	2	3	4	5	
Low	○	○	○	○	○	High

I like this scent ... *

	1	2	3	4	5	
Not at all	○	○	○	○	○	Very much

○ No

Name of the scent:

If your answer to the previous question was "No", please leave this answer blank

Your answer

Description of the scent or an association: *

Your answer

Figure B.1: Study Two Odour Selection Task Questionnaire (OSQ), part I

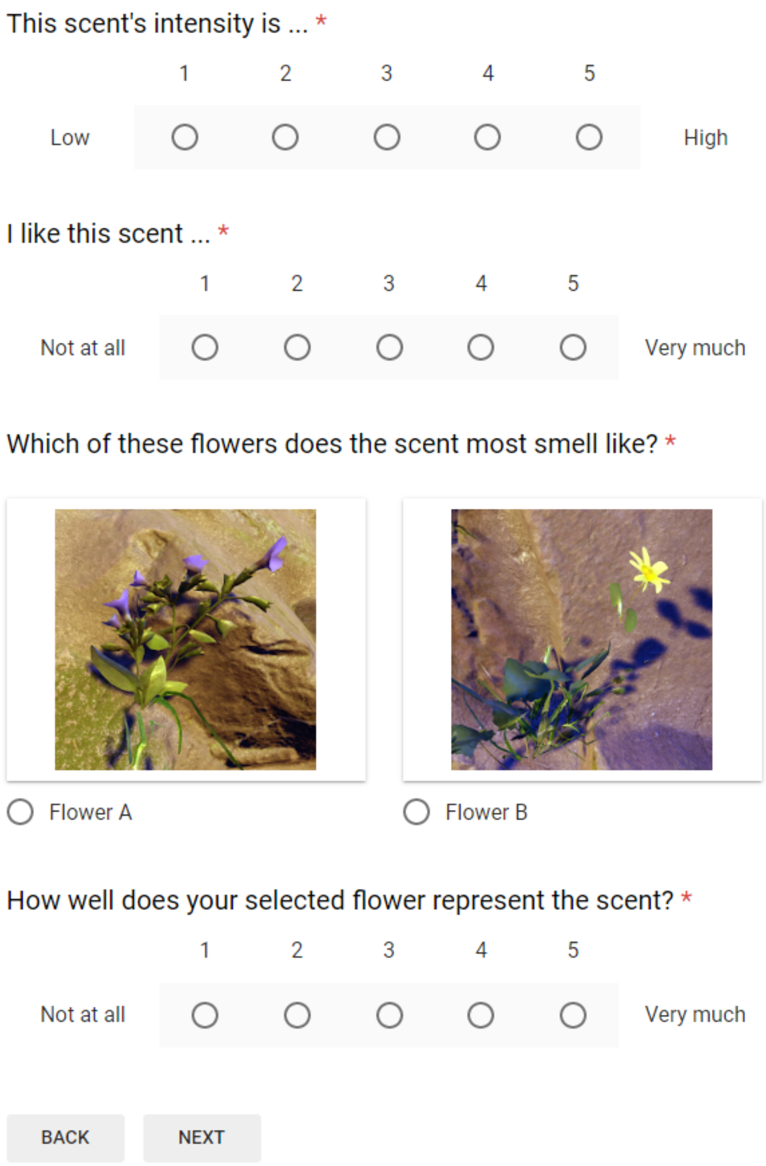


Figure B.2: Study Two Odour Selection Task Questionnaire (OSQ), part II

Participant ID	Gender	Age
1	Female	62
2	Female	27
3	Male	28
4	Female	31
5	Female	30
6	Female	47
7	Male	32
8	Male	31

Table B.1: Odour selection task participant demographics.

B.2 Participant Odour Associations and Descriptions

ID	Mimosa	Passion Flower
1	flowery, perfume smell	shaving creaM
2	detergent	mens perfume
3	Floral, sweet, sugary and fruity	Sweet, flowery with a hint of caramel
4	very sweet like passion fruit juice or sherbert	light hippie floral extract
5	orange-y, fruity	fruity, creamy
6	Fruit-flavoured sweets	Pot pourri
7	fruit juice	Sandalwood soap
8	Very sweet, like a nice shampoo	like a medicine

Table B.2: Participant Odour Associations and Descriptions

ID	Gardenia	Lily of the Valley
1	FRUITY CHEWING GUM	BABY POWDER
2	detergent/shampoo	toilet paper
3	Like the cosmetics and perfume floor of a large and busy department store	Flowery, sweet, light
4	soft sweet smell	soft rose smell
5	bath oil, sweet, a bit fake, soapy	vanilla
6	Floral fabric softener, maybe jasmine?	Floral air freshener-ish
7	Perfume	Room freshners
8	soapy	A flowery shampoo, very mellow

Table B.3: Participant Odour Associations and Descriptions

ID	White Rose	Forget Me Not
1	Lilac	Flowery peony smell
2	moisturiser	flowery, body wash
3	Flowery, sweet, caramelly overtones with leathery end note	Citrusy with wood notes and a harsh earthy/peaty end
4	baby powder	a hint of hay - reminds me of fields with buttercups
5	almond, vanilla-y	Lavender soap
6	Flowery	Nasty, cheap toilet air freshener
7	car freshner	Flowers bouquets
8	sweet, soapy, laundry detergent-like	Soap or flower

Table B.4: Participant Odour Associations and Descriptions

ID	**Freesia**	**Honeysuckle**
1	Sweet fruity smell	sweet flowery smell
2	bad soap	sweet flower
3	Sweet, colourful and floral	Chemically smell with floral undertones
4	its smells sweet like juice or sherbert	soft floral scent like a good bathroom spray or candle
5	orange peel, a bit cinnamon-y, honey, sweet, floral	chamomille
6	Flowery, but fresh and slightly fruity, sweet	Old lady flower arrangement
7	Car freshner	flower
8	sweet at first, strong bitter smell after	a yellow flower

Table B.5: Participant Odour Associations and Descriptions

ID	**Chamomile**	**Bergamot**
1	Flowery	Woody musky smell
2	bubblegum, sweets	Orange liqueur
3	Fruity with a slight floral tone	Citrusy, floral with top notes of lemon-grass and a hint of peach or nectarine
4	fresh floral, very natural and wile	lemon cleaner, but also beachy
5	fruity, a bit creamy	Grapefruit, Cherry, very familiar
6	Flowery but slightly fruity	Citrussy. Fresh.
7	Room freshner	Leather
8	zesty, like a candy	some kind of Indian spice or peppercorn, kind of fishy after a while

Table B.6: Participant Odour Associations and Descriptions

ID	**Geranium**	**Lavender**
1	citrus, grassy, herb	harsh, sterilizing liquid,
2	mosquito spray	musky, mountains
3	Citrus, Ethanol and Iodine	Chemically and astrigent
4	smells just like those Fishermans Helper lozenges taste	lavendar
5	Lemony, a bit eucaluptus-y or minty, fresh	Lavender. I was wrong before I suppose - this is Lavender.
6	Cheap pot pourri	Lavender, relaxing, sleeping
7	Shopping malls	Room freshner
8	Smells like a flower or paint thinner	Smells like flowers or soap

Table B.7: Participant Odour Associations and Descriptions

B.3 Odour Selection Task Questionnaire Results

Abbreviation	Meaning
Perceive	Do you perceive a scent?
Recognise	Do you recognize the scent?
Intensity	This scent's intensity is ...
Pleasantness	I like this scent ...
Congruence	Which of these flowers does the scent most smell like?
How well	How well does your selected flower represent the scent?

Table B.8: Abbreviations of questionnaire items for the odour selection task questionnaires

Mimosa

ID	Perceive	Recognise	Intensity	Pleasantness	Congruence	How well
1	Yes	No	4	3	Flower A	3
2	Yes	Yes	2	3	Flower A	2
3	Yes	Yes	5	5	Flower B	3
4	Yes	Yes	4	5	Flower B	2
5	Yes	No	5	2	Flower B	2
6	Yes	Yes	2	4	Flower B	1
7	Yes	No	5	5	Flower A	3
8	Yes	No	3	5	Flower A	4

Table B.9: Odour Selection Task Questionnaire Results

Passion Flower

ID	Perceive	Recognise	Intensity	Pleasantness	Congruence	How well
1	Yes	No	2	2	Flower A	2
2	Yes	No	3	2	Flower B	1
3	Yes	Yes	4	4	Flower A	3
4	Yes	No	4	2	Flower B	1
5	Yes	No	3	4	Flower B	4
6	Yes	No	2	1	Flower A	2
7	Yes	Yes	3	5	Flower B	1
8	Yes	Yes	3	1	Flower B	2

Table B.10: Odour Selection Task Questionnaire Results

Gardenia

ID	Perceive	Recognise	Intensity	Pleasantness	Congruence	How well
1	Yes	No	2	1	Flower B	1
2	Yes	Yes	2	3	Flower A	3
3	Yes	Yes	5	4	Flower A	4
4	Yes	Yes	2	5	Flower B	2
5	Yes	Yes	4	2	Flower A	4
6	Yes	No	2	3	Flower A	4
7	Yes	Yes	4	4	Flower A	4
8	Yes	Yes	4	3	Flower A	3

Table B.11: Odour Selection Task Questionnaire Results

Lily of the Valley

ID	Perceive	Recognise	Intensity	Pleasantness	Congruence	How well
1	Yes	No	1	1	Flower B	1
2	Yes	No	1	2	Flower A	3
3	Yes	Yes	5	4	Flower A	4
4	Yes	Yes	4	5	Flower A	2
5	Yes	No	2	2	Flower A	4
6	Yes	No	2	2	Flower A	3
7	Yes	No	4	4	Flower B	4
8	Yes	No	4	4	Flower A	5

Table B.12: Odour Selection Task Questionnaire Results

White Rose

ID	Perceive	Recognise	Intensity	Pleasantness	Congruence	How well
1	Yes	No	2	1	Flower A	2
2	Yes	Yes	2	3	Flower A	2
3	Yes	Yes	5	5	Flower A	4
4	Yes	Yes	4	4	Flower A	1
5	Yes	Yes	4	3	Flower A	2
6	Yes	No	3	1	Flower A	2
7	Yes	No	5	4	Flower A	1
8	Yes	No	3	4	Flower A	3

Table B.13: Odour Selection Task Questionnaire Results

Forget Me Not

ID	Perceive	Recognise	Intensity	Pleasantness	Congruence	How well
1	Yes	Yes	3	4	Flower A	3
2	Yes	No	2	3	Flower A	2
3	Yes	Yes	5	2	Flower A	1
4	Yes	No	4	3	Flower B	4
5	Yes	Yes	4	3	Flower A	3
6	Yes	No	4	1	Flower A	1
7	Yes	Yes	4	4	Flower B	3
8	Yes	Yes	3	5	Flower B	2

Table B.14: Odour Selection Task Questionnaire Results

Freesia

ID	Perceive	Recognise	Intensity	Pleasantness	Congruence	How well
1	Yes	Yes	3	4	Flower B	3
2	Yes	No	2	2	Flower B	2
3	Yes	Yes	5	5	Flower B	4
4	Yes	Yes	4	5	Flower B	2
5	Yes	Yes	4	4	Flower B	4
6	Yes	No	3	3	Flower A	2
7	Yes	No	3	2	Flower B	3
8	Yes	No	4	3	Flower B	2

Table B.15: Odour Selection Task Questionnaire Results

Honeysuckle

ID	Perceive	Recognise	Intensity	Pleasantness	Congruence	How well
1	Yes	Yes	2	2	Flower A	3
2	Yes	Yes	3	4	Flower B	3
3	Yes	No	3	3	Flower A	3
4	Yes	Yes	1	4	Flower A	3
5	Yes	Yes	4	3	Flower B	4
6	Yes	No	2	1	Flower A	2
7	Yes	Yes	5	5	Flower B	4
8	Yes	Yes	3	4	Flower B	5

Table B.16: Odour Selection Task Questionnaire Results

Chamomile

ID	Perceive	Recognise	Intensity	Pleasantness	Congruence	How well
1	Yes	No	2	2	Flower A	1
2	Yes	Yes	3	3	Flower B	3
3	Yes	Yes	5	4	Flower B	1
4	Yes	No	4	4	Flower A	4
5	Yes	No	5	2	Flower B	4
6	Yes	No	3	4	Flower B	3
7	Yes	No	4	3	Flower B	3
8	Yes	Yes	4	4	Flower A	3

Table B.17: Odour Selection Task Questionnaire Results

Bergamot

ID	Perceive	Recognise	Intensity	Pleasantness	Congruence	How well
1	Yes	Yes	3	2	Flower B	2
2	Yes	No	2	2	Flower A	1
3	Yes	Yes	5	3	Flower B	2
4	Yes	Yes	5	2	Flower B	1
5	Yes	No	5	4	Flower B	4
6	Yes	Yes	3	5	Flower B	1
7	Yes	No	5	2	Flower A	2
8	Yes	No	3	1	Flower A	2

Table B.18: Odour Selection Task Questionnaire Results

Geranium

ID	Perceive	Recognise	Intensity	Pleasantness	Congruence	How well
1	Yes	Yes	3	3	Flower B	3
2	Yes	Yes	3	3	Flower B	3
3	Yes	No	4	2	Flower A	1
4	Yes	Yes	5	3	Flower B	1
5	Yes	Yes	4	4	Flower B	3
6	Yes	No	4	1	Flower A	2
7	Yes	No	5	3	Flower A	1
8	Yes	No	3	3	Flower B	4

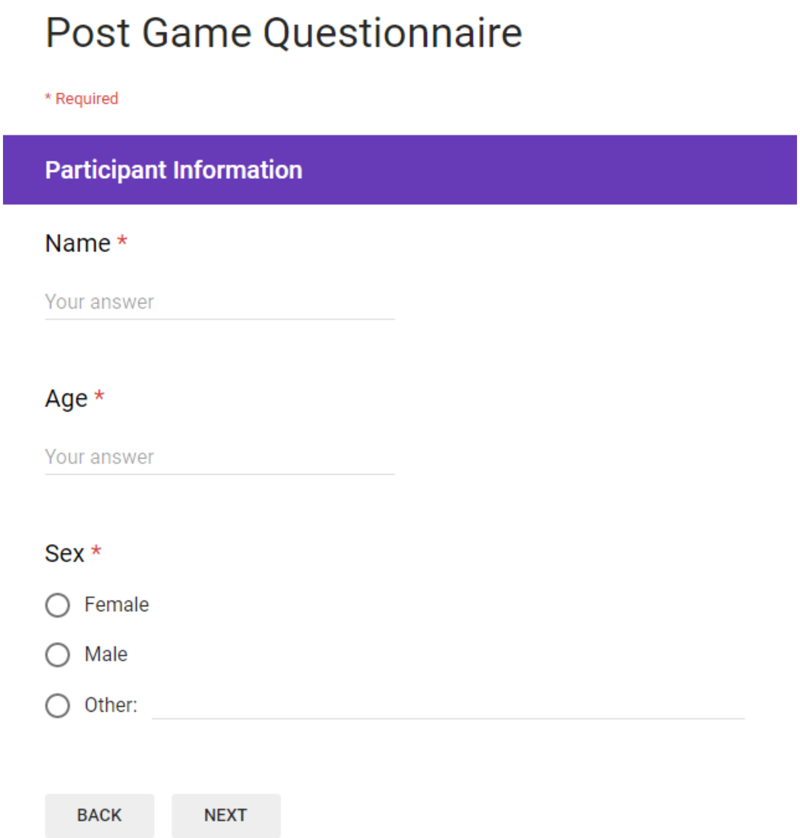
Table B.19: Odour Selection Task Questionnaire Results

Lavender

ID	Perceive	Recognise	Intensity	Pleasantness	Congruence	How well
1	Yes	Yes	3	1	Flower B	1
2	Yes	Yes	3	4	Flower A	3
3	Yes	No	3	2	Flower A	1
4	Yes	Yes	5	4	Flower A	4
5	Yes	Yes	4	4	Flower A	3
6	Yes	Yes	3	4	Flower A	4
7	Yes	No	4	2	Flower B	3
8	Yes	Yes	4	5	Flower A	5

Table B.20: Odour Selection Task Questionnaire Results

B.4 Post Game Questionnaire



Post Game Questionnaire

* Required

Participant Information

Name *

Your answer

Age *

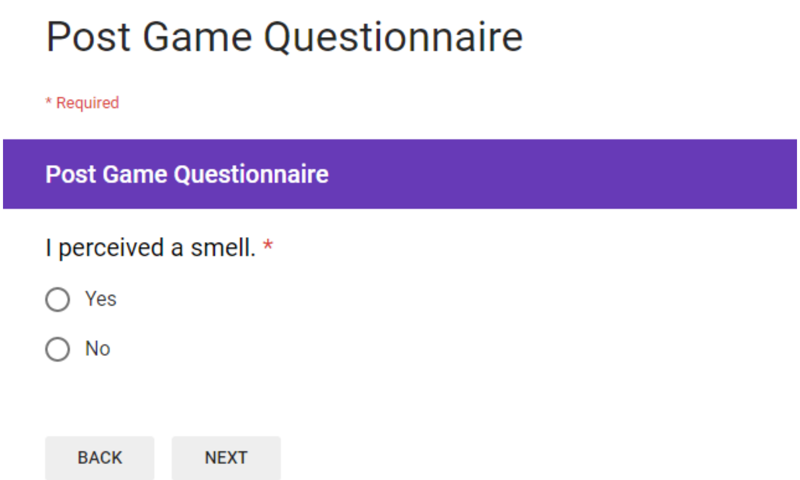
Your answer

Sex *

- Female
- Male
- Other:

BACK NEXT

Figure B.3: Post Game Questionnaire - Page 1



Post Game Questionnaire

* Required

Post Game Questionnaire

I perceived a smell. *

- Yes
- No

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Figure B.4: Post Game Questionnaire - Page 2

Post Game Questionnaire

* Required

Presence Questionnaire

Please answer the following questions by marking the relevant number. In particular, remember that these questions are asking you about how you felt at the end of the game.

To what extent did you feel you were focused on the game? *

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	A lot

To what extent were you aware of yourself in your surroundings? *

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very aware

At any point did you find yourself become so involved that you were unaware you were even using controls? *

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very much so

Were there any times during the game in which you just wanted to give up? *

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	A lot

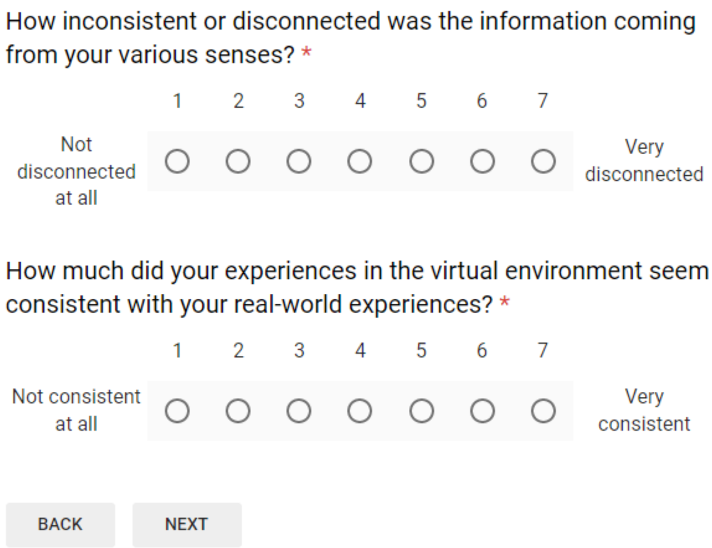
To what extent did you feel emotionally attached to the game? *

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very much so

How completely were all of your senses engaged? *

	1	2	3	4	5	6	7	
Not complete at all	○	○	○	○	○	○	○	Very complete

Figure B.5: Post Game Questionnaire - Page 3



How inconsistent or disconnected was the information coming from your various senses? *

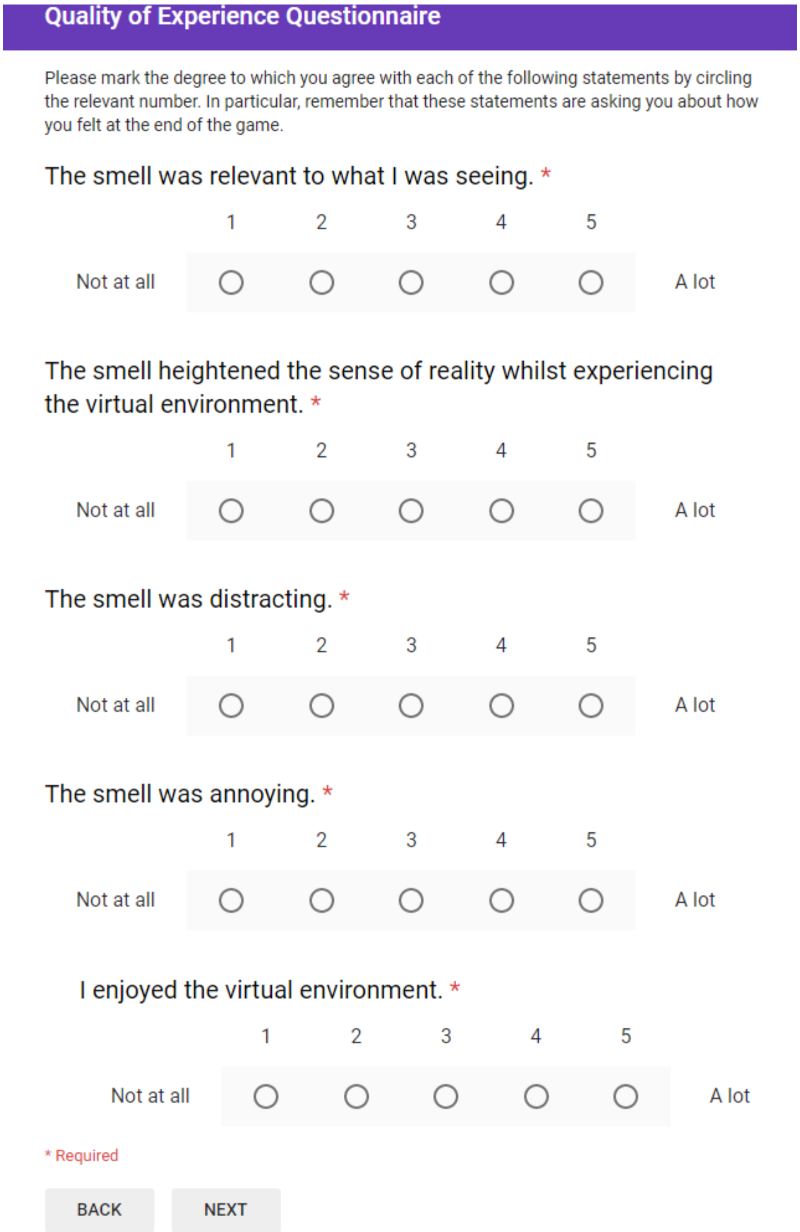
	1	2	3	4	5	6	7	
Not disconnected at all	○	○	○	○	○	○	○	Very disconnected

How much did your experiences in the virtual environment seem consistent with your real-world experiences? *

	1	2	3	4	5	6	7	
Not consistent at all	○	○	○	○	○	○	○	Very consistent

BACK NEXT

Figure B.6: Post Game Questionnaire - Page 3 continued



Quality of Experience Questionnaire

Please mark the degree to which you agree with each of the following statements by circling the relevant number. In particular, remember that these statements are asking you about how you felt at the end of the game.

The smell was relevant to what I was seeing. *

	1	2	3	4	5	
Not at all	○	○	○	○	○	A lot

The smell heightened the sense of reality whilst experiencing the virtual environment. *

	1	2	3	4	5	
Not at all	○	○	○	○	○	A lot

The smell was distracting. *

	1	2	3	4	5	
Not at all	○	○	○	○	○	A lot

The smell was annoying. *

	1	2	3	4	5	
Not at all	○	○	○	○	○	A lot

I enjoyed the virtual environment. *

	1	2	3	4	5	
Not at all	○	○	○	○	○	A lot

* Required

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Figure B.7: Post Game Questionnaire - Page 1

B.5 Post Game Questionnaire Results

ID	Age	Gender
O-NO1	30	Female
O-NO2	33	Female
O-NO3	32	Male
O-NO4	27	Male
O-NO5	30	Male
O-NO6	42	Male
O-NO7	28	Female
O-NO8	36	Male
O-NO9	29	Female
O-NO10	24	Female
NO-O1	31	Male
NO-O2	29	Male
NO-O3	40	Female
NO-O4	30	Male
NO-O5	34	Male
NO-O6	28	Male
NO-O7	28	Female
NO-O8	29	Female
NO-O9	27	Female
NO-O10	26	Female

Table B.21: Participant Demographics

Abbreviation	Question
Focused	To what extent did you feel you were focused on the game?
Aware	To what extent were you aware of yourself in your surroundings?
Involved	At any point did you find yourself become so involved that you were unaware you were even using controls?
Give Up	Were there any times during the game in which you just wanted to give up?
Emotional	To what extent did you feel emotionally attached to the game?
Senses Engaged	How completely were all of your senses engaged?
Inconsistent	How inconsistent or disconnected was the information coming from your various senses?
Consistent	How much did your experiences in the virtual environment seem consistent with your real-world experiences?

Table B.22: Abbreviations for the Jennet et al. and Witmer and Singer Presence Questionnaire items.

ID	Focused	Aware	Involved	Give Up	Emotional	Senses Engaged	Inconsistent	Consistent
O-NO1	4	4	2	4	5	3	3	2
O-NO2	7	1	5	1	7	6	3	6
O-NO3	6	6	4	1	2	6	5	5
O-NO4	6	3	5	3	5	4	4	5
O-NO5	7	1	7	1	4	2	1	3
O-NO6	5	6	4	6	6	5	4	4
O-NO7	7	1	6	1	6	4	2	6
O-NO8	5	2	4	1	6	4	4	2
O-NO9	6	3	5	1	6	5	3	4
O-NO1	7	5	5	1	3	2	6	7
NO-O1	7	1	6	1	7	5	4	6
NO-O2	6	6	6	3	5	6	2	6
NO-O3	7	2	5	1	7	6	1	5
NO-O4	6	2	6	3	7	7	3	6
NO-O5	7	5	3	1	3	5	3	4
NO-O6	7	5	5	1	6	5	2	2
NO-O7	7	2	2	1	7	5	4	5
NO-O8	7	2	7	3	5	5	1	5
NO-O9	6	2	5	1	3	4	3	5
NO-O1	6	2	3	1	6	6	2	7

Table B.23: Results of the Jennet et al. and Witmer and Singer Presence Questionnaire for the Odour Condition

ID	Focused	Aware	Involved	Give Up	Emo-tional	Senses En-gaged	Incon-sistent	Consis-tent
O-NO1	6	2	3	3	6	6	2	6
O-NO2	7	3	7	1	6	6	2	5
O-NO3	7	2	6	1	3	6	4	6
O-NO4	7	2	3	5	6	6	1	6
O-NO5	7	1	7	1	5	5	1	5
O-NO6	7	4	4	6	7	7	3	4
O-NO7	7	3	5	2	6	6	2	5
O-NO8	5	1	5	1	5	5	4	1
O-NO9	7	3	4	1	6	6	3	5
O-NO1	7	5	6	1	7	7	2	6
NO-O1	7	1	6	1	7	7	1	6
NO-O2	6	6	2	1	6	6	2	6
NO-O3	7	1	5	1	7	7	2	6
NO-O4	7	2	5	1	6	4	2	6
NO-O5	7	4	5	1	3	6	2	5
NO-O6	7	3	6	1	7	7	5	4
NO-O7	7	3	6	5	7	6	5	5
NO-O8	7	2	7	1	6	6	1	4
NO-O9	6	2	6	1	6	6	2	6
NO-O1	7	2	5	1	7	7	3	7

Table B.24: Results of the Jennet et al. and Witmer and Singer Presence Questionnaire for the Odour Condition

Abbreviation	Question
Relevant	The smell was relevant to what I was seeing.
Sense of Reality	The smell heightened the sense of reality whilst experiencing the virtual environment.
Distracting	The smell was distracting.
Annoying	The smell was annoying.
Enjoyment	I enjoyed the virtual environment.

Table B.25: Abbreviations for the Quality of Experience Questionnaire items.

ID	Relevant	Sense of Reality	Distracting	Annoying	Enjoyment
O-NO1	5	5	1	1	4
O-NO2	4	4	1	1	4
O-NO3	5	5	2	1	5
O-NO4	4	4	1	1	5
O-NO5	4	5	1	1	5
O-NO6	3	5	1	1	5
O-NO7	4	5	1	1	5
O-NO8	1	5	3	1	5
O-NO9	5	5	2	1	5
O-NO10	4	5	2	2	5
NO-O1	5	5	1	1	5
NO-O2	5	5	1	1	5
NO-O3	2	5	1	1	5
NO-O4	4	4	1	2	5
NO-O5	4	5	1	2	5
NO-O6	5	5	3	1	5
NO-O7	3	3	1	1	5
NO-O8	4	3	2	2	5
NO-O9	3	5	1	1	5
NO-O10	4	4	3	2	5

Table B.26: Quality of Experience Questionnaire Results

B.6 Performance Results

ID	Flower Score No-Odour	Flower Score Odour
O-NO1	5	3
O-NO2	5	3
O-NO3	4	2
O-NO4	9	4
O-NO5	4	2
O-NO6	1	1
O-NO7	6	4
O-NO8	5	4
O-NO9	7	5
O-NO10	4	2
NO-O1	3	8
NO-O2	2	6
NO-O3	2	5
NO-O4	2	6
NO-O5	4	6
NO-O6	4	9
NO-O7	4	6
NO-O8	5	9
NO-O9	4	9
NO-O10	2	5

Table B.27: Performance Results

B.7 Participant Information Sheet

PARTICIPANT INFORMATION SHEET

Title of study: Exploring the effect of scent on immersion and quality of experience in virtual reality experiences

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?
The purpose of this study is to identify how different scents affect immersion and quality of experience in Virtual Environments.

Why have I been invited?
I am looking for 20 adults to take part in this study. You do not need any expertise or prior knowledge to take part. You must be at least 18 years old, have a functioning sense of smell and be able to undertake the activities described below. You cannot take part in this study if you are known to suffer from virtual reality induced motion sickness or fear of heights.

Do I have to take part?
Participation in the project is voluntary, and you can choose not to participate in the project. You can withdraw at any stage of the project without being penalised or disadvantaged in any way.
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?
If you choose to take part in this study, you will be invited to the City, University of London Interaction Lab for an in-person session.
The session will be approximately one hour. It will begin with an overview of what will occur during that time, completing the consent form, and an introduction to a questionnaire, which you will complete several times throughout the session, each time after playing a virtual reality game. The purpose of this questionnaire is to understand how you felt about the virtual environment that we are showing to you. You will be asked to indicate how immersed you felt into the virtual reality environment and how you feel about the quality of your experience. During the session, you will be asked to wear a virtual reality headset and you will be given time to familiarize yourself with the equipment. You will be given a task that involves exploring a virtual climbing game. You will be prompted to look for certain objects in this virtual environment. We will be releasing certain scents while you are exploring the virtual environment.

Expenses and Payments (if applicable)
Your participation in this research project is greatly appreciated. As thanks, your travel to and from the in-person meeting will be reimbursed, and you will be provided with sweets and refreshments.

What are the possible disadvantages and risks of taking part?
We have identified no reasonably foreseeable risks of harm, safety, or side effects to you as a result of taking part in this study. However, some users of virtual reality headsets have reported mild motion sickness after extended use, however as the sessions are quite short, we do not expect you to experience this. If you feel discomfort at any point please let the study facilitator know immediately.

What are the possible benefits of taking part?
There are no direct benefits to you for taking part in this study. However, as a participant you will help us understand the use of smell in Virtual Environments, which may help the design of future technology.

What will happen when the research study stops?
When the research study stops, all collected information will be stored on a personal external hard drive which is password protected. It is City University London's policy to retain all research records for ten years. After ten years have passed, all documents related to the participants will be destroyed. Participation in the project is voluntary, and you can choose not to participate in part or all of the project. You can withdraw at any stage of the project without being penalized or disadvantaged in any way. If you choose to withdraw from the research study, your data will be excluded from the research and destroyed.

Will my taking part in the study be kept confidential?
Your participation will be kept confidential. We will ensure your anonymity in the following way:

- You will be assigned a unique identification number which will be used for all data and records, rather than your personal name.
- Only anonymized data will be shared with other researchers interested in the work. No information containing identifiable features, or names will be shared with other individuals.
- All signed consent forms will be kept in a sealed envelope, stored in a locked cabinet and destroyed after one year.

Your questionnaire responses are regarded as strictly confidential and will be held securely until the research is finished. Your participation is entirely voluntary. If you change your mind, you are free to stop your participation and to have your data withdrawn without giving any reason up to the point of publication. All data for analysis will be anonymised. In reporting on the research findings, we will not reveal the names of any participants or the organisation where you work. At all times there will be no possibility of you as individuals being linked with the data.

The UK Data Protection Act 1998 will apply to all information gathered within the interviews and held on password-locked computer files and locked cabinets within City, University of London. No data will be accessed by anyone other than the primary researcher Marius Braun; and anonymity of the material will be protected by using unique identification numbers. No data will be able to be linked back to any individual taking part in the study. You may withdraw your data from the project anytime up to the point of publication in September 2018. If you ask us to withdraw your data at any time before September 2018 we will remove all traces of it from the records.

What will happen to results of the research study?
The results of the study will be documented in a written report. Possible future publications might arise from the research, but will not include your personal details or identifiable features/comments – your anonymity will be maintained. If you wish to receive a copy of the summary of results, please send a request email to [redacted]

What will happen if I do not want to carry on with the study?
You are free to discontinue the study at any time, without explanation or penalty to you.

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 City's 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: *Exploring scent-object congruence in virtual reality environments*

You could also write to the Secretary at:
Anna Ramberg
Research Governance & Integrity Manager
Research & Enterprise
City, University of London
Northampton Square
London
EC1V 0HB
Email: [redacted]

City 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 of London's Computer Science Research Ethics Committee

Further information and contact details
Researcher: Marius Braun, PhD student
[redacted]

Supervisor: Dr. Jon Bird
[redacted]

Thank you for taking the time to read this information sheet.

Figure B.8: Main Study Participant Information Sheet

B.8 Participant Consent Form

CITY
UNIVERSITY OF LONDON
EST 1894

CONSENT FORM

Title of Study: **Exploring the effect of scent on immersion and quality of experience in virtual reality experiences**

Please initial box

1.	I confirm that I have had the project explained to me, and I have read the participant information sheet, which I may keep for my records. I understand this will involve: • completing questionnaires asking me about my perception of quality of experience and immersion of a Virtual Reality environment. • use a virtual reality headset and controllers while being exposed to scents.	
2.	This information will be held and processed for the following purpose(s): of the completion of Marius Braun's PhD thesis and future publications. 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 identifiable data will not be shared with any other organisation.	
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 of 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 City complying with its duties and obligations under the Data Protection Act 1998.	
5.	I agree to the use of anonymised quotes in publication.	
6.	I agree to take part in the above study.	

______________________ ______________________________ ______________
Name of Participant Signature Date

______________________ ______________________________ ______________
Name of Researcher Signature Date

Figure B.9: Study Two Odour Selection Task Questionnaire

Appendix C

Study Three

C.1 Odour Selection Task Questionnaire

C.2 Participant Odour Associations and Descriptions

ID	Apple	Bubblegum
1	soooo familiar! it's not the right smell... but i can't help but think of the scent of someone specific i used to know in my teens (worst kisser EVER).	lemons and dust
2	apple picking.	tutti fruity jelly belly
3	like apple shampoo by fructis	bubble gum or cotton candy
4	it's sweet and fruity but it's also a bit synthetic	bubblegum.
5	shampoo	toothpaste
6	washing liquid	oral solution
7	something nondescript and chemically. Perhaps a little like apple	A little bit like bubblegum
8	Very fruity, sweet	minty mouthwash
9	Not entirely sure. Again, something like confection	Deep heet, for muscle pain or for smearing on yourself before Sunday football matches
10	Medical, chemical	Stuff you put on wounds - injury and cleanliness
11	crisp green apple	sweet bubblegum

Table C.1: Participant Odour Associations and Descriptions

ID	Chocolate-Chip Cookie	Strawberry
1	torrone, because it's a bit nutty... but torrone that has been warming	sugary sweets. it is fruity. strawberry??
2	chocolate mixed with something. or flavored coffee beans	orange soda. sweet
3	baking smell	fruity, somewhat fake, but not unpleasant
4	it almost smells of cookie but it doesn't.	it smells like sherbet
5	chocolate	something sweet
6	nutella	body spray
7	Coffee-ish. Also a bit unpleasant	This smells like a strawberry scented doll I had as a child: "strawberry cupcake"
8	immediately burnt, sort of sweet afterward	fruity like bubble bath or juice
9	Smells of biscuits	Might be licorice – smells of red and white hard sweets – the swirly ones
10	Sweet, spicy	Sickly sweet, vague hint of chemicals
11	hazelnut chocolate, nutella	sweet, bubblegum

Table C.2: Participant Odour Associations and Descriptions

ID	Cherry	Vanilla
1	licorice and shoe polish in a leather bag full of sugar	whiskey? warm and earthy... if a bit synthetic.
2	cherry! water ice :)	vanilla
3	cherry lip balm	cookie dough, maybe with cinnamon
4	smells synthetic.	it smells sweet.
5	alcohol	visit to a dentist
6	almond liquid	alcolol
7	Smells like the taste of bakewell tarts	A little chemical. A bit like nail varnish remover
8	cherry juice	can't remember sort of alcoholish after a while
9	It smells of something you'd find in a sweet – like a hard sweet	Baking and good ice cream
10	Sweet, fruity, sickly	Warm, sweet and slightly alcoholic
11	drinking cherry juice	cookie dough

Table C.3: Participant Odour Associations and Descriptions

ID	Gingerbread	Mint
1	Kind of like spices mixed with juice	Fresh mint leaves
2	Spices	Peppermint oil
3	spicy, edible, probably curry sauce or an ingredient of it	Pepermint essence
4	it kind of smells of curry.	it smells like vanilla and mint mixed together
5	cinnamon	toothpaste
6	semolina	chewing gym
7	A bit like a mix between popcorn and cardamon	This smell reminds me of the dentist! It smells like mouthwash to me.
8	woody, spicy	Cart interior, almost like chewing gum
9	Slightly biscuity. But not much association	it smells like oil and mint – peppermint oil perhaps
10	Cakes, making curries	Polos, mints
11	winter cookies	freshness, cold

Table C.4: Participant Odour Associations and Descriptions

ID	Lavender	Freesia
1	quite outdoorsy. but sharp synthetic twang which throws me off. lavender?	cleaNING PRODUCT
2	lemon cleaner	sweet floral
3	Lavender	flower
4	floral	it's sweet and fruity
5	lavender	alcohol
6	laventer the flower	washing liquid
7	Nondescript. Chemical.	A bit like parma violet sweets
8	Tree sap smell	flowery
9	Very much lavender flower – as if you're walking through a field of the stuff	It smells of lotion that you might apply after a shower to keep skin smooth
10	Medicine, health, injury	Flowers, sugar, purple.
11	lavander flowers under the scorching sun, bees buzzing	crisp lemon scent

Table C.5: Participant Odour Associations and Descriptions

C.3 Odour Selection Task Questionnaire Results

Abbreviation	Meaning
Perceive	Do you perceive a scent?
Recognise	Do you recognize the scent?
Intensity	This scent's intensity is ...
Pleasantness	I like this scent ...
Congruence	Does this scent match this flower?

Table C.6: Abbreviations for Odour Selection Questionnaire Items

Apple					Congruence	Congruence
ID	**Perceive**	**Recognise**	**Intensity**	**Pleasantness**	**P. Flower**	**Y. Flower**
1	Yes	No	5	4	6	5
2	Yes	Yes	5	5	4	4
3	Yes	Yes	5	3	1	2
4	Yes	Yes	3	5	1	2
5	Yes	Yes	5	4	2	4
6	Yes	No	4	4	1	1
7	Yes	No	3	2	3	5
8	Yes	Yes	3	5	2	4
9	Yes	No	2	3	1	1
10	Yes	Yes	3	2	4	4
11	Yes	Yes	4	5	1	3

Table C.7: Odour Selection Task Questionnaire Results

Bubblegum					Congruence	Congruence
ID	**Perceive**	**Recognise**	**Intensity**	**Pleasantness**	**P. Flower**	**Y. Flower**
1	Yes	No	5	2	1	3
2	Yes	Yes	5	2	1	1
3	Yes	Yes	5	3	1	1
4	Yes	Yes	3	4	1	1
5	Yes	Yes	5	4	1	1
6	Yes	Yes	4	4	1	1
7	Yes	No	3	3	3	3
8	Yes	Yes	3	4	6	1
9	Yes	Yes	4	2	1	1
10	Yes	Yes	4	3	2	5
11	Yes	No	5	3	5	3

Table C.8: Odour Selection Task Questionnaire Results

Chocolate-Chip Cookie					Congruence	Congruence
ID	**Perceive**	**Recognise**	**Intensity**	**Pleasantness**	**P. Flower**	**Y. Flower**
1	Yes	No	5	3	1	1
2	Yes	Yes	5	3	1	1
3	Yes	Yes	5	3	1	1
4	Yes	No	5	4	1	1
5	Yes	Yes	5	4	1	1
6	Yes	Yes	4	4	1	1
7	Yes	No	3	4	2	2
8	Yes	Yes	3	4	1	1
9	Yes	No	4	3	1	1
10	Yes	Yes	3	3	1	3
11	Yes	Yes	4	5	3	1

Table C.9: Odour Selection Task Questionnaire Results

Strawberry ID	Perceive	Recognise	Intensity	Pleasantness	Congruence P. Flower	Congruence Y. Flower
1	Yes	Yes	4	5	2	3
2	Yes	Yes	5	4	3	4
3	Yes	Yes	4	3	1	3
4	Yes	No	4	5	1	3
5	Yes	No	4	3	1	1
6	Yes	Yes	5	4	1	1
7	Yes	Yes	4	4	2	2
8	Yes	Yes	4	4	7	1
9	Yes	No	4	4	1	1
10	Yes	Yes	4	2	4	2
11	Yes	Yes	4	4	4	1

Table C.10: Odour Selection Task Questionnaire Results

Cherry ID	Perceive	Recognise	Intensity	Pleasantness	Congruence P. Flower	Congruence Y. Flower
1	Yes	No	5	5	5	2
2	Yes	Yes	4	4	4	1
3	Yes	Yes	5	4	2	2
4	Yes	No	4	5	1	2
5	Yes	No	4	3	2	1
6	Yes	Yes	5	4	1	1
7	Yes	Yes	3	4	4	3
8	Yes	Yes	4	5	5	1
9	Yes	No	4	4	1	1
10	Yes	Yes	4	3	5	2
11	Yes	Yes	5	5	4	1

Table C.11: Odour Selection Task Questionnaire Results

Vanilla ID	Perceive	Recognise	Intensity	Pleasantness	Congruence P. Flower	Congruence Y. Flower
1	Yes	No	4	4	3	1
2	Yes	Yes	3	4	2	3
3	Yes	Yes	5	2	1	1
4	Yes	Yes	4	5	1	2
5	Yes	No	3	2	1	3
6	Yes	Yes	4	2	1	1
7	Yes	No	2	2	4	3
8	Yes	No	1	2	5	1
9	Yes	Yes	4	4	1	1
10	Yes	Yes	2	3	3	3
11	Yes	Yes	3	5	5	1

Table C.12: Odour Selection Task Questionnaire Results

Gingerbread					Congruence	Congruence
ID	**Perceive**	**Recognise**	**Intensity**	**Pleasantness**	**P. Flower**	**Y. Flower**
1	Yes	No	5	3	2	2
2	Yes	Yes	4	4	2	1
3	Yes	Yes	5	4	1	1
4	Yes	No	5	3	1	2
5	Yes	No	5	4	2	2
6	Yes	Yes	3	2	1	1
7	Yes	No	3	3	3	3
8	Yes	No	4	3	4	2
9	Yes	No	3	2	1	1
10	Yes	Yes	3	4	5	3
11	Yes	Yes	4	5	2	5

Table C.13: Odour Selection Task Questionnaire Results

Mint					Congruence	Congruence
ID	**Perceive**	**Recognise**	**Intensity**	**Pleasantness**	**P. Flower**	**Y. Flower**
1	Yes	Yes	3	5	4	1
2	Yes	Yes	2	3	1	1
3	Tes	Yes	2	2	1	2
4	Yes	No	4	5	1	2
5	Yes	Yes	4	4	5	1
6	Yes	Yes	3	3	1	1
7	Yes	Yes	4	3	1	1
8	Yes	No	1	3	4	4
9	Yes	Yes	2	3	1	1
10	Yes	Yes	2	4	3	5
11	Yes	Yes	3	5	1	5

Table C.14: Odour Selection Task Questionnaire Results

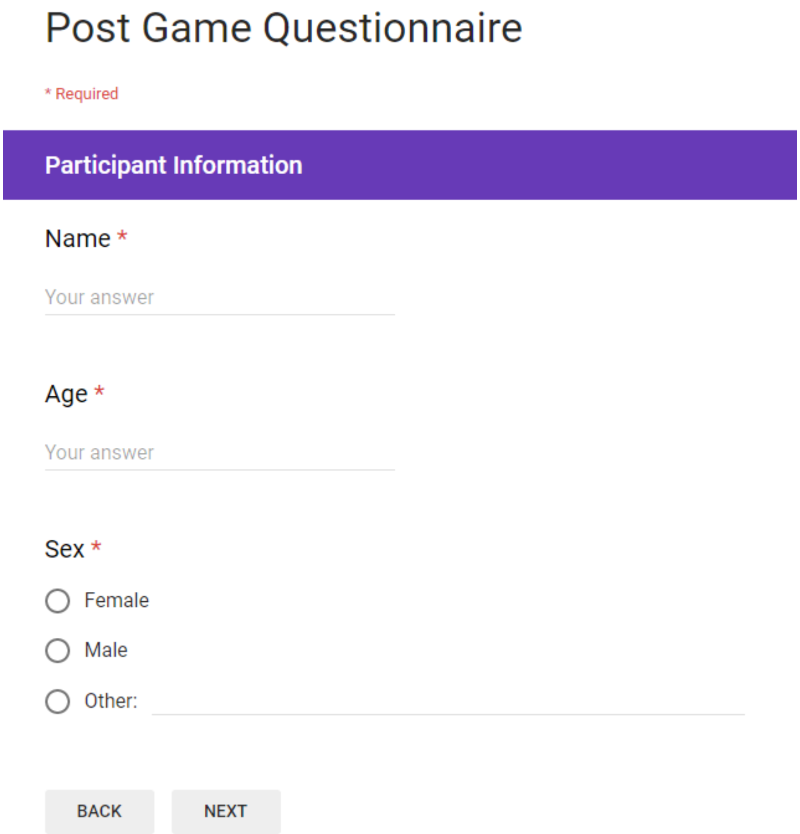
Lavender					Congruence	Congruence
ID	**Perceive**	**Recognise**	**Intensity**	**Pleasantness**	**P. Flower**	**Y. Flower**
1	Yes	Yes	4	2	5	4
2	Yes	No	5	2	1	3
3	Yes	Yes	5	5	6	3
4	Yes	Yes	4	5	6	2
5	Yes	No	5	4	5	3
6	Yes	Yes	3	4	4	1
7	Yes	No	4	2	3	3
8	Yes	Yes	4	3	6	1
9	Yes	Yes	4	4	1	1
10	Yes	Yes	4	3	3	5
11	Yes	Yes	5	4	7	1

Table C.15: Odour Selection Task Questionnaire Results

Freesia ID	**Perceive**	**Recognise**	**Intensity**	**Pleasantness**	**Congruence P. Flower**	**Congruence Y. Flower**
1	Yes	No	4	4	1	2
2	Yes	No	4	4	6	6
3	Yes	No	5	3	4	4
4	Yes	No	3	5	1	2
5	Yes	No	4	3	1	1
6	Yes	Yes	3	4	4	4
7	Yes	No	4	3	5	3
8	Yes	No	3	3	1	4
9	Yes	Yes	3	3	1	1
10	Yes	Yes	5	5	7	1
11	Yes	Yes	2	5	1	7

Table C.16: Odour Selection Task Questionnaire Results

C.4 Post Game Questionnaire



Post Game Questionnaire

* Required

Participant Information

Name *

Your answer

Age *

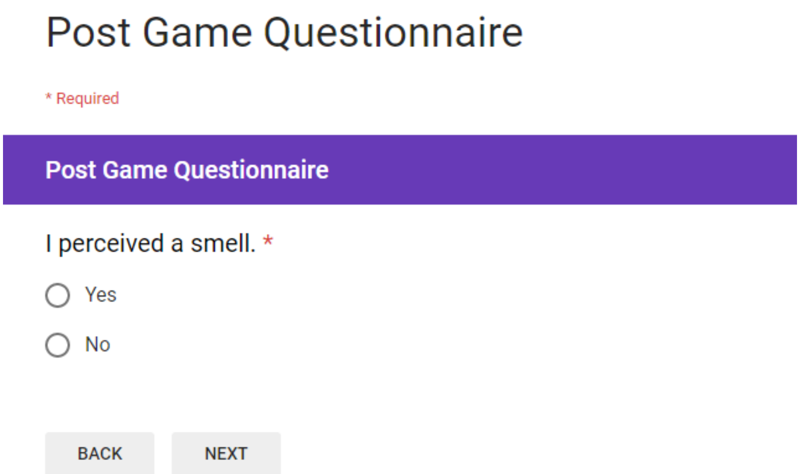
Your answer

Sex *

- Female
- Male
- Other:

BACK NEXT

Figure C.1: Post Game Questionnaire - Page 1



Post Game Questionnaire

* Required

Post Game Questionnaire

I perceived a smell. *

- Yes
- No

BACK NEXT

Figure C.2: Post Game Questionnaire - Page 2

Post Game Questionnaire

* Required

Presence Questionnaire

Please answer the following questions by marking the relevant number. In particular, remember that these questions are asking you about how you felt at the end of the game.

I enjoyed the virtual environment. *

	1	2	3	4	5	
Not at all	○	○	○	○	○	A lot

To what extent did you feel you were focused on the game? *

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	A lot

To what extent were you aware of yourself in your surroundings? *

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very aware

At any point did you find yourself become so involved that you were unaware you were even using controls? *

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very much so

Were there any times during the game in which you just wanted to give up? *

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	A lot

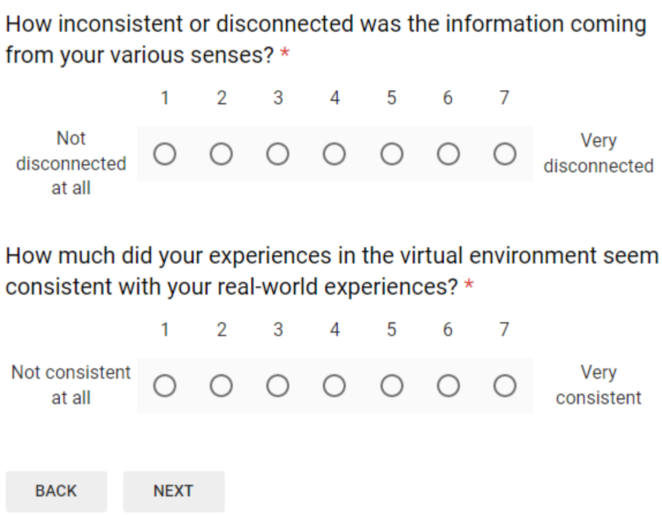
To what extent did you feel emotionally attached to the game? *

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very much so

How completely were all of your senses engaged? *

	1	2	3	4	5	6	7	
Not complete at all	○	○	○	○	○	○	○	Very complete

Figure C.3: Post Game Questionnaire - Page 3



How inconsistent or disconnected was the information coming from your various senses? *

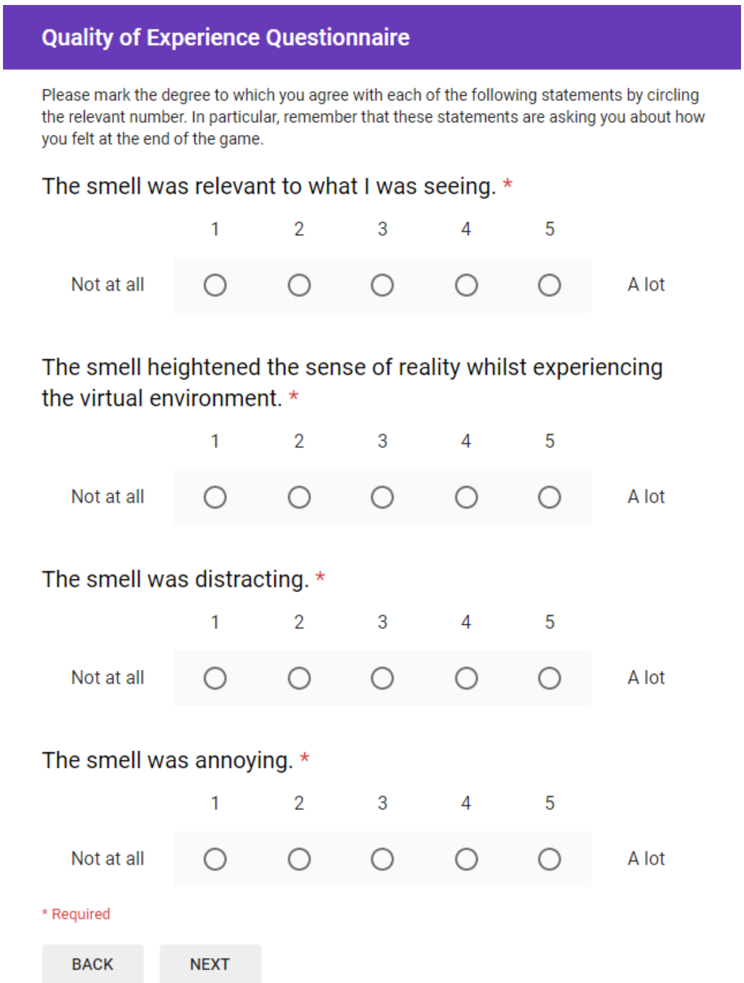
	1	2	3	4	5	6	7	
Not disconnected at all	○	○	○	○	○	○	○	Very disconnected

How much did your experiences in the virtual environment seem consistent with your real-world experiences? *

	1	2	3	4	5	6	7	
Not consistent at all	○	○	○	○	○	○	○	Very consistent

BACK NEXT

Figure C.4: Post Game Questionnaire - Page 3 continued



Quality of Experience Questionnaire

Please mark the degree to which you agree with each of the following statements by circling the relevant number. In particular, remember that these statements are asking you about how you felt at the end of the game.

The smell was relevant to what I was seeing. *

	1	2	3	4	5	
Not at all	○	○	○	○	○	A lot

The smell heightened the sense of reality whilst experiencing the virtual environment. *

	1	2	3	4	5	
Not at all	○	○	○	○	○	A lot

The smell was distracting. *

	1	2	3	4	5	
Not at all	○	○	○	○	○	A lot

The smell was annoying. *

	1	2	3	4	5	
Not at all	○	○	○	○	○	A lot

* Required

BACK NEXT

Figure C.5: Post Game Questionnaire - Page 5

C.5 Post Game Questionnaire Results

ID	Age	Gender
NO-O 1	35	Male
NO-O 2	30	Female
NO-O 3	28	Male
NO-O 4	27	Male
NO-O 5	24	Female
NO-O 6	27	Female
NO-O 7	23	Male
NO-O 8	24	Female
NO-O 9	21	Male
NO-O 10	28	Male
O-NO 1	26	Male
O-NO 2	31	Male
O-NO 3	40	Female
O-NO 4	49	Male
O-NO 5	22	Female
O-NO 6	29	Male
O-NO 7	25	Female
O-NO 8	22	Female
O-NO 9	33	Female
O-NO 10	27	Female

Table C.17: Participant demographics

Abbreviation	Question
Relevant	The smell was relevant to what I was seeing.
Sense of Reality	The smell heightened the sense of reality whilst experiencing the virtual environment.
Distracting	The smell was distracting.
Annoying	The smell was annoying.
Enjoyment	I enjoyed the virtual environment.

Table C.18: Abbreviations for the Quality of Experience Questionnaire Items.

ID	Relevant	Sense of Reality	Distracting	Annoying	Odour Enjoyment	No-Odour Enjoyment
NO-O 1	1	1	3	2	4	4
NO-O 2	1	5	3	1	5	4
NO-O 3	3	4	3	3	5	5
NO-O 4	3	4	1	1	5	5
NO-O 5	1	2	5	5	5	5
NO-O 6	3	4	2	2	5	5
NO-O 7	2	4	3	2	5	5
NO-O 8	2	4	2	2	5	4
NO-O 9	1	4	3	2	5	5
NO-O 10	2	1	5	4	5	5
O-NO 1	3	4	1	1	5	4
O-NO 2	1	2	4	3	5	3
O-NO 3	1	1	5	3	2	3
O-NO 4	2	3	2	3	4	5
O-NO 5	1	2	4	3	4	4
O-NO 6	3	4	2	1	4	4
O-NO 7	2	5	4	2	5	5
O-NO 8	3	4	1	1	5	5
O-NO 9	4	5	1	1	5	5
O-NO 10	2	5	2	1	5	5

Table C.19: Quality of Experience Results

Abbreviation	Question
Focused	To what extent did you feel you were focused on the game?
Aware	To what extent were you aware of yourself in your surroundings?
Involved	At any point did you find yourself become so involved that you were unaware you were even using controls?
Give Up	Were there any times during the game in which you just wanted to give up?
Emotional	To what extent did you feel emotionally attached to the game?
Senses Engaged	How completely were all of your senses engaged?
Inconsistent	How inconsistent or disconnected was the information coming from your various senses?
Consistent	How much did your experiences in the virtual environment seem consistent with your real-world experiences?

Table C.20: Abbreviations for the Jennet et al. and Witmer and Singer Presence Questionnaire items.

ID	Focused	Aware	Involved	Give Up	Emo-tional	Senses En-gaged	Incon-sistent	Consis-tent
NO-O 1	6	2	4	2	2	3	4	2
NO-O 2	6	6	5	7	5	5	1	6
NO-O 3	7	4	6	3	5	5	3	4
NO-O 4	7	7	6	1	6	6	3	5
NO-O 5	7	7	1	1	4	3	4	6
NO-O 6	7	7	5	1	6	7	1	6
NO-O 7	6	3	5	2	5	4	4	3
NO-O 8	7	6	7	1	5	6	2	6
NO-O 9	7	6	6	1	6	5	3	6
NO-O 10	5	4	1	3	2	4	4	4
O-NO 1	6	5	6	2	5	4	5	5
O-NO 2	5	5	5	3	3	2	3	2
O-NO 3	7	5	6	2	6	4	1	3
O-NO 4	7	7	6	1	7	7	1	7
O-NO 5	6	6	3	2	7	2	3	5
O-NO 6	5	6	4	1	4	3	5	3
O-NO 7	7	7	5	2	7	6	3	4
O-NO 8	7	6	4	1	7	5	4	4
O-NO 9	7	7	7	1	6	6	4	5
O-NO 10	7	5	5	1	6	5	2	5

Table C.21: Jennet et al. and Witner and Singer Presence Questionnaire Results in the No-Odour Condition

ID	Focused	Aware	Involved	Give Up	Emotional	Senses Engaged	Inconsistent	Consistent
NO-O 1	6	2	5	2	6	5	4	4
NO-O 2	6	6	5	2	5	5	3	5
NO-O 3	7	6	7	3	5	6	2	6
NO-O 4	7	6	6	1	7	6	6	5
NO-O 5	7	7	2	1	6	6	3	2
NO-O 6	7	7	7	1	6	7	1	6
NO-O 7	6	6	4	2	4	5	3	3
NO-O 8	7	6	6	1	6	6	6	5
NO-O 9	6	6	7	1	6	6	2	6
NO-O 10	4	4	1	4	3	2	6	5
O-NO 1	6	1	6	1	4	6	2	6
O-NO 2	7	5	7	1	6	5	6	4
O-NO 3	7	4	6	5	6	7	5	5
O-NO 4	7	7	6	5	7	7	1	6
O-NO 5	7	7	3	6	7	5	5	3
O-NO 6	6	7	5	1	6	6	4	5
O-NO 7	7	7	5	6	6	4	6	6
O-NO 8	6	6	3	1	7	7	1	6
O-NO 9	7	7	7	6	6	7	3	5
O-NO 10	7	7	6	1	7	5	2	6

Table C.22: Jennet et al. and Witner and Singer Presence Questionnaire Results in the Odour Condition

C.6 Task Performance Results

ID	No-Odour Flower Score	Odour Flower Score
NO-O 1	3	7
NO-O 2	1	5
NO-O 3	3	8
NO-O 4	3	5
NO-O 5	5	8
NO-O 6	3	5
NO-O 7	3	5
NO-O 8	4	7
NO-O 9	3	8
NO-O 10	4	8
O-NO 1	3	5
O-NO 2	1	6
O-NO 3	4	4
O-NO 4	2	3
O-NO 5	3	5
O-NO 6	6	6
O-NO 7	2	3
O-NO 8	4	4
O-NO 9	3	5
O-NO 10	2	3

Table C.23: Task performance results

Appendix D

Study Four

D.1 Odour Selection Task Questionnaire

Sample Assessment

* Required

Sample Assessment

First Sample

Sample ID *

Your answer

Do you perceive a scent? *

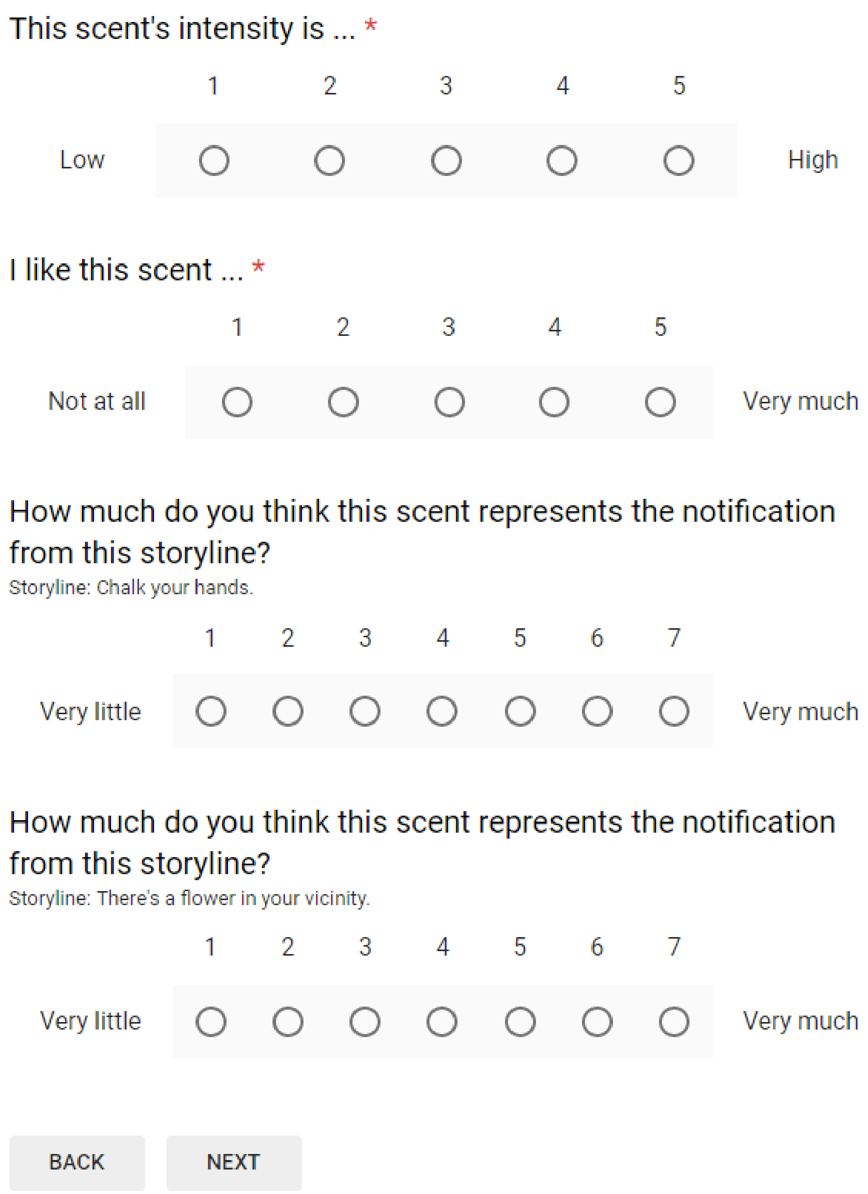
- ◯ Yes
- ◯ No

Do you recognize the scent? *

- ◯ Yes
- ◯ No

Name of the scent or association:

Your answer



This scent's intensity is ... *

	1	2	3	4	5	
Low	○	○	○	○	○	High

I like this scent ... *

	1	2	3	4	5	
Not at all	○	○	○	○	○	Very much

How much do you think this scent represents the notification from this storyline?

Storyline: Chalk your hands.

	1	2	3	4	5	6	7	
Very little	○	○	○	○	○	○	○	Very much

How much do you think this scent represents the notification from this storyline?

Storyline: There's a flower in your vicinity.

	1	2	3	4	5	6	7	
Very little	○	○	○	○	○	○	○	Very much

BACK NEXT

Figure D.1: Odour Selection Task Questionnaire.

D.2 Odour Selection Task Results

ID	Age	Gender
1	30	Female
2	28	Male
3	28	Male
4	27	Male
5	30	Male
6	26	Female
7	29	Female
8	27	Female
9	29	Male
10	29	Female

Table D.1: Demographics of the participants of the odour selection task.

Chalk Hands Congruence

ID	Lavender	Rose	Baby Powder	Pepper-mint	Lemon	Cinna-mon	Black Pepper	Water
1	3	2	5	3	5	4	5	2
2	2	1	5	4	4	3	4	1
3	2	3	4	2	5	4	6	1
4	1	2	5	3	3	4	5	2
5	3	2	4	4	3	4	4	1
6	2	2	4	3	4	5	5	1
7	1	1	3	2	5	4	4	2
8	1	2	4	4	3	2	4	1
9	3	1	5	2	4	4	4	1
10	1	1	3	4	5	4	4	2

Table D.2: Responses to the question 'How much do you think this scent represents the notification from the storyline' for the Chalk Hands notification.

There's a Flower in Your Vicinitny Congruence

ID	Lavender	Rose	Baby Powder	Pepper-mint	Lemon	Cinna-mon	Black Pepper	Water
1	6	6	4	3	5	2	1	1
2	7	6	5	4	3	1	1	2
3	6	6	4	3	4	2	2	1
4	6	6	5	3	4	2	1	2
5	6	6	5	5	4	1	1	2
6	7	6	4	5	4	1	1	1
7	7	6	6	3	3	1	2	1
8	6	6	5	2	4	2	2	1
9	7	7	4	3	3	1	1	2
10	7	6	6	2	3	1	1	1

Table D.3: Responses to the question 'How much do you think this scent represents the notification from the storyline' for the Flower in Vicinity notification.

Do you perceive a scent?

ID	Lavender	Rose	Baby Powder	Pepper-mint	Lemon	Cinna-mon	Black Pepper	Water
1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	0
3	1	1	1	1	1	1	1	0
4	1	1	1	1	1	1	1	0
5	1	1	1	1	1	1	1	0
6	1	1	1	1	1	1	1	0
7	1	1	1	1	1	1	1	0
8	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	0
10	1	1	1	1	1	1	1	0

Table D.4: Responses to the question 'Do you perceive a scent?' A 1 represents 'Yes' and a 0 represents 'No'.

Do you recognize the scent?

ID	Lavender	Rose	Baby Powder	Pepper-mint	Lemon	Cinna-mon	Black Pepper	Water
1	0	1	1	1	1	1	1	0
2	0	0	1	1	1	1	0	0
3	1	1	0	1	1	1	1	0
4	1	1	0	1	1	1	0	0
5	0	1	0	1	1	1	1	0
6	0	1	0	1	1	0	1	0
7	1	1	0	1	1	1	0	1
8	1	1	0	1	1	1	1	0
9	1	1	0	1	1	1	0	0
10	1	1	0	1	1	1	1	0

Table D.5: Responses to the question 'Do you recognize the scent?'.

This scent's intensity is ...

ID	Lavender	Rose	Baby Powder	Pepper-mint	Lemon	Cinna-mon	Black Pepper	Water
1	4	3	3	3	4	5	5	1
2	3	4	4	2	2	4	4	1
3	4	3	1	2	4	5	4	1
4	3	4	3	2	3	3	4	1
5	3	4	4	4	5	3	4	1
6	4	3	3	2	4	4	5	1
7	3	5	5	2	2	4	4	1
8	3	4	3	3	3	4	3	2
9	4	3	4	4	2	3	4	1
10	4	5	4	2	4	4	5	1

Table D.6: Responses to the statement 'This scent's intensity is ...'.

I like this scent ...

ID	Lavender	Rose	Baby Powder	Pepper-mint	Lemon	Cinna-mon	Black Pepper	Water
1	5	4	2	3	3	4	2	3
2	2	5	4	5	5	5	1	3
3	4	2	3	5	4	1	1	3
4	5	1	3	3	5	4	4	3
5	2	2	2	4	3	5	3	3
6	3	5	3	3	4	4	1	3
7	4	4	5	3	4	4	3	4
8	2	4	3	4	4	3	4	3
9	4	4	1	5	4	1	1	3
10	4	2	5	4	5	5	1	3

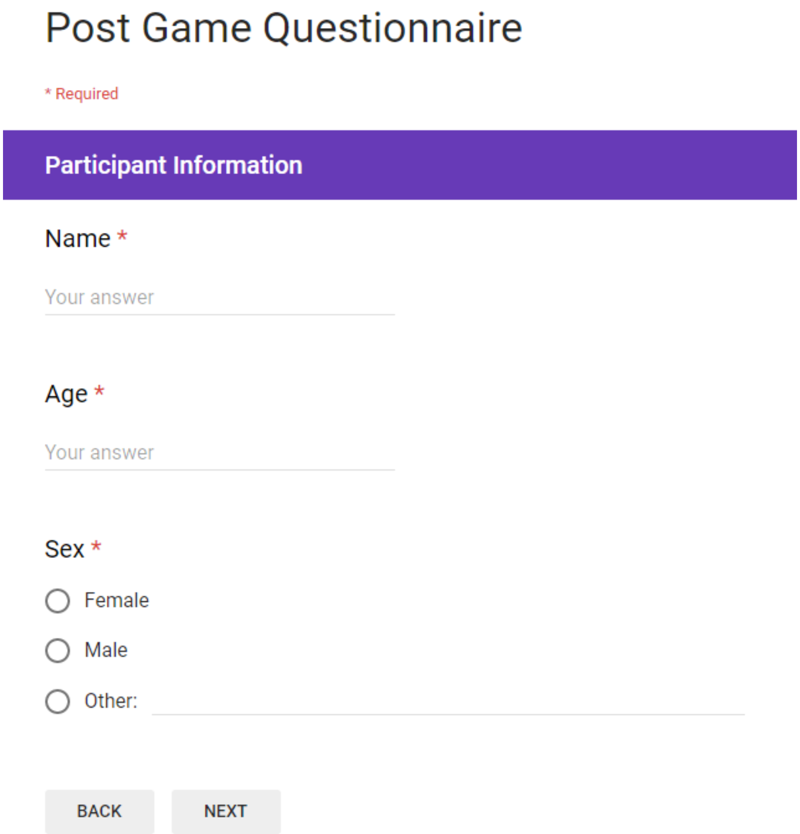
Table D.7: Responses to the statement 'I like this scent ...'.

Which message does the scent convey?

ID	Lavender	Rose	Baby Powder	Pepper-mint	Lemon	Cinna-mon	Black Pepper	Water
1	Flower	Flower	Flower	Chalk	Chalk	Chalk	Chalk	Chalk
2	Flower	Flower	Chalk	Flower	Flower	Chalk	Chalk	Flower
3	Flower	Flower	Chalk	Flower	Flower	Chalk	Chalk	Chalk
4	Flower	Flower	Chalk	Flower	Chalk	Chalk	Chalk	Chalk
5	Flower	Flower	Flower	Chalk	Chalk	Chalk	Chalk	Chalk
6	Flower	Flower	Chalk	Flower	Flower	Chalk	Chalk	Flower
7	Flower	Flower	Flower	Flower	Flower	Chalk	Chalk	Chalk
8	Flower	Flower	Chalk	Flower	Chalk	Chalk	Chalk	Flower
9	Flower	Flower	Chalk	Flower	Chalk	Chalk	Chalk	Chalk
10	Flower	Flower	Chalk	Chalk	Flower	Chalk	Chalk	Flower

Table D.8: Responses to the question "Which message does the scent convey? 'There's a flower in your vicinity', or 'You should chalk your hands?' The message is currently not synchronised with your virtual experience." Flower = 'There's a flower in your vicinity', Chalk = 'You should chalk your hands?'

D.3 Post Game Questionnaire


Post Game Questionnaire

* Required

Participant Information

Name *

Your answer

Age *

Your answer

Sex *

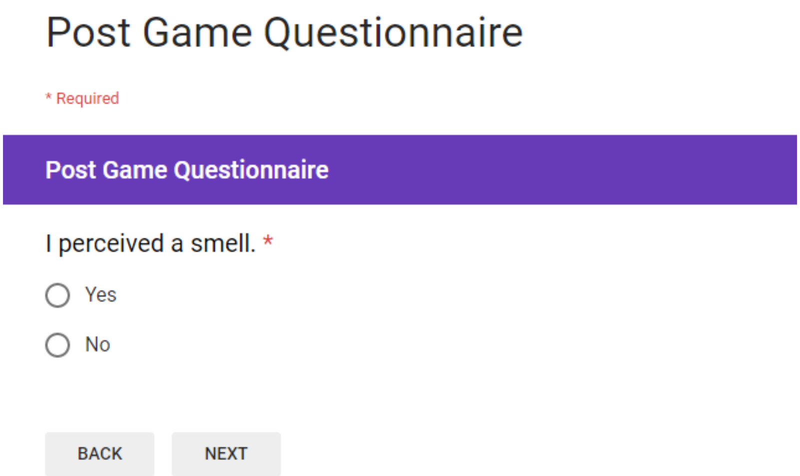
Female

Male

Other:

BACK NEXT

Figure D.2: Post Game Questionnaire - Page 1


Post Game Questionnaire

* Required

Post Game Questionnaire

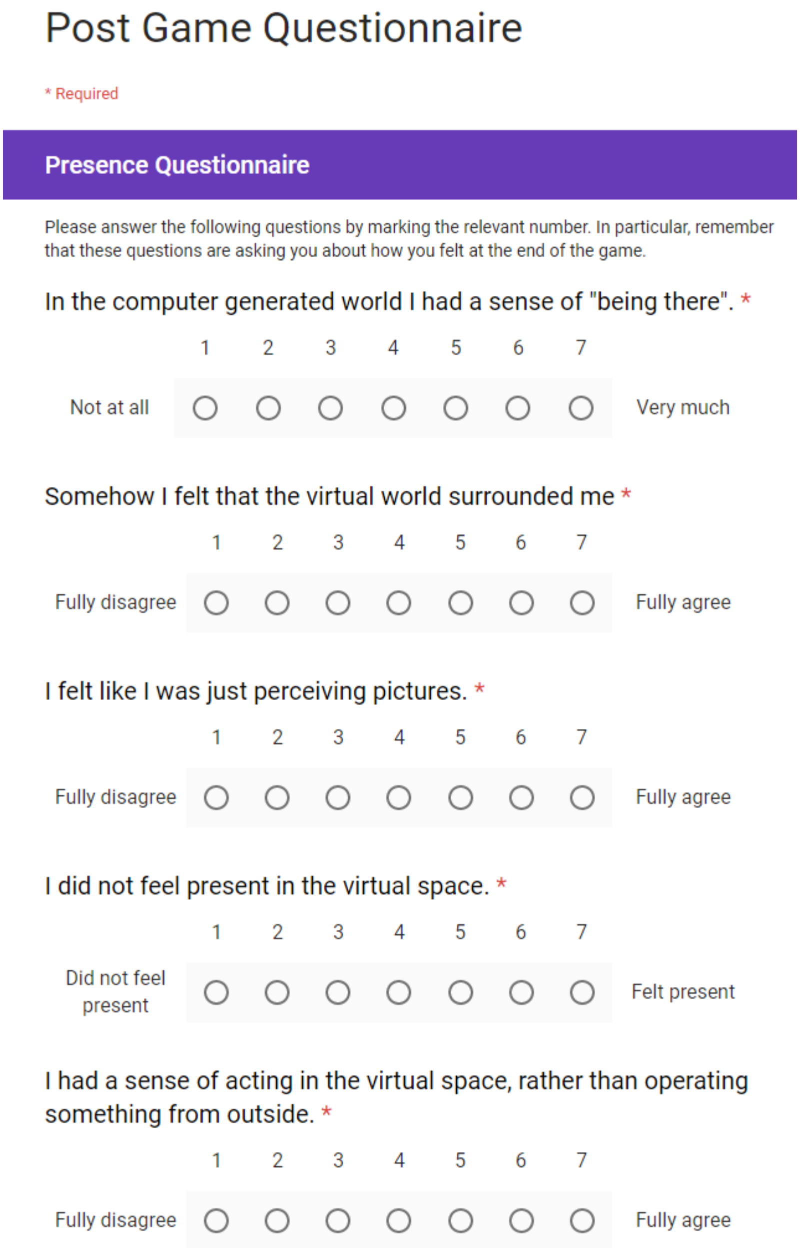
I perceived a smell. *

Yes

No

BACK NEXT

Figure D.3: Post Game Questionnaire - Page 2



Post Game Questionnaire

* Required

Presence Questionnaire

Please answer the following questions by marking the relevant number. In particular, remember that these questions are asking you about how you felt at the end of the game.

In the computer generated world I had a sense of "being there". *

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very much

Somehow I felt that the virtual world surrounded me *

	1	2	3	4	5	6	7	
Fully disagree	○	○	○	○	○	○	○	Fully agree

I felt like I was just perceiving pictures. *

	1	2	3	4	5	6	7	
Fully disagree	○	○	○	○	○	○	○	Fully agree

I did not feel present in the virtual space. *

	1	2	3	4	5	6	7	
Did not feel present	○	○	○	○	○	○	○	Felt present

I had a sense of acting in the virtual space, rather than operating something from outside. *

	1	2	3	4	5	6	7	
Fully disagree	○	○	○	○	○	○	○	Fully agree

Figure D.4: Post Game Questionnaire - Page 3

I felt present in the virtual space. *

	1	2	3	4	5	6	7	
Fully disagree	○	○	○	○	○	○	○	Fully agree

How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)? *

	1	2	3	4	5	6	7	
Extremely aware	○	○	○	○	○	○	○	Not aware at all

I was not aware of my real environment. *

	1	2	3	4	5	6	7	
Fully disagree	○	○	○	○	○	○	○	Fully agree

I still paid attention to the real environment. *

	1	2	3	4	5	6	7	
Fully disagree	○	○	○	○	○	○	○	Fully agree

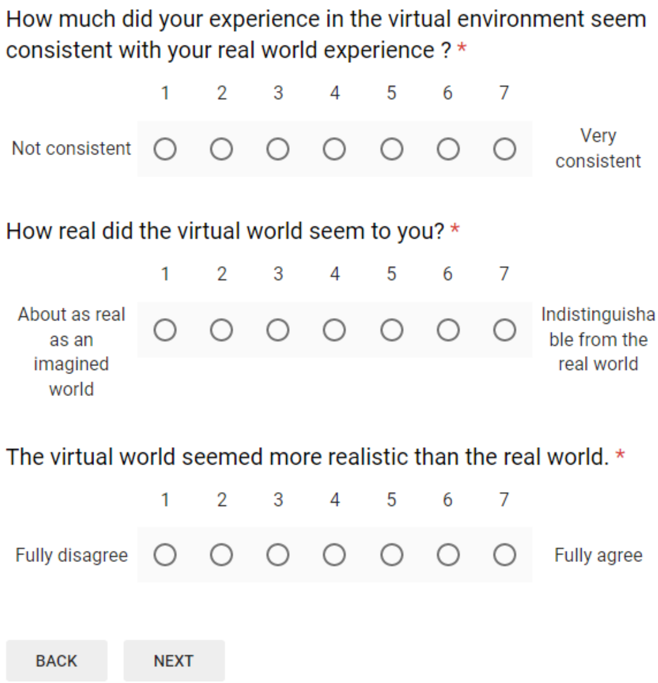
I was completely captivated by the virtual world. *

	1	2	3	4	5	6	7	
Fully disagree	○	○	○	○	○	○	○	Fully agree

How real did the virtual world seem to you? *

	1	2	3	4	5	6	7	
Completely real	○	○	○	○	○	○	○	Not real at all

Figure D.5: Post Game Questionnaire - Page 3 continued I


How much did your experience in the virtual environment seem consistent with your real world experience ? *

	1	2	3	4	5	6	7	
Not consistent	○	○	○	○	○	○	○	Very consistent

How real did the virtual world seem to you? *

	1	2	3	4	5	6	7	
About as real as an imagined world	○	○	○	○	○	○	○	Indistinguishable from the real world

The virtual world seemed more realistic than the real world. *

	1	2	3	4	5	6	7	
Fully disagree	○	○	○	○	○	○	○	Fully agree

BACK NEXT

Figure D.6: Post Game Questionnaire - Page 3 continued II

Post Game Questionnaire

* Required

Chalk Hands Notification

Please mark the degree to which you agree with each of the following statements by circling the relevant number. In particular, remember that these statements are asking you about how you felt at the end of the game.

The smell was relevant to what I was seeing. *

	1	2	3	4	5	
Not at all	○	○	○	○	○	A lot

The smell heightened the sense of reality whilst experiencing the virtual environment. *

	1	2	3	4	5	
Not at all	○	○	○	○	○	A lot

The smell made me feel more present in the virtual world. *

	1	2	3	4	5	
Not at all	○	○	○	○	○	A lot

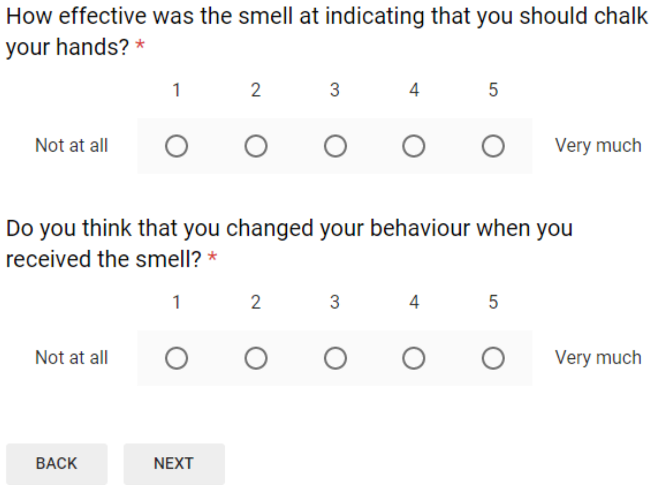
The smell was distracting. *

	1	2	3	4	5	
Not at all	○	○	○	○	○	A lot

The smell was annoying. *

	1	2	3	4	5	
Not at all	○	○	○	○	○	A lot

Figure D.7: Post Game Questionnaire - Page 4


How effective was the smell at indicating that you should chalk your hands? *

	1	2	3	4	5	
Not at all	○	○	○	○	○	Very much

Do you think that you changed your behaviour when you received the smell? *

	1	2	3	4	5	
Not at all	○	○	○	○	○	Very much

BACK NEXT

Figure D.8: Post Game Questionnaire - Page 4 continued II

Post Game Questionnaire

* Required

Flower in your Vicinity Notification

Please mark the degree to which you agree with each of the following statements by circling the relevant number. In particular, remember that these statements are asking you about how you felt at the end of the game.

The smell was relevant to what I was seeing. *

	1	2	3	4	5	
Not at all	○	○	○	○	○	A lot

The smell heightened the sense of reality whilst experiencing the virtual environment. *

	1	2	3	4	5	
Not at all	○	○	○	○	○	A lot

The smell made me feel more present in the virtual world. *

	1	2	3	4	5	
Not at all	○	○	○	○	○	A lot

The smell was distracting. *

	1	2	3	4	5	
Not at all	○	○	○	○	○	A lot

The smell was annoying. *

	1	2	3	4	5	
Not at all	○	○	○	○	○	A lot

Figure D.9: Post Game Questionnaire - Page 5

How effective was the smell at indicating that you should chalk your hands? *

	1	2	3	4	5	
Not at all	○	○	○	○	○	Very much

Do you think that you changed your behaviour when you received the smell? *

	1	2	3	4	5	
Not at all	○	○	○	○	○	Very much

BACK NEXT

Figure D.10: Post Game Questionnaire - Page 5 continued

Post Game Questionnaire

* Required

Immersion Questionnaire

Please answer the following questions by marking the relevant number. In particular, remember that these questions are asking you about how you felt at the end of the game.

I enjoyed the virtual environment. *

	1	2	3	4	5	
Not at all	○	○	○	○	○	A lot

To what extent did you feel you were focused on the game? *

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	A lot

To what extent were you aware of yourself in your surroundings? *

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very aware

At any point did you find yourself become so involved that you were unaware you were even using controls? *

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Very much so

Figure D.11: Post Game Questionnaire - Page 6

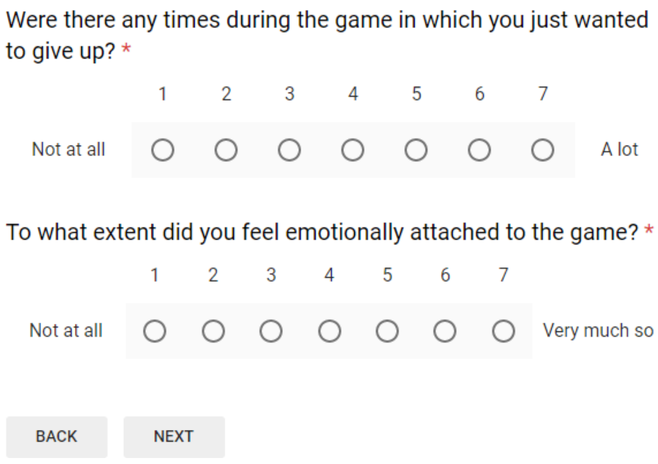


Figure D.12: Post Game Questionnaire - Page 6 continued

D.4 Post-Game Questionnaire Results

	Abbreviation	Question or Statement
1	Being there	In the computer generated world I had a sense of "being there""."
2	Surrounded	Somehow I felt that the virtual world surrounded me.
3	Only pictures	I felt like I was just perceiving pictures.
4	Not present	I did not feel present in the virtual space.
5	Acting	I had a sense of acting in the virtual space rather than operating something from outside.
6	Felt present	I felt present in the virtual space.
7	Aware r. world	How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds room temperature other people etc.)?
8	Not aware r. env.	I was not aware of my real environment.
9	Attention	I still paid attention to the real environment.
10	Captivated	I was completely captivated by the virtual world.
11	VE real (real/not real)	How real did the virtual world seem to you? completely real - not real at all
12	Consistent	How much did your experience in the virtual environment seem consistent with your real world experience ?
13	VE real (imagined/real)	How real did the virtual world seem to you? about as real as an imagined world - indistinguishable from the real world
14	More realistic	The virtual world seemed more realistic than the real world.

Table D.9: Abbreviations for the items of the Igroup Presence Questionnaire.

	Being there	Surrounded	Only pictures	Not present	Acting	Felt present
NO-O 1	6	5	3	6	6	6
NO-O 2	5	5	6	4	3	4
NO-O 3	5	4	2	6	5	6
NO-O 4	7	7	2	7	7	7
NO-O 5	6	6	2	6	7	6
NO-O 6	3	6	3	6	4	4
NO-O 7	3	4	3	5	4	4
NO-O 8	5	5	2	4	4	4
NO-O 9	5	5	2	5	4	5
NO-O 10	5	6	2	6	6	6
O-NO 1	4	4	4	4	4	4
O-NO 2	6	6	2	6	4	5
O-NO 3	5	4	2	5	5	5
O-NO 4	3	4	2	1	3	3
O-NO 5	5	5	1	6	6	4
O-NO 6	4	4	3	4	5	4
O-NO 7	5	5	2	5	6	5
O-NO 8	4	4	2	4	4	3
O-NO 9	5	3	3	4	3	3
O-NO 10	5	4	2	5	4	3

Table D.10: Responses to the Igroup Presence Questionnaire during the No-Odour condition.

	Aware r. world	Not aware r. env.	Attention	Captivated	VE real (real/not real)	Consistent
NO-O 1	5	2	2	3	4	3
NO-O 2	4	3	2	4	4	4
NO-O 3	2	2	2	6	2	4
NO-O 4	4	3	1	7	2	6
NO-O 5	6	3	2	6	2	4
NO-O 6	6	2	3	3	4	1
NO-O 7	5	4	3	5	4	3
NO-O 8	6	3	2	4	2	4
NO-O 9	4	3	2	5	3	4
NO-O 10	5	4	2	5	2	6
O-NO 1	4	3	3	4	4	3
O-NO 2	3	6	2	4	2	5
O-NO 3	6	6	2	5	5	2
O-NO 4	5	5	3	6	4	2
O-NO 5	6	6	2	6	1	5
O-NO 6	2	3	3	5	3	4
O-NO 7	2	2	4	5	3	4
O-NO 8	2	3	3	5	5	3
O-NO 9	3	2	3	4	4	3
O-NO 10	2	4	2	4	5	3

Table D.11: Responses to the Igroup Presence Questionnaire during the No-Odour condition.

	VE real (imagined/real)	More realistic
NO-O 1	5	1
NO-O 2	3	2
NO-O 3	4	1
NO-O 4	4	2
NO-O 5	3	2
NO-O 6	3	1
NO-O 7	3	1
NO-O 8	4	1
NO-O 9	5	1
NO-O 10	4	1
O-NO 1	3	1
O-NO 2	4	2
O-NO 3	3	1
O-NO 4	2	1
O-NO 5	5	1
O-NO 6	2	1
O-NO 7	3	2
O-NO 8	3	1
O-NO 9	3	1
O-NO 10	4	1

Table D.12: Responses to the Igroup Presence Questionnaire during the No-Odour condition.

	Being there	Surrounded	Only pictures	Not present	Acting	Felt present
NO-O 1	5	5	4	5	6	6
NO-O 2	4	5	5	6	3	4
NO-O 3	6	5	2	2	4	6
NO-O 4	6	7	1	7	7	7
NO-O 5	6	6	2	5	5	5
NO-O 6	4	4	2	5	5	5
NO-O 7	6	6	4	6	6	6
NO-O 8	5	5	3	5	5	6
NO-O 9	4	5	4	5	6	5
NO-O 10	6	7	2	7	7	6
O-NO 1	6	5	3	5	4	5
O-NO 2	6	5	2	3	6	6
O-NO 3	6	5	2	6	6	6
O-NO 4	6	5	1	5	4	5
O-NO 5	6	6	1	1	5	6
O-NO 6	6	6	2	2	6	6
O-NO 7	6	6	3	2	6	5
O-NO 8	5	5	2	6	6	7
O-NO 9	6	5	1	5	5	6
O-NO 10	6	6	2	4	6	6

Table D.13: Responses to the Igroup Presence Questionnaire during the Odour condition.

	Aware r. world	Not aware r. env.	Attention	Captivated	VE real (real/not real)	Consistent
NO-O 1	3	3	2	4	3	2
NO-O 2	4	3	2	5	4	4
NO-O 3	5	2	2	6	3	4
NO-O 4	5	4	1	7	2	6
NO-O 5	4	5	2	5	2	4
NO-O 6	2	1	2	5	4	6
NO-O 7	6	4	1	6	2	6
NO-O 8	5	4	1	7	2	5
NO-O 9	4	3	2	5	3	4
NO-O 10	5	3	1	7	3	6
O-NO 1	4	3	2	5	3	5
O-NO 2	6	4	3	4	2	3
O-NO 3	7	5	2	6	2	4
O-NO 4	6	3	2	5	2	4
O-NO 5	5	5	2	5	2	5
O-NO 6	2	2	2	6	4	5
O-NO 7	4	3	4	5	3	4
O-NO 8	6	2	2	6	1	5
O-NO 9	6	3	2	6	2	4
O-NO 10	7	3	2	5	2	4

Table D.14: Responses to the Igroup Presence Questionnaire during the Odour condition.

	VE real (imagined/real)	More realistic
NO-O 1	3	1
NO-O 2	3	1
NO-O 3	5	3
NO-O 4	5	2
NO-O 5	5	2
NO-O 6	3	2
NO-O 7	5	1
NO-O 8	5	1
NO-O 9	5	2
NO-O 10	5	1
O-NO 1	4	2
O-NO 2	4	2
O-NO 3	3	1
O-NO 4	3	2
O-NO 5	5	1
O-NO 6	3	1
O-NO 7	3	1
O-NO 8	4	2
O-NO 9	5	1
O-NO 10	3	1

Table D.15: Responses to the Igroup Presence Questionnaire during the Odour condition.

Abbreviation	Question
Relevant	The smell was relevant to what I was seeing.
Sense of Reality	The smell heightened the sense of reality whilst experiencing the virtual environment.
Present	The smell made me feel more present in the virtual world.
Distracting	The smell was distracting.
Annoying	The smell was annoying.
Flower	How effective was the smell at indicating that a flower was in your vicinity?
Chalk	How effective was the smell at indicating that you should chalk your hands?
Behaviour	Do you think that you changed your behaviour when you received the smell?

Table D.16: Abbreviations for the Quality of Experience Questionnaire items.

	Relevant	Sense of Reality	Present	Distracting	Annoying	Chalk	Behaviour
NO-O 1	5	5	5	2	1	4	4
NO-O 2	5	5	4	2	2	4	5
NO-O 3	5	4	5	2	2	5	5
NO-O 4	3	4	4	1	1	3	4
NO-O 5	2	2	2	4	2	2	4
NO-O 6	2	1	1	2	1	2	4
NO-O 7	3	5	5	2	1	5	5
NO-O 8	5	5	4	2	2	5	4
NO-O 9	4	4	5	1	1	3	5
NO-O 10	3	5	4	1	1	5	5
O-NO 1	3	4	3	1	1	3	4
O-NO 2	2	2	2	3	1	2	3
O-NO 3	3	2	2	2	1	5	5
O-NO 4	4	5	3	4	4	4	5
O-NO 5	5	4	4	1	1	4	5
O-NO 6	4	4	4	2	2	5	5
O-NO 7	2	2	3	1	1	2	4
O-NO 8	3	5	3	2	1	5	4
O-NO 9	4	5	5	2	1	4	5
O-NO 10	5	5	4	1	1	5	5

Table D.17: Quality of Experience responses for the Chalk Hands notification.

	Relevant	Sense of Reality	Present	Distracting	Annoying	Flower	Behaviour
NO-O 1	4	4	4	2	1	5	4
NO-O 2	5	4	4	2	2	5	5
NO-O 3	4	4	5	2	2	5	5
NO-O 4	4	4	4	1	1	4	4
NO-O 5	4	4	4	1	1	4	5
NO-O 6	4	5	5	2	1	4	5
NO-O 7	4	5	4	1	2	5	5
NO-O 8	5	4	5	2	1	4	5
NO-O 9	5	5	5	1	2	5	4
NO-O 10	4	4	4	1	1	5	4
O-NO 1	4	3	4	2	1	5	4
O-NO 2	3	2	2	1	1	2	2
O-NO 3	4	3	4	2	1	5	5
O-NO 4	5	5	3	3	3	4	4
O-NO 5	5	5	5	1	1	5	5
O-NO 6	4	4	4	2	2	5	5
O-NO 7	5	5	4	1	1	4	5
O-NO 8	5	5	3	1	1	5	4
O-NO 9	5	3	5	1	1	5	5
O-NO 10	5	5	4	2	1	4	3

Table D.18: Quality of Experience responses for the Flower in vicinity notification.

Abbreviation	Question
Focused	To what extent did you feel you were focused on the game?
Aware	To what extent were you aware of yourself in your surroundings?
Involved	At any point did you find yourself become so involved that you were unaware you were even using controls?
Give Up	Were there any times during the game in which you just wanted to give up?
Emotional	To what extent did you feel emotionally attached to the game?

Table D.19: Abbreviations for the questions of the Jennet et al. Presence Questionnaire.

	Focused	Aware	Involved	Give Up	Emotional
NO-O 1	5	5	2	3	5
NO-O 2	3	5	2	5	4
NO-O 3	5	6	6	1	4
NO-O 4	7	7	6	1	7
NO-O 5	7	6	5	1	6
NO-O 6	4	3	3	4	5
NO-O 7	4	3	3	2	4
NO-O 8	5	7	4	4	4
NO-O 9	3	4	3	5	5
NO-O 10	4	5	3	3	4
O-NO 1	4	5	2	6	3
O-NO 2	5	5	6	4	6
O-NO 3	5	3	5	1	4
O-NO 4	3	2	2	1	3
O-NO 5	7	7	6	1	4
O-NO 6	5	4	3	2	2
O-NO 7	5	4	3	1	6
O-NO 8	5	5	3	5	3
O-NO 9	4	5	2	6	4
O-NO 10	4	5	2	6	3

Table D.20: Jennet et al. Presence Questionnaire Responses from the No-Odour Condition.

	Focused	Aware	Involved	Give Up	Emotional
NO-O 1	5	4	3	5	5
NO-O 2	6	6	4	2	5
NO-O 3	6	6	6	1	5
NO-O 4	7	2	6	1	7
NO-O 5	7	5	4	1	5
NO-O 6	4	3	4	3	3
NO-O 7	7	3	6	2	6
NO-O 8	6	3	6	3	6
NO-O 9	6	5	4	3	5
NO-O 10	7	4	5	2	5
O-NO 1	5	5	1	5	5
O-NO 2	5	5	5	4	3
O-NO 3	6	3	6	1	5
O-NO 4	6	5	1	3	7
O-NO 5	6	3	5	3	3
O-NO 6	6	2	4	3	5
O-NO 7	7	4	4	2	5
O-NO 8	6	3	6	4	6
O-NO 9	7	3	1	1	4
O-NO 10	7	5	5	2	5

Table D.21: Jennet et al. Presence Questionnaire Responses from the Odour Condition.

ID	Flower Score	Falls	Chalking	Savepoints
NO-O10	1	5	1	1
NO-O9	3	4	7	5
NO-O8	2	6	2	2
NO-O7	3	2	6	3
NO-O6	2	6	2	2
NO-O5	6	0	11	4
NO-O4	3	6	4	3
NO-O3	4	1	6	3
NO-O2	2	6	2	1
NO-O1	1	10	1	1
O-NO10	2	3	14	4
O-NO9	3	9	10	4
O-NO8	4	0	10	5
O-NO7	6	0	11	6
O-NO6	2	3	15	10
O-NO5	3	4	23	8
O-NO4	4	2	16	10
O-NO3	4	1	8	9
O-NO2	6	1	7	5
O-NO1	3	9	10	3

Table D.22: Performance scores from the No-Odour condition.

ID	Flower Score	Falls	Chalking	Savepoints
NO-O10	6	2	12	4
NO-O9	9	0	25	10
NO-O8	7	2	11	5
NO-O7	9	1	24	9
NO-O6	7	3	10	4
NO-O5	9	0	17	7
NO-O4	6	3	9	9
NO-O3	9	1	25	10
NO-O2	5	0	8	7
NO-O1	6	3	8	4
O-NO10	7	1	16	5
O-NO9	6	5	15	5
O-NO8	6	0	22	5
O-NO7	8	0	22	4
O-NO6	6	2	18	7
O-NO5	5	2	16	4
O-NO4	6	1	19	4
O-NO3	6	0	17	6
O-NO2	5	5	8	5
O-NO1	6	5	15	6

Table D.23: Performance scores from the Odour condition.