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CITY UNIVERSITY
LONDON

Department of Optometry
and Visual Science

Optimising computer displays for normal and visually impaired users

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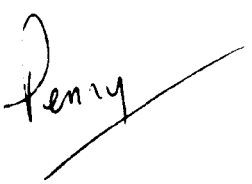
My thanks also to my long-suffering flatmate for the home cooked meals and homespun common-sense. To my colleagues such as J-B for not switching off her office lights, locking the door and hiding under the desk whenever I came to visit. To Brendan for distracting me with a good murder. Also thanks to my family for giving me a surname thus ensuring a lifetime of ridicule and to my friends for blurring the jagged edges in the manner of anti-aliasing only with gin. Works much better!

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Enjoy!



Declaration

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Abstract

Computers have become ubiquitous in the modern world and most people spend several hours each day viewing computer displays. With the advent of LCD flat panel displays and the increase in graphical processing power, computer displays have rapidly evolved from barely legible text displays to the modern graphical user interface. Despite the improvement in the design and legibility of computer displays, complaints of visual discomfort are still surprisingly common amongst computer users. In many cases, the problems stem from poor workstation design, inappropriate working practices or uncorrected refractive errors or binocular vision anomalies. However, the fact that symptoms often persist when these factors have been addressed suggests that the design of computer displays may be sub-optimal in a number of respects.

There is a vast literature relating to the ergonomics of displays and yet there is still a lack of good quality data on the effects of key parameters on user efficiency and reading speed. In particular, there is very little information about the potential benefits of changing screen colours.

The first part of this thesis describes a series of experiments designed to systematically examine the effects of contrast, font size, font style, letter spacing, contrast polarity, anti-aliasing and screen colour on the comfort and visual efficiency of users with normal vision. A series of tests were devised to assess user efficiency including search tasks and modified versions of the MNRead and Wilkins Rate of Reading tests. In general, user efficiency judged by performance in these tasks proved to be remarkably immune to changes in screen parameters and it is concluded that the default settings used on most displays is close to optimal. Many subjects subjectively preferred a background colour other than white although this preference was seldom rewarded by a measurable improvement in efficiency. However, changing the background colour did seem to reduce the prevalence of asthenopic symptoms.

The second part of the thesis describes a series of investigations designed to examine the potential benefits of changing selected display parameters for individuals with Age Related Maculopathy, Primary Open Angle Glaucoma and Retinitis Pigmentosa. Of particular interest was the effect of changing screen colours given the anecdotal evidence that some patients with these conditions gain some benefit from coloured lenses. The relatively small number of subjects and the heterogeneous nature of the groups limited the scope of the conclusions that could be drawn from this study. However, it is clear that the visual performance of many visually-impaired individuals can be greatly enhanced by the correct

selection of screen parameters, particularly font size, contrast and in some case, colour. A computer programme to assist in the optimisation of these parameters was developed as the final part of this work.

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Life shrinks or expands in proportion to one's courage.

Anais Nin (1903 – 1977)

1. Introduction

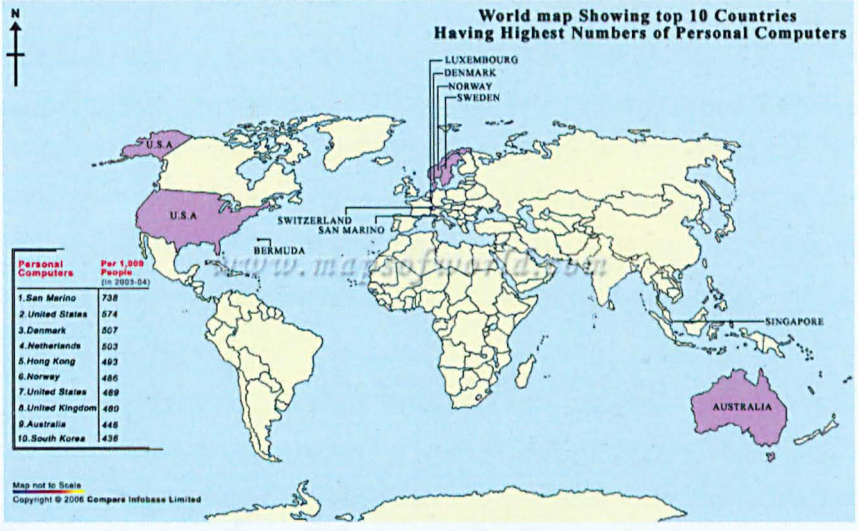
1.1 Introduction

According to the founder of Microsoft, Bill Gates, "personal computers have become the most empowering tool we've ever created. They're tools of communication, they're tools of creativity, and they can be shaped by their user" (Woopidoo Quotations, 2007).

Computers have become an integral part of modern life. Many people now spend a significant proportion of their working day interacting with computers. Computers have also pervaded the domestic environment where they are used increasingly for communication, entertainment (games, music, films) whilst the internet has revolutionised the way that we search for information, shop and interact with others.

The BBC reports that on average, people in the UK spend approximately 10 hours/ week using the internet with people in London spending 4 hours longer (BBC, 2006). Figure 1 shows that in the period 2003-2004, 46% of the population in the UK regularly used a computer, a ranking of 8th in the world (Mapsofworld.com, 2006). By 2007, 60% of the population in the UK owned a computer, a ranking of 12th in the world (Aakre & Doughty, 2007; Fernandez, 2007).

Figure 1 – World map showing top 10 countries having highest number of personal computers (From: (Mapsofworld.com, 2006))



National Statistics (2006) report similar figures for computer use. They show that between January and April 2006, more than half of all households (56%) in the UK had a desktop computer, almost a third (30%) owned a portable or laptop computer and 7% possessed handheld computers. During the same period, almost 90% of people aged between 16 and

30 years had used a computer in the previous three months compared with only 45% of people in the age group of 50 years or over (National Statistics, 2006). The Office for National Statistics (2006) also reported that in a five year period from 2000 to 2005, the average time spent using computers rose from 96 mins to 120 mins/ day.

These figures confirm that computers are having an increasing impact on almost every aspect of life and most people spend many hours each day interacting with computers in various guises. Despite advances in speech synthesis/recognition and other interface technologies, visual displays remain the most common medium for interacting with computers. Whilst there have been significant developments in display technology over the past decade, complaints of visual problems associated with using displays are still common and it is likely that the visual characteristics of display screens are still sub-optimal in a number of respects.

This thesis describes a series of studies designed to quantify the effects of key display parameters on the visual performance of normal and visually-impaired observers.

1.2 Computers in society – past, present and future

1.2.1 History of computers

Just ten years ago, the dictionary definition of a computer was "an electronic machine for carrying out complex calculations, dealing with numerical data or with stored items of other information, also used for controlling manufacturing processes, or coordinating parts of a large organisation; a calculator" (The Chambers Dictionary, 1999). Whilst this definition is still accurate in terms of the core function of a computer, the increase in computer power coupled with the development of sophisticated software and peripheral devices has meant that computers are now far more than a calculator but, in fact, lie at the heart of virtually all aspects of modern day life.

The Encyclopaedia Britannica describes the earliest computer as the abacus (Encyclopaedia Britannica, 2007), though the origins and exact time are often disputed, with some historians claiming it was invented in Mesoptamia sometime between 1,000 BC and 500 BC, others assert it was actually invented by the Chinese (Wikipedia, 2007).

The French mathematician Blaise Pascal invented the first true calculating machine between 1642 and 1644. The functions were limited. The first programmable machine was not described until the 1830s by Charles Babbage, which he called "The Analytical Engine" (www.maxmom.com, 2007). Babbage's invention was never finished. The next significant milestone in computing history was the development of "punched cards" for information processing which was a move towards true automation (www.history.rochester.edu, 2007).

The first "freely programmable computer" was invented in 1936 by Konrad Zuse (www.inventors.about.com, 2007). This was a binary computer which was essentially a large calculator. The advent of the Second World War meant that computing technology developed at a fast pace. In 1942, John Presper Eckert and John W Mauchly designed a high-speed electronic computer which they called ENIAC (Electrical Numerical Integrator and Calculator). It consisted of 18,000 vacuum tubes and used 180,000 watts of electricity (www.softlord.com, 2007).

Jeremy Meyers in his "A Short History of the Computer" (www.softlord.com, 2007) describes the development of the computer from ENIAC through "controlled control transfer", through random access memory (RAM) and into the 1950s. In the 1950s, according to Meyers, the two major milestones were the use of magnetic core memory and the transistor-circuit element. Jack Kilby (1958) invented the microchip which, in real terms, meant that large amounts of information and data could be stored on something smaller than the size of a pinhead where previously it had taken office floors. The 1960s saw advancements in speed and memory, and increased widespread use of computers in a number of different

environments. The 1970s saw the introduction of the microcomputer; the precursor of the personal computers of today.

IBM introduced the first personal computer in 1981 (www.blinkenlights.com). However, it was Sir Alan Sugar, director of Amstrad, who brought personal computers to the masses with the introduction of the PCW8256 word processor in 1985 at affordable prices (www.biogs.com).

The introduction of the world-wide web by Tim Berners-Lee in the 80s brought the world to peoples' doorsteps. It made possible immediate contact with people on the other side of the globe at the click of a button. It also made normal daily activities such as grocery shopping accessible and opened the door for people with disabilities. Leiner et al (1999) said: "The Internet has revolutionised the computer and communications world like nothing before" (www.arxiv.org).

In a five year period from September 1998 to September 2003, the number of households in the UK with internet access increased five fold from 9% to 48% (National Statistics, 2003) with 64% of the population having used the internet at some point prior to interview (National Statistics, 2003). By 2007, this figure had increased to 61% of households having internet access with 67% of people aged 16 years or over having used it in the three months prior to interview (National Statistics, 2007). Eighty-eight percent of people in the age range 16-24 years used the internet compared to only 16% of those aged 65 yrs or over (National Statistics, 2003). This increased to 90% for the 16-24 yrs group and 24% for those aged 65 years and above (National Statistics, 2007). The three main uses for the internet in 2003 were emails (84%), information regarding 'goods and services' (80%) and, travel and accommodation information (68%) (National Statistics, 2003). In 2007, information regarding 'goods and services' overtook email use as the most common use of the internet (86%). Emails accounted for 85% of use whilst travel and accommodation dropped to 63%. Men (70%) were more likely than women (63%) to use the internet on a daily or almost daily basis (National Statistics, 2007). Almost 80% of all UK internet connections were broadband connections (National Statistics, 2006).

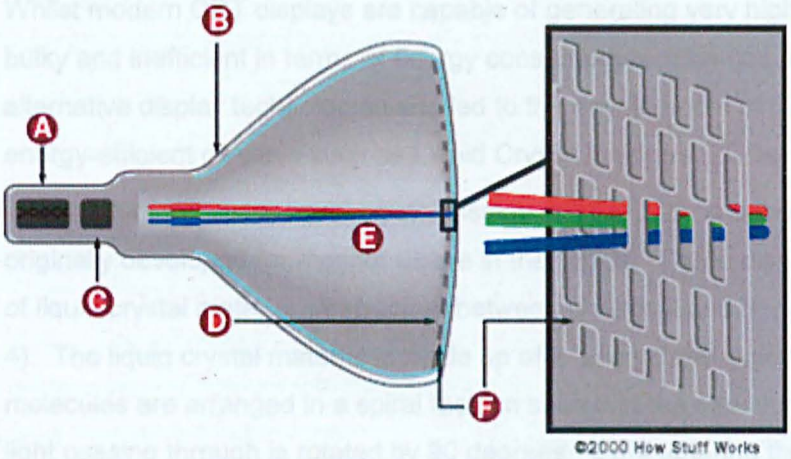
1.3 Display technologies

1.3.1 Cathode Ray Tube (CRTs)

The earliest computers used mechanical "flags" or lights to signal the result of calculations. The development of Cathode Ray Tubes (CRTs) provided a new output device for computers and CRTs were widely used in the computing industry from the 1960s onwards. These displays developed from small, low resolution screens to sophisticated units capable of producing large, high-resolution images. Over the past decade, new display technologies including Liquid Crystal Displays (LCD) and Plasma screens have largely replaced CRTs except for specialist applications where exceptionally high resolution or precise colour rendering is required.

A CRT is an evacuated glass tube with a phosphor-coated screen at one end and a filament and deflection coils at the other (see Figure 2). Electrons are emitted by the filament and accelerated, focused and deflected by the action of the deflection coils. The electron beam strikes the screen at the other end of the tube and at the point of impact the phosphor emits light. The brightness of the light emitted is related to the intensity of the electron beam which in turn is determined by the accelerating voltage.

Figure 2 – Figure showing conventional CRT



(After: http://www.howstuffworks.com/tv3.htm)

There are several methods for presenting information on the screen but the most common is by raster scanning (see Figure 3). This involves the deflection of the beam in a series of horizontal lines (scan lines), which are conventionally drawn from the top to the bottom of the screen. To avoid the perception of flicker on the screen, this process must be repeated many times a second. Each screen-full of lines is called a field and the number of screens

drawn per second is called the field scan frequency or refresh rate. Most CRTs display between 500 and 1000 scan lines and use refresh rates between 50 and 100 Hz. Information is presented on the screen by modulating the intensity of the electron beam as it is swept across the screen.

Figure 3 – Raster scanning



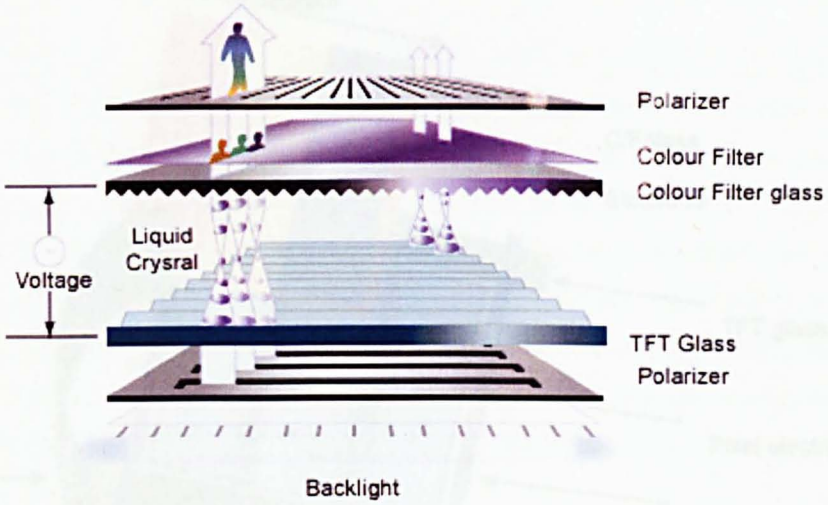
(After: Thomson (2007), 2nd year optometry lecture)

1.3.2 Flat Panel (LCD) Displays

Whilst modern CRT displays are capable of generating very high quality images, they are bulky and inefficient in terms of energy consumption. This has stimulated the search for alternative display technologies and led to the development of thinner, lighter and more energy-efficient displays such as Liquid Crystal Displays (LCDs) and plasma screens.

The thin film transistor liquid crystal display or TFT-LCD, is a modern form of the LCD originally developed for monitor usage in the 1970s. These displays consist of a thin layer of liquid crystal material sandwiched between a vertical and horizontal polarizer (see Figure 4). The liquid crystal material is made up of long crystalline molecules. The individual molecules are arranged in a spiral fashion such that the direction of polarization of polarized light passing through is rotated by 90 degrees. Light entering through the vertical polarizer is thus rotated by 90 degrees and passes through the horizontal polarizer. However, when an electric field is applied to the crystals, they all line up and lose their polarizing characteristics. Without the polarizing effect of the liquid crystal layer, the vertical and horizontal polarizers will attenuate most of the light.

Figure 4 – Figure showing how conventional Liquid Crystal Displays work



(After: www.teac.com.au/pages/howdoesanlcdwork)

Conventional Liquid Crystal Displays use horizontal and vertical grids of wires to generate a matrix. Individual cells within the matrix can then be turned on or off by applying a current across specific elements in the grid.

Thin Film Transistor (active matrix) LCD panels have a transistor for each cell in the matrix. The transistors allow the state of the crystals to be changed more rapidly allowing images to be moved without smearing. The transistors also allow the degree of polarization to be varied giving a range of grey levels between on and off. The transistor also serves as a memory for the cell allowing it to stay on without being refreshed. TFT LCD panels are, therefore, virtually flicker-free (www.cs.ndus.nodak.edu, 1996).

Colour displays are possible by dying the liquid crystals and juxtaposing red, green and blue cells. The individual coloured cells are too small to be resolved by the eye. Consequently, a wide gamut of colours can be produced by varying the relative intensity of the red, green and blue cells in each triad.

Figure 5 - Summarises the differences between a CRT display and an LCD display

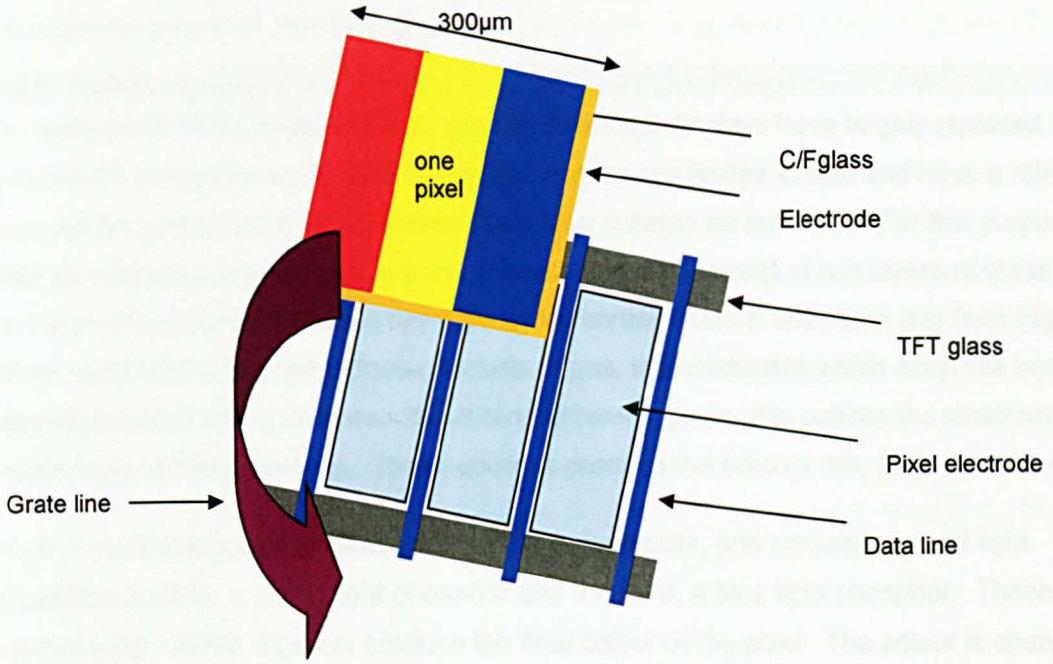


Table 1 – *Comparison of LCD versus CRT displays*

Consideration	LCD	CRT
Image flicker	None	Prone to flicker
Image brightness	Bright, uniform	Bright, tends to be spatially non-uniform and varies over time
Image geometry	Uniform	Distorted
Image sharpness	High	Moderate to high
Screen viewing area	Full area, very space efficient	Partial area, space inefficient
Screen size	Smaller screen for equivalent CRT viewing area	Larger screen for equivalent LCD viewing area
Specular screen glare	Low	Prone to specular glare
Energy consumption	Low	High
Electromagnetic emissions	No	Yes
Heat emissions	Minimal	High
Space efficiency	High	Low
Flexible positioning	High	Moderate
Weight	Light	Heavy
Colour range	Very Good	Excellent

(Adapted from: Alan Hedge www.ergo.human.cornell.edu/Pub/LCD_vs_CRT_AH.pdf)

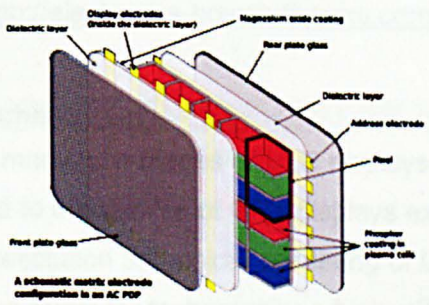
Wang and Chen (2003) found no significant difference in reading performance when participants used CRT and LCD displays.

1.3.3 Plasma Screens

Co-invented in 1964, it was not until recently that LCD displays have largely replaced CRT screens for computer work. The current generation are limited in size and have a relatively poor temporal resolution which makes them less suitable for television. For this purpose plasma screens have become popular. Plasma displays consist of two layers of glass between which are sandwiched tiny cells which contain Xenon and Neon gas (see Figure 6). When electricity is applied to these pockets of gas, the electrodes within each cell become activated thus creating photons. By utilising different gases, this causes the electrodes to collide thus emitting photons. These photons produce the colours red, green and blue.

Each pixel is composed of three individual subpixed cells; one containing a red light phosphor, another a green light phosphor and the third, a blue light phosphor. These colours when added together produce the final colour of the pixel. The colour is changed by changing the current that travels through these cells many thousands of times per second thus producing millions of different combinations of colour. This means that most of the colours that lie within the visible spectrum can be replicated on a computer. The current plasma screens use the same system of colour devised from these phosphors as the conventional CRTs which enables them to have very good colour reproduction properties.

Figure 6 - Figure showing how conventional Plasma screens work



(After: http://en.wikipedia.org/wiki/Plasma_screen)

1.3.4 Organic Light Emitting Diodes (OLEDs)

The first diode device which later gave rise to the term OLED (Organic light emitting diode) was developed in the 1980s by Kodak. This device used two layers; one for hole transporting and the other for electron transporting with the result that light was produced between these two layers. An OLED is the equivalent of a high definition television screen or computer display which can be rolled up and put away when it is not being used (see

Figure 7). Billed as the latest advance in technology, this new generation devices produces sharper and brighter images than an LCD is capable of by creating light from electricity which passes through thin layers of molecules.

The advantages of an OLED over other similar flat panel displays is that they can be printed onto significantly more materials than either LCDs or plasma displays. This lends itself to a wealth of possibilities such as the clothing industry. In addition, The OLEDs have a much better viewing angle close to 90 degrees and has a much better range of colours than conventional LCDs. Conventional LCDs require a backlight. However, an OLED does not produce any light when switched off and, consequently, uses no power. This makes them ultimately more economical than an LCD. Their thinness is achieved by them not having to have a backlight and this means that they can be ¼ inch thick. Currently, the main disadvantage of OLEDs is the limited lifespan; they only last about five years (assuming 8 hrs use per day) due to the organic materials that they use.

Figure 7 - *Figure showing a conventional OLED*



(After: http://electronics.howstuffworks.com/oled.htm)

1.3.5 Emerging display technologies

Over the past ten years, the many advantages of LCD displays coupled with a dramatic reduction in their cost has led to the demise of CRT displays except for specialist applications. However, the resolution and colour rendering of LCD screens is still no match for printed documents and the quest for technologies which will match the resolution, quality and versatility of printed matter goes on. In recent years, this has been driven by the need to miniaturise displays for mobile phones and the development of electronic readers to replace books, newspapers, magazines etc.

It is predicted that within the next few years, handheld devices capable of storing thousands of books will be available. These devices will also be capable of downloading newspapers and magazines thus transforming the way that we read in much the same way that mp3

players have transformed the way that we access music. However, such a device requires a display that matches the quality of printed matter whilst being light and energy efficient.

Hsin-Chieh et al (2007) compared the reading performance, subjective satisfaction and visual fatigue of three e-books; an e-book reader, a notebook computer and a personal digital assistant. Whilst they found no significant differences in actual reading performance between either of these three e-books with their group of 22 university students, the subjects preferred the notebook computer to the other two e-books on offer. In addition, visual fatigue was rated as significantly higher for the personal digital assistant than with either of the other two e-books.

A number of manufacturers have taken up this challenge. For example, the Sony Reader uses a new technology known as "electronic paper" to display high resolution text and images on a 6" screen (see Figure 8). The unit is currently capable of storing up to 80 complete books and yet weighs less than 8oz (Sony Reader, 2007).

Figure 8 – Sony Reader

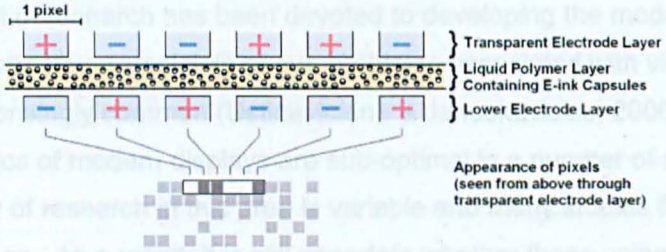


(After: http://www.mobilewhack.com/images/Sony-Reader.jpg)

Electronic paper or electronic ink works using positive white and negative black electrodes. Sandwiched between these electrodes, is a thin layer of liquid polymer which acts as a conductor (see Figure 9). Applying a positive charge to the electrodes results in pushing the black particles to the bottom whilst forcing the white electrodes to the surface. The resultant effect gives the pixels a white appearance. Applying a negative force has the opposite effect and results in a black appearance. The advantages of electronic ink are that they overcome many of the problems associated with reading from a display screen in that they produce the same high contrast effects of reading from a hard copy whilst eliminating unwanted reflections caused by variations in viewing angle or illumination including direct

sunlight. It also requires no front or backlight and is as thin as a piece of paper (E-ink: *Electronic Paper Displays, 2007).*

Figure 9 - Electronic ink (From: Electronic Paper, 2007)



Apple have just launched their latest iPod which is rumoured to be able to be used as an e-book through the Note Reader option (see Figure 10). It is possible that items such as iPods could be developed in the future for this purpose.

Figure 10 – iPod screen showing text



(After: http://blog.wired.com/gadgets/DSC_1367.jpg)

1.4 The visual ergonomics of displays

1.4.1 Prevalence of eye complaints

The legibility of visual displays has improved significantly over recent years and a considerable amount of research has been devoted to developing the modern graphical user interface. Despite this, complaints of eye problems associated with viewing computer displays are still surprisingly common (Ustinaviciene & Januskevicius, 2006) and it is likely that the characteristics of modern displays are sub-optimal in a number of respects. However, the quality of research in this area is variable and many studies failed to use suitable control groups. As a result, it is still uncertain whether those using computer displays are more likely to suffer symptoms than those performing similar visual tasks using printed materials.

The main visual symptoms reported by computer users are "eyestrain", tired eyes, irritation, burning sensation, redness, blurred vision and double vision (Collins, Brown & Bowman, 1998; Berg & Bengt, 1996; Cole, Maddocks & Sharpe, 1996; Bergqvist & Knave, 1994; Bergqvist & Knave, 1994; Lie & Watten, 1994; Lie & Watten, 1994; Dain, Chan & Williams, 1985). These symptoms and signs of eyestrain are collectively referred to as 'asthenopia' or increasingly, as 'computer vision syndrome' (Blehm et al., 2005).

It is generally accepted that these symptoms are temporary. Ustinaviciene & Januskevicius (2006) report that 43% of workers report immediate relief of symptoms upon cessation of computer use, 45% had symptoms for several hours after finishing work and only 12% felt their symptoms continued until the next day.

There is no reliable evidence that work with computers causes any permanent damage to the eyes (Yeow & Taylor, 1991; Yeow & Taylor, 1990; Yeow & Taylor, 1989). Furthermore, there is no good evidence that computer users are more likely to become short-sighted or develop any other form of eye defect (Taino et al., 2006; Mutti & Zadnik, 1996; Hanne & Brewitt, 1994; Toppel & Neuber, 1994; Watten, 1994; Gur & Ron, 1992; Watten & Lie, 1992; Yeow & Taylor, 1990; Yoshikawa & Hara, 1989; Tokoro, 1988; Polakoff, 1986; Starr, Thompson & Shute, 1982). Indeed, it could be argued that because computer displays tend to be viewed from a greater distance than printed documents, the stimulus for myopia to progress is actually reduced although there is no reliable evidence to support this view.

There is good evidence that reports of visual symptoms correlate with the hours spent using a computer (Taino et al., 2006; Tomei et al., 2006; Carta et al., 2003; Tamez et al., 2003; Travers & Stanton, 2002; Belisario et al., 1988; Knave et al., 1985).

Mocci, Serra & Corrias (2001) recruited 212 bank workers with a mean age of 38.6 yrs who had no refractive error or ocular conditions. Of these, almost a third (31.9%) reported

symptoms of asthenopia. They found no association between asthenopia and number of hours of computer use or number of years of computer use. Instead, they found a strong correlation with psychological and environmental conditions. It would seem likely that this relatively low figure for symptoms of asthenopia may be due to the young age of the participants and that any subjects with any refractive error or ocular conditions were excluded at the recruitment stage of the project.

Sheedy (1992) conducted a postal questionnaire of 330 optometrists in the USA. The study showed that 14.25% of patients primarily visit their optometrist complaining of problems associated with computer use. Surprisingly, 39.3% of their patients who use computers are prescribed spectacles for computer use only. This is much higher than is found in the UK (Hayes et al., 2007; Jackson et al., 1997).

From a sample of 324 patients, Salibello & Nilsen (1995) report that a typical computer user "is a 38-year old, mildly myopic female who uses the computer screen for about 5 hours per day".

It would be appropriate to discuss the relative prevalence of individual ocular symptoms. However, many of the studies in this area tend to group 'visual symptoms' into one category. Iwakiri et al. (2004) looked at the effects of computer use on visual and musculoskeletal symptomatology. They found that "visual symptoms" were the most common complaint accounting for 72.1% of a sample of 2,374 office workers and that women reported discomfort more than men. This finding is supported by Taino et al. (2006) and Knave et al. (1985). Neck stiffness was the second most commonly reported symptom but this only accounted for 59.3% of the sample; some 13% less than ocular symptoms.

Ustinaviciene & Januskevicius (2006) reported that 85.6% of the computer users they sampled complained of "unclear vision' compared to only 10.7% of controls. They also reported that 46.1% complained of 'ocular pain'. Nakaishi & Yamada (1999) reported that 33.9% of computer users fulfilled the criteria for dry eyes compared with 10.0% of controls. In an unpublished study looking at the prevalence of symptoms with computer use, Bhatt (n.d.) found that "dry/irritated eye" was the most common symptom accounting for 48% of the sample with "eyestrain/pain" accounting for 40.3%.

Bali, Navin & Thakur (2007) asked 300 Indian ophthalmologists to complete questionnaires about Computer Vision Syndrome. Only 45% of the sample returned their questionnaires and of these, the groups were subdivided further into computer users and non computer users. Computer users accounted for 32/134 questionnaires. The main complaints were "eyestrain" accounting for 97.8% of the sample, "headaches" (82.1%), "tiredness and

burning" (79.1%), "watering" (66.4%) and "redness" (61.2%). Symptoms relating to poor workstation setup (shoulder and neck pain) accounted for 44.0% and 35.8% respectively.

Hayes et al. (2007) sent questionnaires to a random sample of 1000 university employees. "Tired eyes" was the most commonly reported ocular symptom accounting for 77% of the sample. "Eyestrain" was the second most common ocular symptom (74%). Fifty seven per cent of respondents reported symptoms of "dry eyes" and 56% reported "irritating or burning eyes". Just over half the sample (54%) reported "difficulties in refocusing eyes from one distance to another"; 47% reported difficulties with "blurred vision at near distances"; 44% at intermediate distances and 42% at far distances. Headaches were reported by 45% of the sample.

In summary, the prevalence of symptoms among computer-users is difficult to gauge from published studies. The results from a number of studies, summarised in Table 2, show that the prevalence of symptoms reported is very dependent on the design of the study and the nature of the group surveyed. Furthermore, most of these studies relate to the older CRT style displays and the methodology employed in some of these studies is open to criticism; in particular a failure to use appropriate control groups. As a result, it is still not clear whether computer users suffer more eye problems than those carrying out similar visual tasks not involving a computer (Laubli, Hunting & Grandjean, 1980). However, the fact remains that an alarmingly high proportion of computer users complain of some form of eye problem.

In some cases, the symptoms relate to uncorrected refractive errors or binocular vision problems (Piccoli et al., 1989). In other cases, environmental factors such as the organisation of the workstation, poor or inappropriate lighting or inappropriate work practices are responsible. However, for some individuals, these symptoms appear to persist even when these issues are addressed, suggesting that the nature of the display itself may play a part.

Table 2 – Figures for Asthenopia

Author	Year	Type of study	Control group	No. of participants	% complaints (Controls shown in brackets)
Aakre & Doughty	2007	Questionnaire	No	40	82.5
Bali, Navin, & Thakur	2007	Postal survey of eyestrain	Yes	134	97.8 (8.8%)
Shikdar & Al-Kindi	2007	Questionnaire and physical assessment of workstation set up	No	40	58
Ustinaviciene & Januskevicius	2006	Questionnaire and ophthalmolgical examination	Yes	404	88.5 (10.7%)
Adepoju, Pam, & Owoeye	2005	Survey and eye examination	Yes	461	463 (18.7%)
Vertinsky & Forster	2005	Internet based survey to radiologists	No	380	36
Iwakiri et al.	2004	Questionnaire survey	No	2374	72.1
Tamez-Gonzalez et al.	2003	Self-administered questionnaire	No	68	85.3
Mocci, Serra, & Corrias	2001	Job stress questionnaire and asthenopia questionnaire. Ophthalmological examination (only selected Ss with no refractive errors). Also only included those that had similar working environments and computers.	No	212	31.9

(Adapted from: Thomson (1998))

Eye problems amongst computer users can be examined either subjectively (i.e. questionnaires and interviews or, objectively (i.e. examining areas of visual function).

Helander et al (1984) and Dainoff (1982) reviewed some of the earlier papers and concluded that meaningful comparisons were difficult because of variations between the studies in terms of the samples used and the methods of conducting the surveys. One

example was that by Starr et al (1982) where telephone operators were asked to complete a questionnaire look at four symptoms of eye strain ("blurred vision or difficulty focusing", "double vision", "burning, tearing or itching" and "sore eyes"). One hundred and forty five operators who retrieved telephone numbers using a VDT were compared to 105 controls used printed telephone directories. The results showed slightly more ocular complaints in the VDT sample although this was not significant. The commonest reported symptom was "sore eyes" accounting for some 65% of the VDT group compared to 54% of the control group. In 1984, Starr repeated this experiment comparing 211 telephone operators in the VDT group compared with 145 in the control group. Again the results were similar although significance was obtained with "blurred vision or difficulty focusing" with 46% of the VDT sample reporting this symptom compared to 32% of the control group. Starr concluded that there was no difference in reading from a display screen to paper. However, the reality is that the paper group were reading from either handwritten notes or print outs from a computer and so it is likely that these sub-optimal materials attributed to the high prevalences obtained with the control groups in both studies. It is conceivable that had the printed material been of a high quality, then the results would have been different thus highlighting the importance of a good study design.

Knave et al (1985) assessed subjective symptomatology amongst 400 VDT users compared to 150 non-VDT users. They found that VDT users had more ocular discomfort than the control sample. Furthermore, eye discomfort correlated with the number of hours of VDT use. This finding was borne out by Howarth and Istance (1985) who studied four groups of office workers. Half of the groups used VDTs but for different tasks; one group used them for word processing whilst the other was for data). The remaining two groups were similar in that they both performed typing and clerical duties with no VDT use. All groups were studied for one full working week (i.e. five days) and both subjective and objective measurements were obtained at the beginning and end of each day. Results showed that there were statistically different findings between the groups with the end of day measurements. No significant differences were found between the two control groups. Fuelled by the results of this study, Howarth and Istance (1986) performed a further study to ascertain the effectiveness of using a questionnaire. Their findings indicated that there was a significant difference between how the subjects remembered their symptoms compared to the actual symptoms reported.

Other methods of comparing the prevalence of asthenopia might be to use a within subjects design whereby each subject used acts as their own control and so participate in both phases of the study. An example of this would be the work by de Groot and Kamphuis (1983) who used a sample of telephonists to compare a questionnaire on eyestrain

immediately before, immediately after and two years post VDTs being used within the office. Forty three subjects participated in the study and, at baseline, between 30-45% complained of symptoms of asthenopia. A similar figure was obtained after two years of VDT use.

Another way round recording subjective results might be to ask subjects to keep a diary of their symptoms both whilst using a VDT and when not using one. Collins et al (1991) did this so that they could avoid some of the problems of the studies cited above whereby different VDTs and differing control groups adversely impact upon the results. Collins used 98 university staff who were required to record their ocular/ visual symptoms four times a day during one complete working week. They were also required to maintain an accurate record of the task that they were doing, how many breaks they took and any other relevant factors such as work pressure. The results from multiple regression analyses suggested that VDT tasks are more commonly associated with ocular and visual symptoms when carried out as a within groups design with the same person comparing VDT to non-VDT use. The task also seemed to related to the ocular symptoms reported; non VDT tasks had less symptoms whilst tasks such as data entry resulted in higher reportings of ocular symptoms. This was significant. Work pressure was also found to be significantly correlated with more asthenopic symptoms. Longer break times resulted in less ocular symptoms although this was not significant. In addition, subjects were also asked to record if they attributed anything to their symptoms. These were then categorized into sleep deprivation, office set up, general health, ocular problems, and allergies. Another interesting finding was that symptoms were more prevalent towards the end of the day suggesting that perhaps ocular symptoms could be related to general fatigue. In addition to the subjective measurements, one optometrist performed a full eye examination on all subjects and recorded full optometric data. Demographic data was also obtained for all subjects namely age, sex and how long a subject had been using a VDT. From the demographic data, only VDT use was significant in that those that had used a VDT for longer experienced less symptoms. Collins et al suggest that this finding could be because experienced VDT users may have better working practices and are better at setting up their VDTs appropriately. In addition, they suggest that because they have been using their VDTs for longer, that it is possible that they are more senior than those who have not been using their VDTs for as long and so have more flexibility in their working environment. Finally they suggest that it is possible that if someone is experiencing eyestrain through prolonged VDT use, that perhaps they have changed jobs to counter this.

One interesting finding from the Collins et al (1991) study was that none of the optometric data proved to be a good predictor of ocular or visual symptoms. It is possible that this is because the sample was quite young which may suggest that there were few with

uncorrected visual problems. In stark contrast to this finding, Cole et al (1986) found that almost 20% of their sample of 1200 VDT users required spectacle correction or a change to their current refraction. Bergqvist and Knave (1994) performed a similar study examining the effects of VDT usage on ocular symptoms using subjective (i.e. questionnaire) and objective (i.e. eye examination) methods. From their sample of 327 office workers, results showed that ocular discomfort (i.e. grittiness, redness and sensitivity to light) increased with prolonged VDT use. They concluded that VDTs do cause an increase in ocular symptoms.

With all of the studies cited above, the results should be interpreted with trepidation as many of the control groups have been inadequately matched with the experimental group. In an ideal world, both groups should be exactly matched with the only difference being that one group use VDTs whilst the other does not. In reality though, this is almost impossible to achieve because the introduction of VDTs introduces a whole array of different working conditions which can confound any results obtained. In addition, other extraneous factors will also influence results be it the nature of the job either physically, mentally or visually.

Other problems with the studies above are that they are dependent on the subjects' opinions of their ocular symptoms. This in turn is reliant on how well subjects are able to remember their symptoms and this can vary between the experimental and control groups. As a result, it is possible that a between-samples experiment is not necessarily the best option.

Another error that is often introduced is that subjects are asymptomatic prior to the start of the study and, therefore, comparison of complaints between experimental and control groups are on equal footing. Howarth and Istance (1985) suggest that this is unlikely.

Belisario et al (1988) used both subjective (i.e. questionnaire) and objective measurements (i.e. ophthalmological examination) to evaluate ocular symptomatology amongst VDT users. Their findings suggest that symptoms of asthenopia are more common amongst computer users and that those that use computers for more than four hours per day experience more symptoms than those that do not.

Boos et al (1985) performed two studies looking at asthenopic symptoms amongst computer users. In the first study, a questionnaire was used and this yielded higher levels of asthenopia than the subsequent study which compared ophthalmological findings with eyestrain.

Cole et al (1996) followed 692 VDT users and 624 controls over a six year period to ascertain whether or not VDT usage resulted in higher levels of symptoms or eye disease. Subjects were examined annually and results suggested that there was no evidence to suggest that the use of computers resulted in increased ocular disease.

Laubli et al (1980) looked at four groups of office workers; two used VDTs and the remaining two did not. They found that all groups exhibited eye problems although these were observed more often in the VDT groups.

Lie and Watten (1994) performed two studies. In the first, 18 subjects were required to edit text on a VDT for three hours continuously. Nineteen controls performed the same keyboard activities but whilst staring out of the window for three hours. There were significantly more symptoms noted in the experimental group than the control group. In the second study, fourteen VDT users were tested without correction and again when appropriately corrected. Results indicated that there was a significant reduction in visual symptoms suggesting that optical correction plays a role in asthenopia.

Sheedy (1992) sent 1307 optometrists a questionnaire regarding patients in their practices. They found that some 14.25% of patients presenting to optometric practice primarily complain of problems associated with VDT use. More than half the optometrists questioned (55.3%) reported that these patients had symptoms which differed from other patients who performed near tasks. Typically these complaints referred to lighting and glare issues as well as viewing conditions. In almost 21% of these patients, optometrists reported that they were unable to reach a confident diagnosis for their symptoms. This was significant when compared to the figure of approximately 14% for the non VDT patients.

1.4.2 Possible causes of eye problems

The consensus from the literature from both well controlled studies and from studies that just ask VDT users about their symptoms (see Section 1.4.1) is that the prevalence of symptoms is higher amongst computer-users that the rest of the population. If this is the case, we need to consider the specific demands that are placed upon the visual system when using a computer. This can be broken down into:

- the nature of computer displays,
- environmental factors and workstation design,
- the way that computers are used (working practices).

The relative contributions of each of these factors will now be considered.

1.4.2.1 The nature of computer displays

Before the advent of computers, printed matter was the main medium for accessing information. Text was normally printed in black ink on white paper, which, when viewed under reasonable lighting, provided excellent contrast. Although the quality of the print varied depending on the printing processes used, in most cases the quality was more than adequate to facilitate comfortable reading.

With the development of computers came the need to develop an interactive visual interface capable of displaying text and other information on a "refreshable" medium. Until recently, the medium of choice was the Cathode Ray Tube (CRT) (see Section 1.3.1). The first generation of CRT displays were monochrome and had very poor resolution resulting in pixelated characters and poor legibility. Furthermore, the displays had low refresh rates which resulted in the perception of flicker. However, at this stage, computers were used by a few motivated specialists and although visual symptoms were probably common, complaints were surprisingly rare.

However, as the use of computers increased, it was necessary to improve the quality of the displays. Manufacturers of CRT displays responded by producing monitors with increasing resolution, colour and refresh rates which would eliminate the perception of flicker. The latest generation of CRT displays are capable of producing very high quality displays with excellent colour reproduction and no perceptible flicker. Information displayed on these monitors closely matches the characteristics of printed text.

The high voltages and resultant radiation generated by CRT displays were considered to be a possible cause of the symptoms experienced by computer users. However, numerous studies have shown that, based on current biomedical knowledge, there are no health hazards from either ionising or non-ionising radiation emitted from CRTs (Nair & Zhang, 1995; Breysse et al., 1994; Shaw & Croen, 1993; Luchini & Parazzini, 1992; Wiley et al., 1992; Tikkanen et al., 1990; Campos, 1988; Knave et al. 1985). It follows that tints or filters which claim to cut out harmful radiation are superfluous in this context.

Another potential cause of eye problems amongst users of CRT displays was the complex spatio-temporal modulation produced by the raster-scanning used to refresh the screen. Thomson & Saunders (1997) have shown that eye movements made in the direction of the field scan result in a momentary reduction in the "effective" refresh rate and may cause periodic bursts of flicker on an otherwise flicker-free display. There is also some evidence that the spatio-temporal modulation affects the accuracy and nature of eye movements whilst scanning the screen (Montegut, Bridgeman, & Sykes, 1997; Kennedy & Murray, 1993; Dillon, 1992; Wilkins, 1986). This in turn may have some effect on reading rate. Thomson & Saunders (1997) demonstrated that the visual system becomes adapted to the flicker on raster-scanned displays, resulting in a reduction in spatio-temporal sensitivity. Whilst it is possible that the raster-scanning used by CRT displays causes some disruption to vision, the consensus is that this is not a major factor in the high prevalence of symptoms.

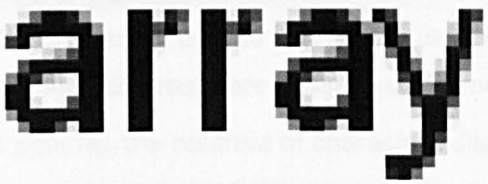
CRT displays are rapidly being replaced by LCD displays which offer many advantages over CRT displays (see Section 1.3.2). LCD displays do not emit any potentially harmful radiation and are not raster-scanned and, therefore, we need to consider the exact nature of

the information displayed on a display screen in the quest for a solution to visual discomfort amongst display users.

1.4.2.2 Pixel size and resolution

Display screens (CRT and LCD) consist of a two-dimensional array of cells known as Picture Elements or Pixels (see Figure 11). Information is presented on the screen by varying the luminance of each pixel. If the pixels are sufficiently small, they will not be resolved individually by the eye and instead the visual system perceives the patterns presented across the array of pixels. Within limits, the smaller the pixels, the sharper the image will appear. However, decreasing the size of the pixels, increases the number of pixels required to form an array of a given size which in turn increases the demand on processing power and speed to control the luminance of each pixel. The number of pixels on a display is referred to as the Display Resolution.

Figure 11 – Figure showing arrangement of pixels



Multisync CRT displays are capable of displaying a number of different resolutions depending on the video signal supplied by the graphics card. The first generation of PCs adopted the VGA standard (640 pixels horizontally by 480 vertically, total 307200 pixels). As the graphics cards and displays evolved, resolution gradually increased to 800 x 600 (Super VGA standard), 1024 x 768 (XGA standard) and beyond.

Al-Harkan and Ramadan (2003) looked at the effects of pixel size on legibility of Arabic characters. They found that Arabic characters were deemed more legible with increasing pixel size.

The resolution of TFT monitors is determined by the physical number of pixels in the array. TFT displays, therefore, have a "native" resolution and any attempt to drive the displays at a higher or lower resolution results in a degradation of the image. As the pixel size is more-or-less fixed (0.25 mm), the resolution is largely determined by the size of the display:

15" – 1024 x 768, 17" – 1280 x 1024 etc.

The pixel size / resolution of the current generation of displays is still no match for good quality printed text. However, by using techniques such as anti-aliasing (see Section 3.7) and ensuring that the font size is adequate, it is generally considered that the resolution is

adequate for comfortable reading and that this aspect of displays is no longer a contributory factor to visual discomfort amongst computer users.

1.4.2.3 Luminance

A fundamental difference between printed matter and computer displays (CRT and LCD) is that the former is reflective and dependent on light falling on the page whilst the latter is luminous and emits light. This results in different and sometimes conflicting requirements for setting up environmental lighting where the two display media are being used (see Section 1.3.2). However, provided that the light levels are within the optimal photopic range (100 - 300 cdm^{-2}) the visual system is unlikely to demonstrate a preference for reflected or luminous sources.

Typically, both LCDs and CRTs are capable of generating screen luminances of between 200 and 400 cd/m^2 and provide the facility for the user to adjust the luminance depending on ambient conditions and personal preference.

1.4.2.4 Contrast

The contrast of printed text varies depending on the printing technology used. However, very high contrasts are possible using modern printing technology.

In general, the contrast of characters displayed on a computer screen is less than printed text (particularly for CRT screens). Contrast in this context is usually defined as the ratio of the maximum luminance to the minimum luminance. Contrast ratios on display screens mave increased significantly in recent years as manufacturers have found ways to decrease the minimum luminance. The contrast of modern display screens (400:1 or more) is usually well above the levels usually recommended for comfortable viewing (> 8: 1) provided that the screen is shielded from ambient light (see Section 1.3.2). The effect of contrast on reading speed will be re-examined in Section 2.3. Operators usually have access to screen luminance and contrast controls to allow the display to be optimised for the prevailing lighting conditions and according to their personal preferences.

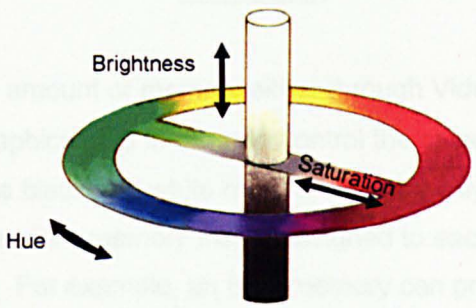
The first generation of CRTs displayed light characters on a dark background because this minimised the mean screen luminance (and hence the refresh rate required to eliminate flicker) and also reduced the effects of phosphor "burn in". However, screen reflections are more apparent with dark backgrounds and it is contrary to the polarity that most people are accustomed to for reading.

Modern displays tend to display dark text on a white background by default and Sheedy & Shaw-McMinn (2003) cite several studies that have demonstrated "better work performance with light background displays". However, the effect of contrast polarity on reading performance in normal and visually impaired users will be re-examined in this thesis.

1.4.2.5 Colour

Colour is defined as "an attribute of things that results from the light they reflect, transmit, or emit in so far as this light causes a visual sensation that depends on its wavelengths" (Ruddock, 1971). The perception of colour can be described by three variables; hue (*the perceptual correlate of the dominant wavelength*), saturation (*the perceptual correlate of colorimetric purity that refers to the difference between chromatic and achromatic visual stimuli of the same brightness*) and brightness (*the perceptual correlate of luminance;*) – see Figure 12. In other words, perception of colour is reliant upon three factors: light, objects which absorb or reflect this light and our perception of how we interpret this light.

Figure 12 – Figure showing dimensions of colour



(After: Thomson (2007), 2nd year optometry lecture)

Normal colour vision is trichromatic. That is to say, that by matching only three variables *(i.e. the three primary colours: red, green and blue*) in different proportions, more than seven million colours can be perceived by a normal human eye.

Modern computer displays exploit the trichromacy of the visual system by employing triads of coloured pixels (red, green and blue). These pixels are too small to be resolved and are perceived as a single point with an additive mixture of the light from each coloured pixel. The perception of a large gamut of colours can be generated by simply varying the relative luminance of the three coloured pixels (see Figure 13).

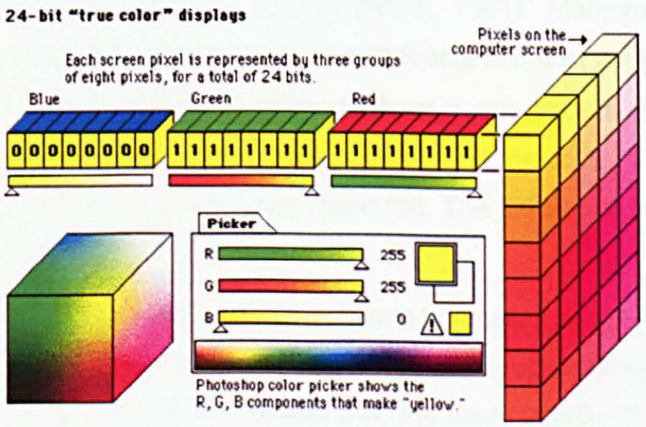
Figure 13 – Additive colour model



(After: http://upload.wikimedia.org/wikipedia/commons/thumb/c/c2/AdditiveColor.svg/220px-thumb.jpg)

Each pixel is assigned an amount of memory either through Video Random Access Memory (VRAM) or by use of a graphics card in order to control the colour of that pixel on the screen. In simple terms, a black and white monitor requires only a 1-bit display system; 0 for black, 1 for white. The more memory that is assigned to each pixel, the more accurately colours can be displayed. For example, an 8-bit memory can produce 256 colours because each bit can hold 2 colours so an 8-bit memory produces 2^8. This is known on older computers as a 256-colour display. 'True colour' or '24-bit' displays assign 24 bits of memory to each individual pixel i.e. 8 for red, 8 for green and 8 for blue.

Figure 14 – A 'true-bit' display



(After: http://services.exeter.ac.uk/cmit/modules/the_internet/figures/twenty-four-bit-colour.gif)

Each of the three primary colours is capable of 255 variations so, for example, pure red would be 255, 0, 0 with maximum input from the red pixel and no input from either the blue or green pixels. Clearly, by altering each of the red, green and blue amounts, millions of

different colours from white (0, 0, 0) through to black (255, 255, 255) can be produced. Typically, these variations are displayed as monochrome layers of red, green and blue, which, when added together, produce the final colour representation (see Figure 15).

Figure 15 – Picture displaying the monochrome layers and the additive effect



(After: Penny J D'Ath, personal photograph, 2008)

There has been much debate (but little agreement) regarding the optimum colour for displays (Sheih & Chen, 1997; Raasch et al., 1991; Misawa & Shigeta, 1986; Osaka, 1985; Sivak & Woo, 1983; Bergman, Aberson, & Duynhouwer, 1981). Many monochrome displays used green phosphors (mainly on the basis that green is at the peak of the $V\lambda$ function). Because of the chromatic aberration of the eye, the amount of accommodation required to focus on a screen will depend to some extent on the colour - marginally less accommodation being required for blue/green than red. The difference is small and probably not a major consideration.

The introduction of colour displays has given software engineers enormous scope for using colour coding to enhance the user interface and it is relatively straightforward for users to change their screen colours. However, despite this, the vast majority of computer users tend to retain the normal black on white default for text displays. This is somewhat surprising given the growing evidence that a significant proportion of the population are more comfortable reading text against a background that is other than white.

The potential benefits of customising the colour of text and the background for normal and visually-impaired users are investigated in this thesis.

1.4.2.6 The user interface

The first generation of computers used a simple text based interface. However, as the graphical capabilities of computers improved, software engineers started to experiment with different models for interacting with computers.

Douglas Engelbart changed the way computers worked by drafting the first prototype for the mouse with a graphical user interface in 1964 (www.about.com, 2007). Patented in 1970, "it was nicknamed the mouse because the tail came out the end". Despite this, the mouse did not become popular until about 1984 when Apple introduced it with their computers (www.about.com, 2003).

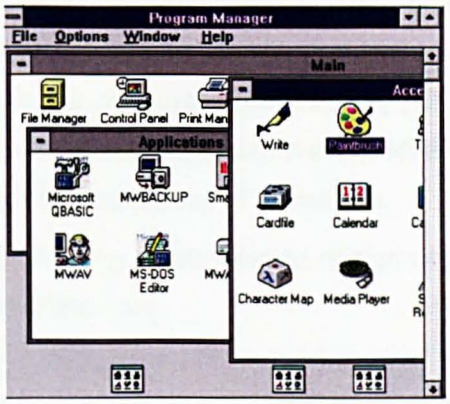
Apple Computers was set up on April Fool's Day 1976 by the two Steves; Jobs and Wuzniak with the release of Apple I. In 1979, Jobs released the Apple Lisa which had a graphical user interface inspired by a visit to Xerox Alto. Not hugely successful, the Apple Macintosh was released in 1984 complete with packages such as MacWrite and MacPaint as well as having a mouse. The release of the Apple Lisa (and subsequently, the Apple Macinstosh) prompted Microsoft to launch their 'Interface Manager' which they did in September 1981.

The 'Interface Manager' originally consisted of menus at the bottom of the screen, this was changed in the first year to drop down menu bars. By November 1983, Microsoft announced Windows 1.0 which promised: "an easy-to-use graphical interface, device-independent graphics and multitasking support". With several delays with its release, Windows 1.0 was finally in the shops in November 1985 (Windows).

Windows 1.0 did not make a large impact with sales. Its package was modest and included: "MS-DOS Executive, Calendar, Cardfile, Notepad, Terminal, Calculator, Clock, Reversi, Control Panel, PIF (Program Information File) Editor, Print Spooler, Clipboard, RAMDrive, Windows Write, Windows Paint" (Windows).

Two years later, Windows 2.0 was introduced. It was significantly easier to use than the earlier version and was more object orientated with the introduction of windows and icons. The icons made the interface markedly easier to use as the user was only required to click on the appropriate icon to open a given program. However, it was not until May 1990, when Microsoft offered a complete revamp of the earlier versions of Windows with its launch of version 3.0, that independent programmers began writing applications for Windows and sales rose to over 10 million copies that Windows became: "the best-selling graphical user interface in the history of computing" (Windows).

Figure 16 – screenshot of Windows 3.1.



(After: (Windows)

On 24th August 1995, Microsoft launched Windows 95. With its 'Start' button at the bottom of the screen with a menu coming off it, this was a significant improvement on all previous windows versions as well as providing integration of Windows products with MS-DOS. Its graphical user interface (GUI) became more intuitive allowing the user greater operational ease (Wikipedia, 2007).

Released in June 1998, Windows 98 offered a browser-like interface allowing the user to 'browse' anything. The 'Active Desktop' allowed the user to customize their desktop and web with automatic updates. Windows 2000 provided a superior platform for the internet with Windows XP simplifying and making things even more user friendly (Windows).

In summary, compared to good quality printed text, the information displayed on a computer screen tends to have lower contrast, lower resolution and, with CRT displays, may flicker slightly (Dillon, 1992). Ten years ago the difference between the legibility of text on a computer screen and printed text was marked and it is likely that this was indeed a contributory factor in the high prevalence of eye problems amongst computer users. However, the quality of displays has improved dramatically over the past decade and most modern computer displays produce legible, flicker-free displays. Although the quality still does not match that of typeset text, it is unlikely that this is a significant cause of eye problems.

If there are no inherent problems with the technology and the quality of text displayed on a screen is similar to printed text, why do computer users experience more eye problems? To answer this question we have to consider how computers are set up in a typical office.

1.4.3 Workstation design

Thomson (1998) reported that approximately 40% of display screen users complain of eye problems. In approximately half of these cases, the problem was primarily related to poor workstation set-up or inappropriate work practices. Sheedy (1992) reports that workstation set up accounts for symptoms in 36.8% of problems whilst Mbaye et al. (1998) report that basic workstation design was the main cause of symptoms.

There are a number of factors relating to workstation design which potentially have a bearing on the visual comfort of the user.

1.4.3.1 Viewing angle

One obvious difference between looking at a display screen and reading printed text is that computer screens tend to be placed at, or just below, eye level whereas printed documents tend to be held well below the horizontal plane so that the eyes are looking down. This can lead to a number of problems for computer users:

a) When looking straight ahead, the eyes are wide open and a large area of the cornea is exposed. This results in less eyelid coverage which can lead to increased tear evaporation and a reduced blink rate by as much as 60% (Blehm et al., 2005) which may contribute to the symptoms of dry eyes. The situation is exacerbated in air-conditioned offices where the atmosphere may be dry. It has also been shown that blink rate tends to decrease when concentrating. These factors taken together provide a cocktail of conditions which could lead to eye irritation (Nakamori et al., 1997; Sotoyama et al., 1996; Hikichi et al., 1995; Sotoyama et al., 1995; Tsubota & Nakamori, 1993; Nakamori et al., 1994; Nakamori et al., 1993; Patel et al., 1991; Yaginuma, Yamada, & Nagai, 1990).

- When looking down to read, the eyelid covers part of the pupil thus increasing the depth of focus of the eye and reducing the amount of accommodation required. This advantage is lost when looking straight ahead. In addition, the loss of eyelid coverage also eliminates the pinhole effect so any uncorrected refractive errors will result in blur. This could, in some cases, contribute to symptoms of fatigue amongst computer users.
- It has been shown that the vergence mechanism is rather more effective with the eyes depressed. However, in view of the relatively small amount of vergence required to view a screen at 60cm, this is unlikely to be a significant factor (Von Noorden, 1996).
- The raised position of a computer display may require those wearing bifocals or varifocals to adopt an uncomfortable head position to view the screen through the appropriate portion of the lens. This problem can sometimes be solved by lowering

the screen but, in most cases, the best solution is to prescribe a separate pair of single vision spectacles adjusted for the computer viewing distance (Bergqvist & Knave, 1994; Burns, Obstfeld, & Saunders, 1993; Good & Daum, 1986).

- When reading printed material, the paper is viewed against a background of a desk or the floor. Paper is an excellent diffuser and specular reflections from the text are rarely a problem. More care is required when positioning a computer screen; a window or light behind the screen will cause glare and reduce the visibility of the screen and movement behind the monitor can be distracting. Likewise, a window behind the user may result in disturbing reflections on the screen (Garcia & Wierwille, 1985; Hultgren & Knave, 1974).

Thomson (1998) suggests that the eyes should be level with the top of the display screen. Blehm et al. (2005) supports this viewpoint by stating that the viewing angle should be between 10-20 degrees.

1.4.3.2 Viewing distance

Another difference between looking at a computer screen and reading printed material is that computer displays are generally viewed from slightly further away than printed matter (Sheih & Chen, 1997; Piccoli et al., 1996; Burns et al., 1993; Jaschinskikruza, 1993; Jaschinskikruza, 1991; Jaschinskikruza, 1990; Gratton et al., 1990; Jaschinskikruza, 1988). This means that viewing a computer display requires less accommodative effort than reading printed documents and it would, therefore, be surprising if this was a cause of eye problems. However, the difference between the computer display viewing distance and the normal reading distance can cause problems for older operators because reading glasses are usually prescribed to provide clear vision at a normal reading distance (e.g. 40 cm). However, if the screen is placed further away (for example, 60 cm), the lenses will be too strong and the computer screen will be slightly blurred. In some cases, the problem can be overcome by simply moving the screen closer. In other cases, it may be necessary to have spectacles specifically for viewing the display screen.

Increasingly, multifocal spectacle lenses such as bifocals and varifocals are being used. Due to the design of these lenses, the user is required to tilt their head back in order to look through the appropriate portion of the lens and this can lead to symptoms in some users.

Lighting

A common cause of eye problems amongst computer users is inappropriate lighting (Hedge, Sims, Jr., & Becker, 1995; Berman et al., 1991; Taptagaporn & Saito, 1990; Doskin et al., 1989; Goodwin, 1987; Hentschel et al., 1987; Wilkins, 1986; Goodwin, 1985; Rowe,

1984; Shahnavaz & Hedman, 1984; Shahnavaz, 1982; Laubli, Hunting, & Grandjean, 1981; Hultgren & Knave, 1974).

In order to read printed text, sufficient ambient light must fall on the page to render the page legible.

Comfortable reading will require the illuminance to be comfortably within the photopic range. With this in mind, lighting engineers have tended to specify relatively high light levels in offices.

However, for computer displays, any light that falls on the computer screen results in reflections which in turn decrease the contrast of the display (see Section 1.4.2.4). This is particularly true for CRT displays.

Ambient light falling on a CRT screen will be reflected in two ways (see Figure 17). Some light will be reflected from the front surface of the glass screen. As this is smooth and slightly curved it will act like a convex mirror and form a minimised image of objects in front of the screen. This is known as *specular* reflection.

Figure 17 – Specular reflection



Some of the light will pass through the glass and hit the phosphor coating on the back surface. Since this is rough, the incident light will be reflected diffusely (see Figure 16).

LCD displays usually have a matt front surface and the polarising filters that make up the display have the fortuitous characteristic of further minimising screen reflections. These displays are therefore, remarkably immune to the effects of ambient light. However, the matt surface does diffuse or "blur" the image to some extent and a number of manufacturers now offer a "gloss" alternative. This results in a slightly sharper image but makes the screen more prone to reflections.

Clearly, the optimum lighting conditions for reading printed text and viewing a computer display are quite different but often the two tasks are carried out in the same location and more or less simultaneously. This means that there must be a compromise.

The CIBSE Lighting Guide (1989) recommends a background illuminance level of 300-500 lux. A study of a number of computer users found that the majority preferred levels at the lower range, 300 lux (Varrell, 1983). The CIBSE Lighting Guide also recommends that the average luminance on the ceiling or other surfaces that are lit directly should not exceed 500 cd/m^2. The peak luminance is recommended to not exceed 1500 cd/m^2. However, in many offices the ambient light level is much higher than this which means that screen contrast is compromised which in turn reduces the legibility of the display and may lead to asthenopic symptoms. However, Lin and Huang (2006) showed that normal office lighting did not affect character recognition on TFT-LCD displays. Furthermore, they surmised that the ambient lighting levels as found with CRT use may also apply to LCDs.

Inappropriate lighting design can also lead to problems of glare. In general, glare may be described as the negative effects of extraneous light on visual perception. The effects of glare can be subdivided into two categories; discomfort and disability. Disability glare refers to a reduction in visual performance caused by the presence of a relatively bright light source. This can occur as a result of light scatter in the eye or neuronal inhibition. Discomfort glare refers to the sense of discomfort/pain experienced in the presence of a relatively bright light source. Light sources (windows and lamps) in the office have the potential to cause both types of glare and therefore good lighting design is important. This is particularly true for display screen users because the screen is usually placed at approximately eye level whereas one tends to look down to read printed documents. This means that windows or bright light sources beyond the screen will be closer to fixation and are more likely to cause discomfort glare (Garcia & Wierwille, 1985; Yamamoto et al., 1985; Hultgren & Knave, 1974).

As a general rule, the immediate surround to the screen should be approximately matched to the mean luminance of the screen. If the surround is too bright, the user will experience glare. Conversely, if the surround is too dark, the user may experience discomfort glare from the screen itself and positive after images.

Care is also required to avoid indirect glare from bright objects behind the operator reflected by the screen. These specular reflections can usually be avoided by careful positioning of the display screen and attention to ambient lighting. However, where specular reflections persist, the use of monitor hoods, partitions or various screen coatings may help.

Glare from display screens can be dealt with in a number of ways. In the first instance, it can be reduced by tilting the screen so the eye is looking down on the screen, placing the screen perpendicular to any windows, using concealed or indirect lighting or by the placing of partitions between workstations.

Other solutions are to use supplementary screens which fit over the display screen thus reducing glare and enhancing screen image thereby improving user comfort (Blehm et al. 2005). These supplementary screens come in various forms: glare filters, mesh filters, polarised glare filters to name but a few. Essentially they all work by reducing glare thus increasing the contrast of the display.

There are, however, additional problems which arise from using a supplementary screen. A mesh screen works by blocking external light from reaching the display screen resulting in a reduction in reflections from the screen. The disadvantages of a mesh screen are that they can reduce image clarity of the display. In addition, they are susceptible to dust particles which reduce the original brightness of the display as they are directionally sensitive. Whilst polarised filters do remove glare by circularly polarising the light that passes through the filter and reversing the direction of rotation as the light reflects back from the display screen which results in absorption of light before it reaches the user, they are not without their disadvantages. These include the need for a multi-anti-reflection (MAR) coating to compensate for the reduction in brightness of the screen image. They also cause peripheral distortions. Neutral density anti-reflection coated filters work in much the same way as the MAR coating on a spectacle lens. They reduce the intensity of the reflected light from the display screen thus making viewing more comfortable. In practical terms, they are probably more likely to reduce glare with little or no other unwanted effects.

In summary, a high proportion of computer-related eye problems are probably caused by poor workstation design and inappropriate lighting (Thomson, 1998). Consequently, good workstation set up is of paramount importance to display user comfort. It should include: a screen below eye level, ambient illuminance of 300-500 lux (The CIBSE Lighting Guide, 1989) achieved by reducing the number or wattage of lamps, fitting baffles, filters or diffusers to the lamps, a screen perpendicular to any windows with adjustable blinds attached to these windows, and concealed lighting.

1.4.4 Workpractices

In many cases, the eye problems reported by computer users are a natural consequence of the way the eyes have been used. Working at a computer involves sustained accommodation and vergence and most tasks involve a high degree of cognitive effort. Poor workstation design, inadequate provision for breaks and a stressful environment often compound the problem and lead to complaints by individuals who are normally asymptomatic (Rey P. & Meyer J.J., 1980; Rechichi, De Moja, & Scullica, 1996; Kurimori & Kakizaki, 1995; Modiano et al., 1987; Kumashiro, 1985; Kanaya, 1990; Watanabe et al., 1993; Berg M. & Bengt A., 1996). Likewise, small refractive errors and oculomotor problems may only cause symptoms under the more demanding conditions associated with

sustained computer work. Cole (2003) found that 20% of display users were insufficiently optometrically corrected and that their asthenopic symptoms were alleviated with their full corrections in situ. North (2001) cites Gunnarsson & Soderberg (1980) who determined that convergence insufficiency and low fusional reserves are major causes of asthenopia with display screen users.

Sheedy, Hayes, & Engle (2003) artificially instigated asthenopic symptoms for a group of 20 subjects. It was determined that symptoms can be divided into two distinct groups related to the causative factor. Sheedy suggested that the external symptom factor (ESF) consisted of symptoms such as burning and tearing, whereas the Internal Symptom Factor (ISF) was related to headache and strain.

O'Leary & Evans (2006) investigated the use of a prismatic correction for reading. They incorporated a low prismatic correction into a spectacle lens and recorded reading speed using the Rate of Reading test. Participants with exo-deviations demonstrated an improvement in reading speed. The study also showed that subjects with horizontal deviations were more likely to exhibit asthenopic symptoms, but did not find a significant relationship between increased rate of reading with prismatic correction compared with degree of presenting symptoms. Dain, McCarthy, & Chan-Ling (1988), however, did find that magnitude of horizontal deviations were significantly different between those that were symptomatic and those that were not.

Research has shown that when regular breaks are introduced, work rate between breaks is increased which usually compensates for time lost during the breaks. In other words, breaks do not necessarily reduce productivity (Grandjean, 1984).

The requirement for breaks will depend on the individual, the situation and the nature of the work. However, some general guidance can be given. Breaks should be taken before the onset of fatigue, i.e. a user should not wait until the eyes feel tired before taking a break. This may be every 20 minutes or every 2 hours depending on the individual and the nature of the work. Short, frequent breaks are generally more satisfactory than occasional longer breaks, i.e. a 5-10 minute break every hour is better than a 15 minute break every 2 hours (Grandjean, 1984).

Balci & Aghazadeh (2003) examined the effects of different breaks on asthenopia using a sample of ten college students. Their study incorporated three different work/ break schedules: a ten minute break every hour, a five minute break every half an hour and a micro break every fifteen minutes. Their results showed that the micro break schedule resulted in the least symptoms of asthenopia as well as increased performance in data entry tasks.

A break should provide an opportunity for display screen users to vary their posture and change the nature of visual and mental activity; in other words, to do something completely different. This does not necessarily mean stopping work altogether. Informal breaks, that is time spent doing other tasks away from the screen, appear from study evidence to be more effective than formal rest breaks. Exercise routines which include blinking and focusing the eyes on distant objects may be helpful.

Wherever practicable, users should be allowed some discretion as to how they carry out tasks and when to take breaks. However, employers should ensure that users are given adequate information and training on the need for breaks and lay down minimum requirements for the frequency of breaks whilst still allowing users some flexibility.

1.4.4 Solutions

The Association of Optometrists offers guidance for practitioners to "indicate the sorts of visual problems which may lead to symptoms or discomfort whilst using VDUs" (Association of Optometrists, 2007).

The guidance includes consideration of:

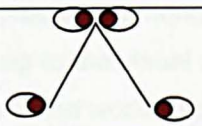
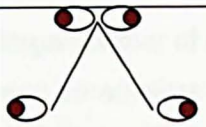
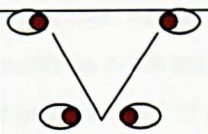
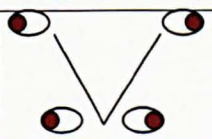
- "***Working Distance***. The distance from the patient's eyes to the VDU should be established fairly accurately along with distances to other objects which need to be viewed whilst working at the VDU (e.g. paperwork or keyboard). Any glasses prescribed should cover the whole range of visual tasks if at all possible. It may be that a reduced reading add is necessary to accommodate the more distant objects such as the VDU itself.
- ***Screen Height***. The height of the VDU screen may be very significant, particularly if it is too high. Generally it is best if the top of the VDU is slightly below the patient's eye level. This is particularly important if the patient wears multifocal lenses.
- ***Phorias***. Decompensated phorias may well lead to symptoms of eyestrain and should be corrected if possible especially if they are causing any difficulties. Poor convergence may require treatment or correction.
- ***Visual Fields***. Should not normally cause problems with VDU use unless there are significant binocular central defects present."

The Association of Optometrists state that "there is little benefit to setting a standard for VDU users as those who "fail" such a standard often continue to use VDUs with no visual or asthenopic problems at all".

A degree of caution is required when interpreting these generic guidelines as they will not apply in all cases. For example, individuals with A and V syndromes may be more

comfortable with the screen placed higher or lower in the visual field respectively. A physiological A pattern is described as a difference of less than 10 prism dioptres between upgaze and downgaze whilst a physiological V pattern is described as a difference of less than 15 prism dioptres between upgaze and downgaze. Table 3 shows the optimum position of the display screen for those with A and V patterns.

Table 3 – Table showing optimum position of display monitor for those with A and V patterns

Deviation	Diagramatic representation of deviation	Description	Monitor positioning
$A_{esophoria}$		In upgaze, the eyes over-converge leading to discomfort and/or diplopia.	Monitor is best placed below the line of sight.
$A_{exophoria}$		In downgaze, the eyes are more divergent and it requires more effort to pull them in and maintain a single image.	Monitor is best placed above the line of sight.
$V_{esophoria}$		In downgaze, the eyes over-converge leading to discomfort and/or diplopia.	Monitor is best placed above the line of sight.
$V_{exophoria}$		In upgaze, the eyes are more divergent and it requires more effort to pull them in and maintain a single image.	Monitor is best placed below the line of sight.

Computer users should also be encouraged to blink more frequently to refresh the tear film and prevent the feeling of dry eyes. In extreme circumstances, artificial tears may be advisable. In a survey of ophthalmologists, 97.8% of the sample felt that artificial tears should be the main type of treatment for computer users experiencing ocular symptoms (Bali, Navin, & Thakur, 2007).

1.5 Summary

- Computers have become ubiquitous in modern society.
- Visual displays remain the principal medium for interacting with computers.
- The quality of visual displays has improved significantly but there is still surprisingly little information about the relationship between key display parameters and visual comfort and performance.
- Despite improvements in the quality of computer displays, complaints of eye problems are still common amongst computer users.
- Eye problems amongst computer users may be caused by a combination of factors relating to the visual status of the user, the nature of the display, environmental factors and working practices.

Despite the large number of studies in this area, there is still a lack of clarity about the optimum screen parameters and their relationship to asthenopic symptoms. This thesis will describe a systematic series of investigations designed to examine the effects of key parameters such as contrast, polarity, font style, font size, spacing, and colour on visual performance and comfort of normal and visually-impaired individuals.

2. Optimisation of screen contrast – normal subjects

2.1 Introduction

Previous studies have indicated that screen contrast and font size are the major determinants of the legibility of computer screens. This chapter describes the development of a computer-based test of reading speed and describes a series of experiments designed to quantify the interaction between font size and contrast in terms of reading speed.

2.2 Methods

2.2.1 Modified MNRead

Computer displays are used for a wide range of tasks but for most users, displays are used primarily for reading text. Therefore, in the first series of studies, the effect of key screen parameters on reading speed was measured.

Reading speed was measured using a computer-based version of the Minnesota Low Vision Reading chart (MNRead). The MNRead test was developed at the Minnesota Laboratory for Low Vision research to be used for subjects both with normal vision and visual impairment. The chart can be used to measure reading acuity, reading speed and critical print size (Subramanian & Pardhan, 2006). The test is designed in such a way so that a subject reads progressively decreasing font sizes until they are no longer able to read any more complete sentences.

The test was originally designed by Legge et al. (1989) using Courier font. Mansfield et al. (1996) modified the test changing the font to Times New Roman (TNR) with three rows of sentences. Each sentence contained 60 characters with no punctuation but including spaces. There are two charts totalling 38 sentences to be read at 40 cm with the appropriate reading correction. Reading speed is calculated by the total number of words read correctly divided by the time taken to complete this. Originally, the test was computerised but printed versions were later devised for ease of use and portability in different environments (Ahn, Legge, & Luebker, 1995).

The MNRead test has been the subject of a number of studies investigating its reliability. Legge et al. (1985) demonstrated the test/ re-test correlation to be 88% for those with visual impairment and non-deteriorating conditions. Subramanian & Pardhan (2006) used 30 adults to examine the English version and found good reliability using the MNRead. The coefficient of repeatability was found to be 0.05 LogMAR for reading acuity, 0.12 logMAR for critical print size and 8.6 words per minute for reading. In addition, they found that a reduced testing distance of 25 cm (40cm is recommended) was less reliable but also

demonstrated there was no significant learning effect. Virgili et al. (2004) investigated the repeatability of the MNRead using 116 Italian children varying from 8 to 13 years. The children were tested monocularly and two versions of the chart were used. The results revealed consistent agreement between the two eyes and showed reliability when compared to the visual acuities recorded.

Mansfield, Legge, & Bane (1996) compared the original Courier version with the more recent TNR version, and found that there was some advantage in using the Courier version especially for those with low vision. TNR was introduced in the modified version because it is proportionally spaced and widely used (The Vision Research Laboratories 1994).

For the purposes of the studies described below, software was written to perform a modified version of the MNRead on a computer screen. The time taken to read two 60 letter sentences was recorded. As the tests required multiple presentations, the original MNRead sentences were complemented by a large number of new sentences generated using the set of rules described by the original authors (The Vision Research Laboratories, 2000). In addition, two sentences were randomly displayed simultaneously to form six lines of 120 characters. A full stop was used to separate the sentences so that meaning was maintained. The mean number of words for each sentence was ten.

In order to ensure that the new sentences were of a comparable difficulty to the standard sentences, a small pilot study was carried out.

2.2.2 Modified MNRead Test validation

2.2.2.1 Methods

Observers viewed a standard LCD display (LG Multisync LCD 1860NX flatscreen) from a distance of 40 cm. The screen measured 360mm horizontally by 290mm vertically. A chin rest was used so that the viewing angle and the distance from the computer screen remained constant throughout.

The background was white and the screen luminance was adjusted to 212 cdm^{-2}. The text was displayed in Times New Roman font, font size 10 and placed in the centre of the screen. The screen contrast was set at maximum (approximately 400:1). The test was performed in a room with subdued lighting and free from distractions.

Following an audible cue, the sentence was displayed and the observer was instructed to read the sentence silently as quickly as possible. On completing the sentence they were instructed to press a response key.

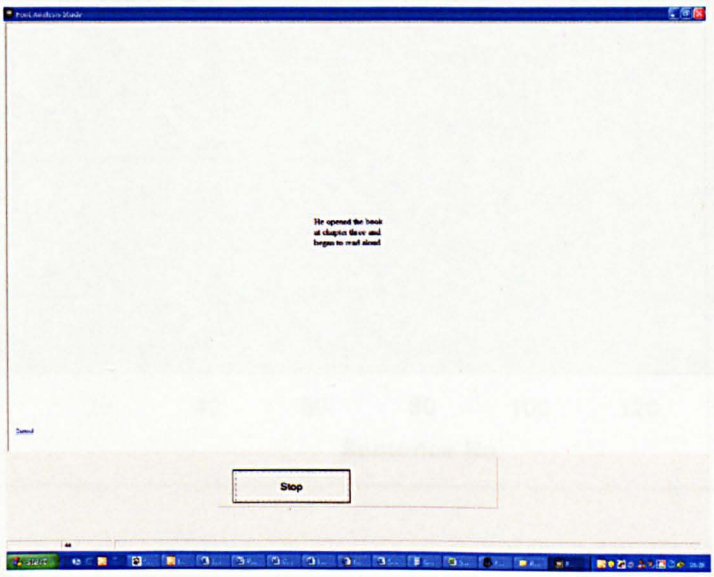
The advantage of requiring participants to read the text silently was that this task more closely resembles the normal activity of display screen users. Requiring participants to

vocalise the words invokes additional neuronal and motor processes which could potentially add irrelevant variables to the results in the context of this study. However, the disadvantage of the method adopted was that the experimenter had no way of checking that participants were reading all words correctly and completing the sentence.

Each observer was required to read 150 different sentences on three separate occasions. Sentences were presented in a random order on each presentation. For each sentence, the average reading time was calculated.

One male and 9 female members of the optometry department at City University aged 23-37 yrs (mean = 30.3 yrs) participated in the study.

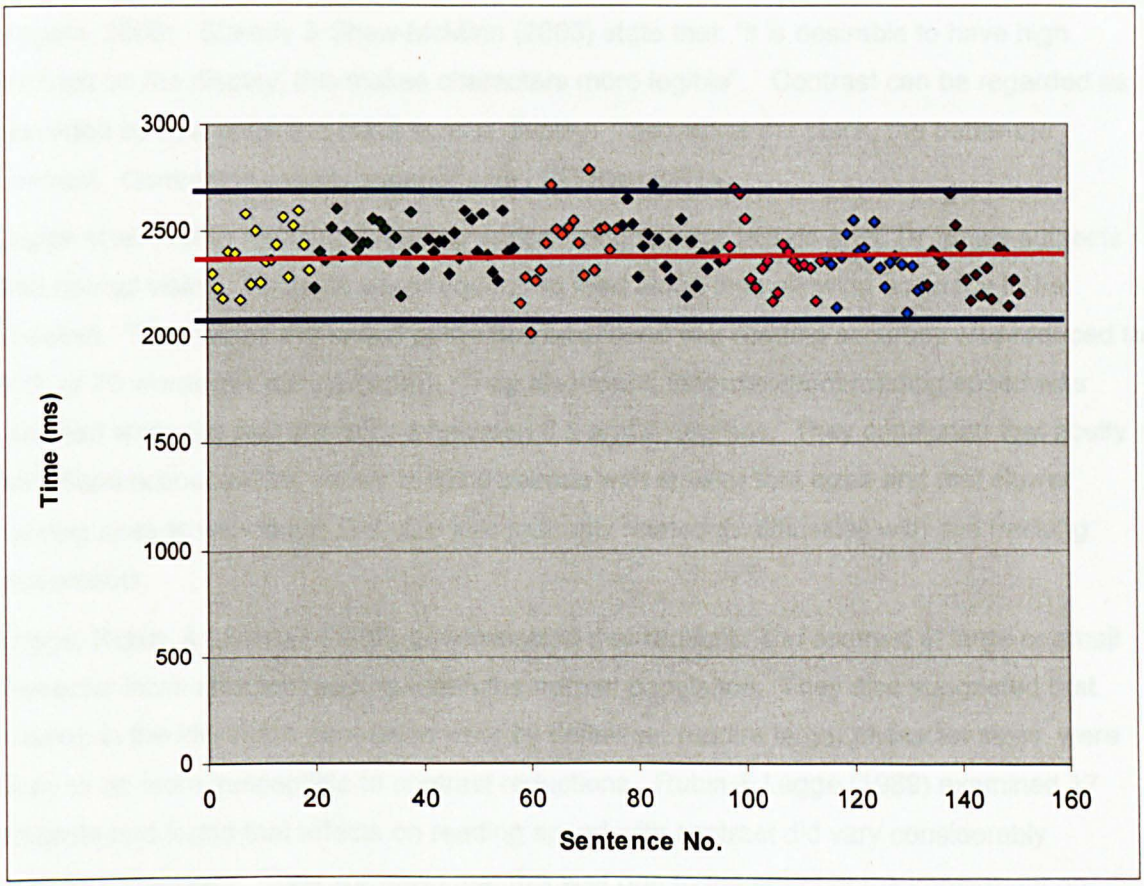
Figure 18 - Image of screen used for modified MNRead test



2.2.2.2 Results

The entire data set is presented in Appendix 3. The mean reading time for each sentence was calculated for all subjects and is shown in Figure 19. The mean time to read the original MNRead sentences was 2404 ms (s.d. = 124 ms).

Figure 19 - Graph showing mean reading time (ms) for 150 sentences. The red bar represents the mean whilst the blue bars represent the mean +/- 2 sd. The different coloured dots depict the different MNRead sentence sets



2.2.2.3 *Discussion*

There was some variation in the time taken to read the read the sentences. As this would add to the noise in the experiments to follow, any sentences with an average falling outside +/- 2 sds of the mean for the standardised MNRead sentences were eliminated from the set for the subsequent studies.

2.3 The effects of screen contrast on reading speed

It is well documented that reduced contrast in older adults affects reading speed (Mitzner & Rogers, 2006). Sheedy & Shaw-McMinn (2003) state that: "it is desirable to have high contrast on the display; this makes characters more legible". Contrast can be regarded as restricted by how black the black is on a display. The darker the black, the better the contrast. Contrast is usually superior with LCD than CRTs.

Legge et al. (1985) measured reading speed using moving text on a CCTV for six subjects with normal vision. Subjects were required to read aloud thus allowing accuracy to be checked. They varied the speed of the text and found that reading accuracy was reduced to 50% at 70 words per minute (wpm). They also found that maximum reading speed was obtained when the text subtended between 0.3 and 2 degrees. They concluded that acuity limitations accounted for slower reading speeds with smaller font sizes and that slower reading speeds with larger font size was probably related to difficulties with eye tracking movements.

Legge, Rubin, & Luebker (1987) demonstrated that reductions in contrast at large or small character sizes affected reading within the normal population. They also suggested that reading in the low vision population who, by definition, require larger character sizes, were likely to be more susceptible to contrast reductions. Rubin & Legge (1989) examined 17 subjects and found that effects on reading speed with contrast did vary considerably between observers. They surmised that this was due to the effect of the impairment on contrast sensitivity. The effect of contrast on reading speed was indeed similar for both the normal and low vision participants providing that the contrast was adjusted in relation to contrast sensitivity.

Wang & Chen (2000) looked at the effects of luminance contrast on visual performance on 48 normal subjects using Landolt Cs which ranged from 0.6' to 2.0' visual angle. Their findings show that visual acuity improves with increased contrast ratio up to 8:1. This is the ratio of light to dark (i.e. the ratio of the luminance of the white background to the luminance of the text). Beyond this, there was no further improvement in visual acuity.

Ayama et al. (2007) examined the effects of luminance contrast between the letters and background as well as character size on reading speed using Japanese text. They used four male subjects with visual acuities (VA) ranging from 1.2 – 2.0 who were required to read aloud five lines each 20 characters in length at 12 (visual angle 18'), 15 (visual angle 23'), and 24 point text size (visual angle 33') under 39 different luminances. Results showed that for all character sizes, legibility increased with luminance contrast.

Knoblauch, Arditi, & Szlyk (1991) examined the effect of colour contrast on reading using moving text on a computer screen. They did this by investigating the effect of chromatic contrast under low and high luminance contrast with a normal population. Their results showed that colour contrast had mimimal effect when the luminance contrast was high and that there was a notable increase in maximum reading speed when the luminance contrast was low for text with chromatic contrast when compared with achromatic text.

2.2.3 Methods

The experimental conditions were as described for the previous experiment (see Section 2.2.2.1). The software was modified to present the selected sentences at ten font sizes corresponding to logMAR values of 0.1 to 1.5. Font sizes were presented in ascending and descending order in different trials to balance for order effects.

The test was repeated at five contrast levels (-0.5. -0.75, -1.00, -1.50, -2.00 log Contrast: 31% to 1.78% approximately – see Table 4), the screen contrast being calibrated using a LMT (Minolta Chroma Meter II).

Table 4 – Contrasts used

Log contrast	Contrast	Character luminance	E	R	G	B
2.00	100.00	0.00	0.048 ^1	0	0	0
1.50	31.62	99.28	0.993 ^2	212	212	213
1.00	10.00	130.68	1.307 ^2	240	241	241
0.75	5.62	137.03	1.37 ^2	247	246	246
0.50	3.16	140.61	1.406 ^2	249	249	248
0.25	1.78	142.62	1.426 ^2	250	251	247
Background luminance			1.452 ^2			

The contrast levels and order of presentation (i.e. whether the font started large (1.5 logMAR) and decreased in size or whether it started small (0.0 logMAR) and increased), were randomised for each subject using a random number generator (www.random.org) to minimise order effects. The sentences from the modified MNRead were also generated randomly by the computer. This ensured that all subjects performed the test in different sequences to each other and consequently, balanced out for any learning effects. In keeping with the original MNRead, any incompletely read sentences were discarded.

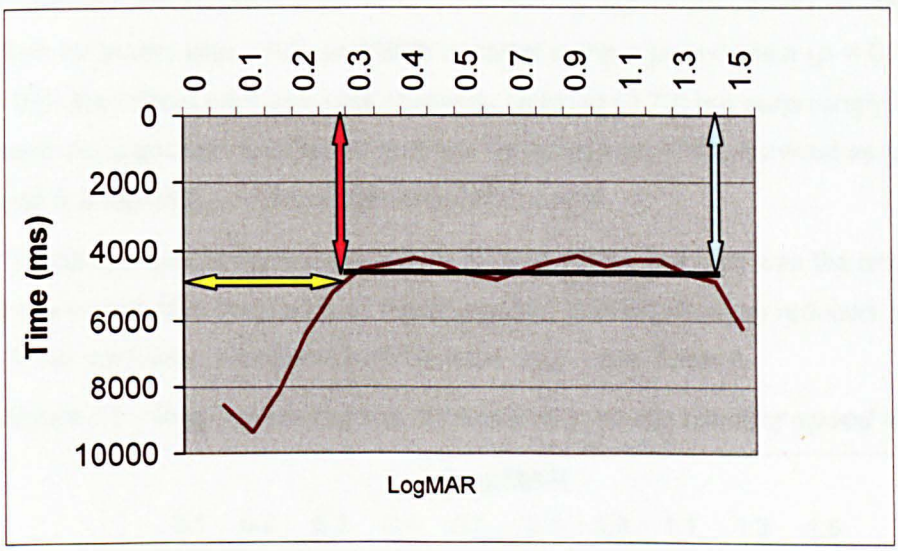
Ten subjects (M:F = 4:6) with vision or visual acuites of 0.0 logMAR or better and no ocular pathologies participated in this study. The mean age was 22.7 yrs (range 22 – 25yrs).

2.2.4 Results

The entire data set is presented in Appendix 3. The mean reading time / sentence for all ten subjects is shown as a function of letter size (logMAR) for the five contrast levels tested in Figure 20.

Critical print size (cps) was determined as the smallest letter size at which optimal reading speed could be maintained. The range of letter sizes which could be read at the maximum reading speed was also recorded (see Figure 20).

Figure 20 – Graph illustrating the terminology used



In Figure 20, the red arrow denotes the critical print size (cps) i.e. the smallest the letters can be read whilst maintaining maximum reading speed. In this example, the cps is approximately 0.25 logMAR. The yellow arrow indicates minimum reading time (maximum reading speed). In this example, maximum reading time is approximately 5000ms. The black line shows the range of letter sizes which can be read at maximum reading speed. These plateau between the red arrow and the blue arrow and are depicted by the black line. In this example, the range of letters which can be read at maximum reading speed (MRS) is approximately 0.25 logMAR to 1.4 logMAR. The MRS is, therefore, the average reading time between these points i.e. 4499 ms. Reading acuity, which is normally measured using the MNRead, was not considered to be a useful metric in the context of these studies as we were mainly interested in the effects of various screen parameters on reading speed.

Graphs of reading time as a function of font size (LogMAR) are undoubtedly the best way of visualising the data and are given throughout the thesis. Summary statistics are used sparingly but it was thought that the minimum print size that results in optimum reading

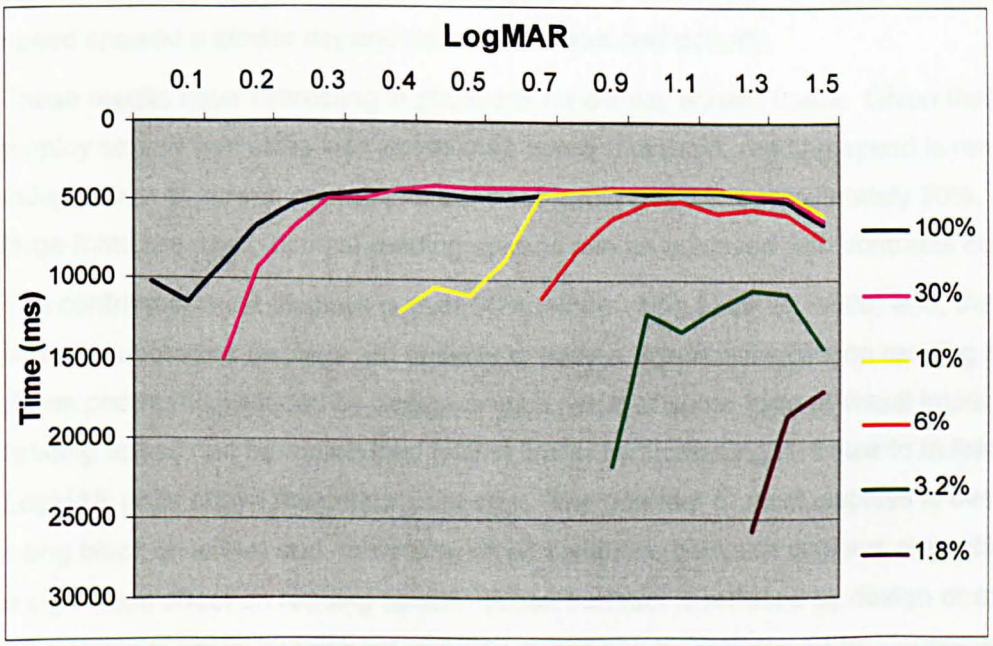
speed (called critical print size) and the maximum reading speed were both useful summary metrics.

For all contrast levels, reading speed was poor for letter sizes close to the acuity threshold for that contrast. Reading speed then improved with increasing letter size and, in most cases, was optimum at 0.2 to 0.3 logMAR above threshold. Increasing the letter size beyond this did not result in any further increase in reading speed. Indeed, there is some evidence for a decrease in reading speed with the largest letter sizes, presumably reflecting the increased time to scan the text.

Except for the smallest letter size, there was no significant difference between the reading time for letters with 100% and 30% contrast using a paired t-test ($p = 0.170$; NS). For the 10%, the critical print size was markedly reduced (0.73) but surprisingly, reading speeds were not significantly different to those obtained with 100% contrast as long as print size was 0.3 logMAR or more above critical print size.

For the two lowest contrast levels (3.2% and 1.8%), not only was the acuity threshold reduced but also the optimum reading speed was significantly reduced compared to the higher contrasts, irrespective of the letter size – see Table 5.

Figure 21 - Graph showing the increase in average reading speed vs' log contrast



The outcome of paired t-tests for the different levels of contrast (with Bonferroni correction applied) is shown in Table 5.

Although there were some individual variations, reading speed was optimal for the high contrasts for all subjects. It is interesting to speculate if individuals who suffer from pattern

glare might prefer to read text of a slightly lower contrast. This question warrants further study.

Table 5 – Table showing paired t-test values for the different levels of contrast for MRS

	100%	30%	10%	6%	3.2%	1.8%
100%						
30%	p=0.170					
10%	p=0.242	p=0.432				
6%	p=0.005	P=0.0004	P=0.0002			
3.2%	P=0.0004	P=0.0002	P=0.0003	P=0.001		
1.8%	Not equal numbers	Not equal numbers	Not equal numbers	Not equal numbers	Not equal numbers	

2.2.5 Screen contrast and reading speed: Conclusions

Re-examination of the outliers indicated that these were mainly attributable to one subject who seemed to have particular difficulties with this task or at least adopted a different stategy. Although this participant read significantly slower than the others, their reading speed showed a similar dependence on font size and polarity.

These results have interesting implications for display screen users. Given that most users employ screen font sizes well above their acuity threshold, reading speed is remarkably independent of screen contrast for contrast levels down to approximately 30%. Indeed, if large fonts are used, optimal reading speeds can be achieved with contrasts down to 6%.

The contrast of most displays is over 90% (when using black on white) and, therefore, small variations between displays are unlikely to have a significant effect on reading speed. When contrast is reduced by design or as a result of some form of visual impairment, reading speed can be maintained (within limits) by increasing font size to at least 0.3 LogMAR units above the critical print size. The contrast of most displays is over 90% (when using black on white) and, therefore, small variations between displays are unlikely to have a significant effect on reading speed. When contrast is reduced by design or as a result of some form of visual impairment, reading speed can be maintained by increasing font size to at least 0.3 logMAR units above the critical print size. However, this only applies down to a contrast level of approximately 10%, since below this the reading speed is slowed, regardless of font size. This supports the earlier work of Whittaker and Lovie-Kitchin (1993) whose review of the literature suggested that a contrast reserve of at least 10:1 is required to achieve the maximal reading speed. It is important to note that although reading speed

seems to be independent of contrast over a surprisingly wide range, this does not necessarily mean that lower contrasts would be as comfortable to view, or that reading performance could be sustained over longer periods of time.

It is important to note that although reading speed seems to be independent of contrast over a surprisingly wide range, this does not necessarily mean that lower contrasts would be as "comfortable" to view or that visual performance would be sustained over longer periods of time.

2.3 The effects of contrast polarity

The first generation of computer displays used "light" letters on a dark background. This was principally because these displays had a relatively low refresh rate and if "dark" letters were used against a "light" background, the screen would appear to flicker (the flicker fusion frequency being higher for higher luminances). With the evolution of graphics cards and CRT display technology, higher refresh rates were possible and software designers tended to opt for dark letters against a light background, thus simulating the polarity of printed documents.

Many CCTV devices designed for low vision use offer the option of reverse polarity to the user. This enables the user to view documents in reverse contrast, i.e. black text on a white background viewed as white text on a black background. Wolffsohn & Peterson (2003) note that some studies have reported that preference for contrast reversal may depend on the cause of the vision loss. They report that whilst some studies demonstrate a preference for contrast reversal, some show an equal preference. They also allude to a study by Ehrlich (1987) which established that patients with retinitis pigmentosa (RP) perform better with reverse contrast, whereas those with age related macular degeneration (ARMD) have no preference.

Patel, Elliott, & Whitaker (2001) examined reading speed in subjects where they simulated the effects of cataract. As part of this study, they looked at measurements with reverse contrast polarity. They demonstrated that with contrast reversal, the word acuity was improved as was optimal reading speed for the cataract simulation group. They found that critical print size was not affected by contrast polarity.

Wang & Chen (2000) examined the effects of polarity on visual performance for normal subjects using Landolt Cs. They found no difference in visual acuities with black-on-white compared to white-on-black either objectively by using Landolt Cs or subjectively by asking subjects to rate the display screen quality on a scale of 0 – 100. The average preference for white on black was 49.4 compared with 49.6 for black on white. There was no statistically significant relationship between polarity and contrast. Wang and Chen also conclude that there is a "lack of consistency in past relevant research results" regarding polarity.

Using 40 normal subjects with VAs of 0.9 or better, Sheih (2000) examined the effects of polarity using viewing distance and subjective responses to questions. Viewing distance was slightly reduced with white-on-black although this was not significant. There were no differences in subjective visual fatigue between either condition.

Rubin & Legge (1989) studied the effects on reading performance, notably reading speed on 19 subjects with varying degrees of visual impairment. As confirmed by Wolffsohn & Peterson (2003), they stated that "it has long been known in clinical practice that some low-vision observers read better with "reverse contrast" text". They refer to an earlier study by Legge who had demonstated that subjects with cloudy media could read up to 50% faster with contrast reversal. It was felt that this improvement was related to abnormal light scatter in the eye. Rubin and Legge also looked at reverse contrast with their subject group. The results were inconclusive although four out of seven patients with cloudy media actually performed better with white-on-black.

Many websites specifically for people with visual impairment offer a choice of reverse contrast or high contrast combinations. Examples include black text on off-white (Blind in Business, 2005; South Ayrshire Visually Impaired Children, 2007; white text on blue, pale green text on black (South Ayrshire Visually Impaired Children, 2007; black on yellow, yellow on black, blue on yellow, yellow on blue (Blind in Business, 2005) etc. Whilst it is widely believed in the field of visual impairment that reverse contrast is preferable for some sight impaired people, the evidence is mainly anecdotal and there is a lack of good quality evidence to support this view. The aim of this experiment was to investigate the effects of screen contrast polarity on reading speed in normal observers. The effects on visually impaired observers are described in Section 5.7.

2.3.1 Methods

The experimental conditions were as described for the previous experiment (see Section 2.3.1). The software was modified to present the text with positive and negative contrast polarity.

Reading speeds were measured using the modified MNRead as described in Section 2.2.1.

Twenty subjects (M:F = 9:11) with vision or visual acuites of 0.22 logMAR or better and near vision/ visual acuities of N5 and no ocular pathologies participated in this study. The mean age was 41.9 yrs (range 21 – 73yrs).

2.3.2 Results

The entire data set is presented in Appendix 3.

The mean reading time for all subjects is shown as a function of letter size in Figures 22 and 23 for positive and negative polarity displays. This graph shows the familiar effect of letter size on reading speed but suggests that contrast polarity has a minimal effect on reading speed.

Figure 22 – Graph showing polarity for subjects

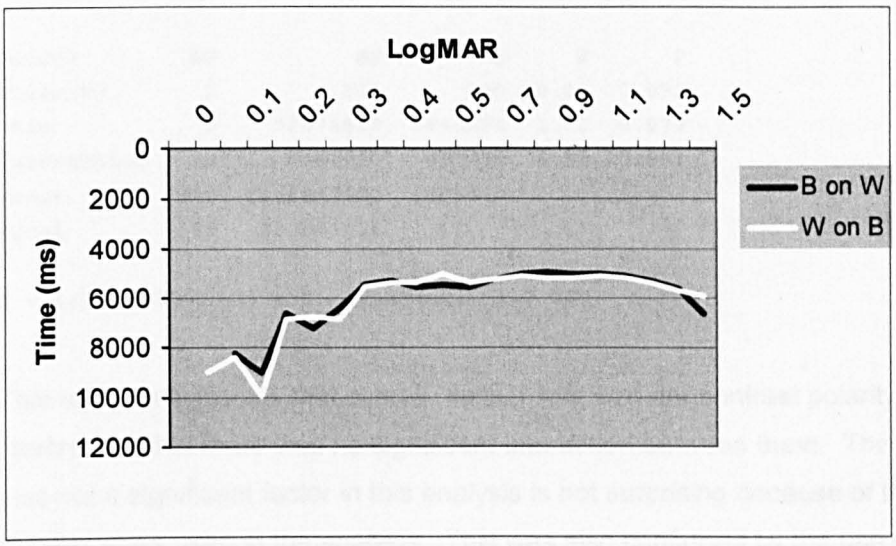
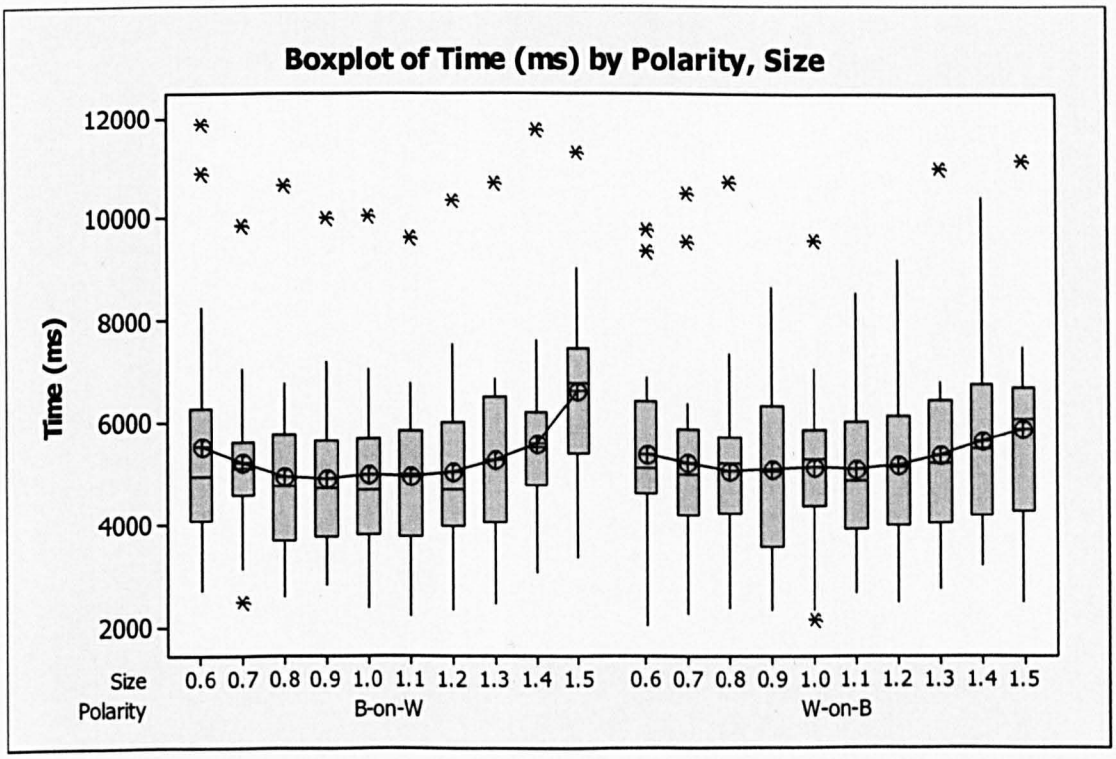


Figure 23 - Boxplot of reading time (ms) by letter size (LogMAR) for positive and negative contrast displays for all subjects. The boxes for each of the letter sizes represent the central 50% of the data whilst the lines at either end of the boxes indicate the remainder of the data showing the full range. The horizontal central line in each box marks the median for each letter size. The asterisk demonstrates any outliers in the data.



This is confirmed by a two way ANOVA using font size and polarity as factors as shown below.

Two-way ANOVA: Time (ms) versus Polarity, Size

Source	DF	SS	MS	F	P
Polarity	1	305	305	0.00	0.992
Size	9	52571619	5841291	1.78	0.070
Interaction	9	6461990	717999	0.22	0.992
Error	380	1244847402	3275914		
Total	399	1303881316			

S = 1810 R-Sq = 4.53% R-Sq(adj) = 0.00%

This analysis suggests that overall, neither font size nor contrast polarity were significant factors and that there was no significant interaction between them. The fact that font size was not a significant factor in this analysis is not surprising because of the restricted range of letter sizes used in the analysis. This was also confirmed by the use of a paired t-test comparing the two polarities ($p = 1$; NS). MRS was also looked at using a paired t-test for the two polarities. Again this was also not significant ($p = 0.206$; NS).

The mean critical print size for both conditions was 0.44 logMAR.

2.4 Screen contrast polarity and reading speed: Conclusions

The aim of this study was to ascertain whether or not there were any differences in reading speed using black text on a white background compared with white text on a black background in normal subjects. Subjects showed the familiar change in reading speed with font size for both polarities. Re-examination of the outliers indicated that these were mainly attributable to one subject who seemed to have particular difficulties with this task or at least adopted a different stategy. Although this participant read significantly slower than the others, their reading speed showed a similar dependence on font size and polarity. Although there were individual differences in the effects of contrast polarity (with the majority of subjects reading slower with reverse polarity), this difference failed to reach statistical significance overall. These findings are in agreement with those of Wang & Chen (2000).

3. Optimisation of fonts – normal subjects

3.1 Introduction

Modern computers come equipped with hundreds of fonts. However, there is little agreement in the literature regarding the relative efficiency of different fonts in terms of reading speed and user preference / comfort.

3.2 Fonts and reading

3.2.1 Terminology

It is important to differentiate between '*legibility*' and '*readability*'. Legibility refers to how easy it is to decipher individual characters of a word whilst readability refers to how easy it is to read a passage of text. There are different readability formulae and grade levels available which include the Flesch-Kincaid Readability Test, the Fry readability formula and the SMOG readability calculator. This thesis is concerned with '*legibility*'.

3.2.2 How is reading defined?

Reading occurs through a number of perceptual and physiological processes; we need to have vision to be able to see the text, a brain to interpret the words, and concentration to maintain the words and place them into meaningful sentences. Typically when we read, we make a number of saccadic eye movements with as many as 6 or 7 saccades per one line of text. Occasionally, if a sentence is difficult or there is a word we are unsure about, the eye refixates on a previously read section (i.e. reverse saccade). At the end of each line, the eye jumps back to the start of the next line and repeats the process. The visual system also capitalises on the differences in contrast between letters and spacing to allow further discrimination of characters either side of the fixation point. This helps with the identification of familiar word patterns (Rayner & Pollatsek, 1989). Rauding looks at the phonetical limitations on reading speed with Carver (1990) stating that a standard word length should be six characters.

There are three main areas of vision involved in the reading process:

(1) **Foveal** – this extends approximately 2 degrees of visual angle around the fixation point. In real terms, this usually equates to about 4-5 characters. The foveal area is the most sensitive area as this is the area which has the highest cone density required for fine vision.

(2) **Parafoveal** – this extends approximately 10 degrees (4 degrees either side of the foveal area). It is thought that we gain cues from this region which help us interpret the next part of the sentence.

(3) **Peripheral** – this is everything else on the line and any surrounding lines.

(Rayner & Pollatsek, 1989)

It is known that human beings have been writing (and therefore reading), for many thousands of years. Early examples include hieroglyphics from the Egyptians. More recently, Times New Roman font was designed by Stanley Morrison in 1932 and then subsequently it was used as a space saving font for newspapers during the 1939-1945 war (Wikipedia, 2007).

Dehaene et al (2005) state that: "Visual word recognition is a remarkable feat. Within a fraction of a second, a pattern of light on the retina is recognized as a word, invariantly over changes in position, size, CASE and font". This is true but reading is more than this and can be thought of in two stages; the recognition and decoding of the symbols as words (lexical route) followed by the second stage of processing which is interpreting the symbols into meaningful words, i.e. comprehension (phonological route). Gough et al (1986) refer to this as the 'Simple View of Reading'. Shaywitz and Shaywitz (2008) argue that reading differs significantly from spoken language as the latter is a natural process that does not need to be taught whereas the former is an artificial process which involves sets of rules which need to be learnt. These rules include learning letters and ultimately, by recognising the composition of these letters, as words. In addition, the reader is required to comprehend the meaning of the words they are reading. Whilst interesting and relevant within the field of psychology particularly with reference to studies of reading disabilities, these definitions are not overly helpful for the research within this thesis. This raises the next question of 'how do you define reading?' When you look up a student's marks, are you reading? When you scan the web for a film to watch, are you reading? If you skim read a novel, are you reading? Rayner and Pollatsek (1989) define reading as: "the ability to extract visual information from the page and comprehend the meaning of the text". That said however, reading can be categorized into different types. Skim reading allows the reader to read passages of text quickly without reading every single word. This enables the reader to identify key words or phrases and then read them.

3.2.3 Normal readers

A 'normal' reader reads approximately 200-300 words per minute (wpm) (which equates to 200 msec per word) and understands approximately 60% of the information. In contrast, an excellent reader can read in the region of 1000 wpm. These readers do not read aloud or

indeed, sub-vocalise. Normal readers often skim read and allow the brain to fill in the gaps (Rayner & Pollatsek, 1989). Reading speeds differ according to the different types of reading. For instance, skim reading which allows a reader to read a passage of text quickly without necessarily reading every single word commands a much higher reading speed typically in the region of 400 – 700 wpm. In contrast, a reading task which requires good comprehension of the printed material will slow reading to a speed of 200 – 400 wpm depending on the difficulty of the material. In addition, learning the information simultaneously will further reduce reading speeds to 100 – 200 wpm whilst memorising the written text will slow the reading speed to less than 100 wpm (Legge, 2006). Whittaker and Kitchen (1993) report that factors which influence reading speed include the ability of the subject, the complexity of the reading material and the attention of the reader.

There are other types of reading such as proofreading whereby a person is required to read a passage of text specifically looking for errors. In this instance, meaning is insignificant. Searching is where a subject skims a passage of text in order to find a specific piece of information and speed reading; a commercial enterprise whereby people aim to achieve faster reading speed through the use of controlled eye movements combined with a skimming technique.

Subvocalising is where the reader speaks the words to him/herself whilst reading compared with silent reading when the person reads the text without vocalisation. Vocalising is where the reader speaks the words aloud. This is slower than silent reading and is dependent on how quickly the subject can speak the words. Any speech impediments such as a stammer would reduce the reading speed.

3.2.4 Methods for assessing reading

Reading can be assessed in a number of ways; both silently and by reading aloud. Methods for assessing reading include tests which look at fluency (typically a subject is asked to name words), comprehension (subjects are required to read a passage of text and answer questions on it), sight word reading (subjects are presented with words of increasing difficulty until they are no longer able to read or comprehend the words shown to them), non-word reading (subjects are required to read nonsense words) and accuracy (subjects are assessed on the accuracy of correctly naming words). Other methods of assessing reading which are commonly used in reading experiments include rapid serial visual presentation (RSVP), drifting-text method, and flashcard method (Legge et al, 2007).

Rapid Serial Visual Presentation presents words singly in the centre of a display screen. Again the exposure time of each word can be increased until such a point where the subject is unable to read the words. It has been shown that reading speed is much faster using this method (Legge, 2007).

The drifting-text method is where one line of scanned text drifts across a computer screen from right to left. The speed at which it drifts can remain constant or can be speeded up until a subject is no longer able to read the words. This is referred to as 'forced scrolling test' (Legge, 2006). With this method, subjects are required to read aloud so accuracy in scoring can be maintained. Threshold is achieved when the fastest drift rate produces accurate reading results. The psychometric function of the relationship between percentage of correctly read words against drift rate is usually plotted as a graph and from this, the reading speed can be obtained (see Figure 24). The disadavantage of assessing reading speed using this method is that it is limited by how quickly the subject can talk rather tan read. The advantage of this method though is that reading accuracy can be assessed.

Figure 24 – Graphs showing (a) Reading accuracy vs' drift rate and (b) Reading speed vs' drift rate (After: Legge GE (2007)

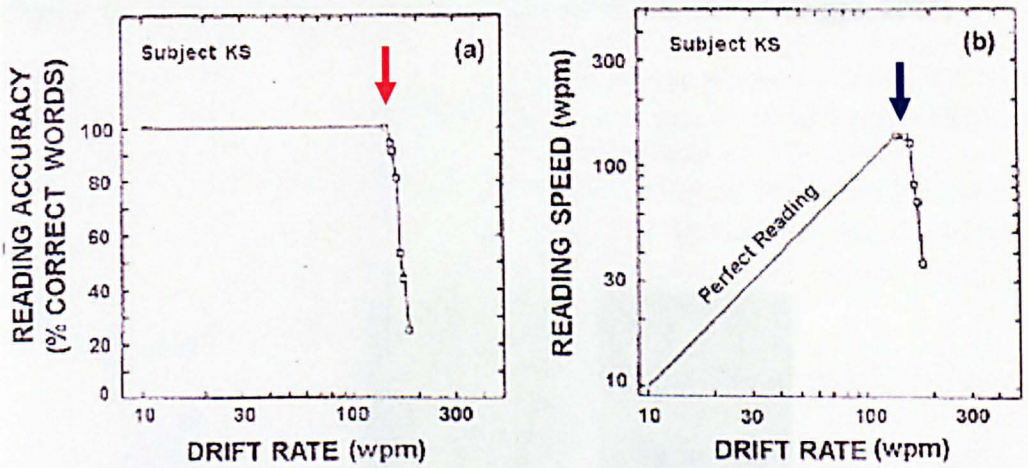


Figure 24(a) shows that subjects are able to maintain 100% reading accuracy up to drift rates of approximately 150 wpm but once the rate increases beyond this, then accuracy plummets with increasing speed. This junction as denoted by the red arrow indicates what Legge et al (2006) refer to as the "critical drift rate". Figure 24(b) shows the same data replotted as a reading speed. This is calculated by the drift rate multiplied by the percentage of correctly read words (e.g. drifting rate = 100wpm and 80% of words are read accurately then the reading speed is calculated as 80wpm). The blue arrow shows the critical drift rate for this subject.

Introduced in 1989, the flashcard method was designed by the Minnesota Low Vision Laboratories as a method of determining reading speed which incorporated both static and drifting assessment. With this method, subjects are presented with a passage of text which

they are required to read. The words are stationary and again the exposure time is varied until the subject is unable to read the words. The MNRead (originally computer based) has been described elsewhere (see Section 2.2). End point is achieved when subjects are unable to read the entire flashcard accurately. Reading speed is then determined by dividing the exposure time by the number of correctly read words. Legge et al (1988) showed that normal subjects read static text faster than drifting text whereas visually impaired subjects read drifting text approximately 15% faster. This is in contrast to Bowers (2004) who were unable to demonstrate a difference between either method for either normal subjects or those with visual impairment and Whittaker and Lovie-Kitchen (1991) who demonstrated that drifting text produced faster reading speeds which they attributed to the scrolling mechanism involved with drifting text thus forcing subjects to read at their maximum speeds.

Figure 25 – Figure showing MNREAD acuity charts (After: Legge, 2007)

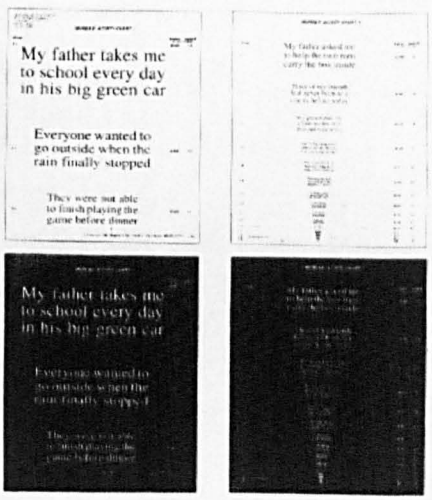


図 15 MNREAD Acuity Charts
(Rosenthal, B. P. & Cole, R. G., 1996, Functional Assessment of Low Vision, Mosby)

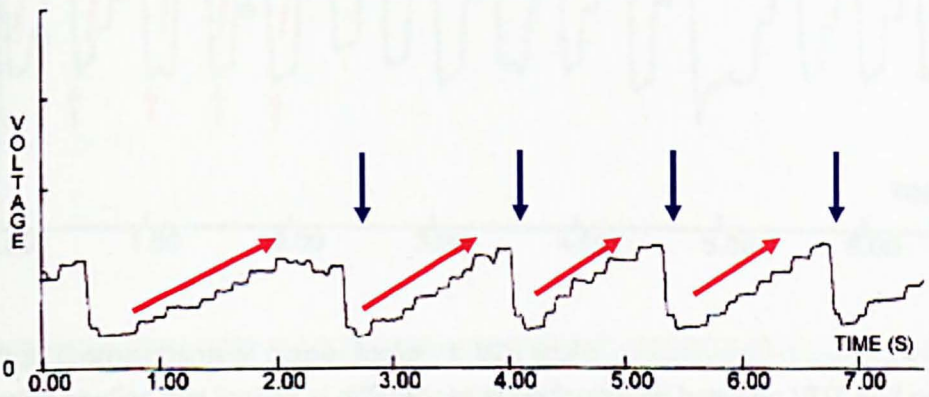
Ziefle (1998) compared reading speeds of hard copy versus CRT displays. She found no differences between low and high resolution screens in keeping with results by Miyao et al. (1989). However, she found that subjects both subjectively and objectively preferred reading from a hard copy with reading speeds being approximately 10% faster supporting the findings of Gould et al. (1987) and Mayes et al (2001). This result was significant.

3.2.5 Eye movements in reading

Eye movements play a critical role in reading. The reader normally makes a series of small saccadic eye movements from one word to the next with a larger saccade back to the beginning of the next row. The number of fixations/saccades per row depends on the reader

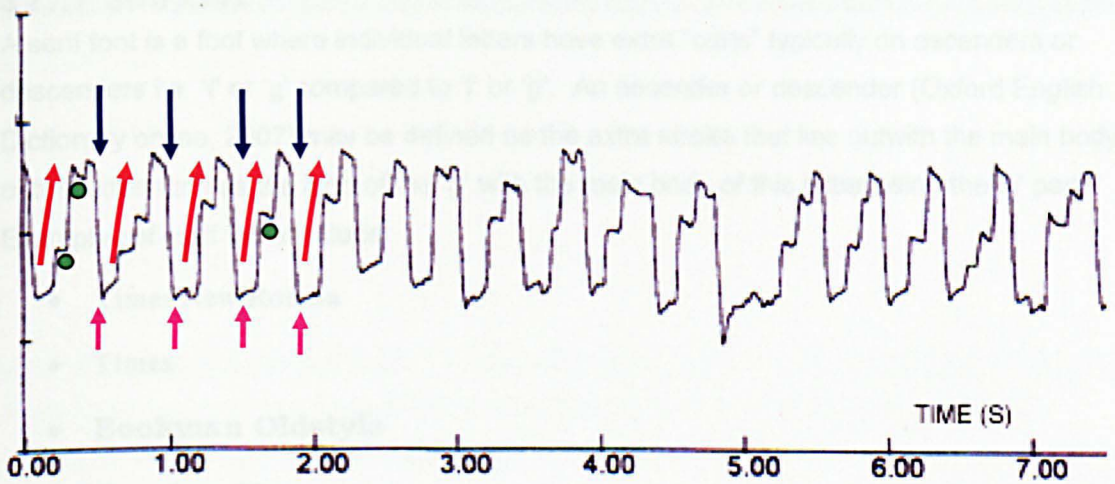
and the nature of the text. An alternative approach involves keeping the eyes steady and moving the book (i.e. Steady Eye Strategy). Clearly, the latter involves more effort and, therefore, is only used as a means of helping those with visual impairment. Figure 26 shows typical eye movements for a poor reader. .

Figure 26 – Typical eye movements shown for a poor reader taken from an Electro-oculogram recording from 02 Visual Perception at City University.



In contrast, Figure 27 shows typical eye movements for a good reader. It can be seen that the good reader makes fewer fixations/saccades per row and is presumably able to assimilate more information from the parafoveal field and interpolate more effectively between fixations.

Figure 27 – Typical eye movements shown for a good reader taken from an Electro-oculogram recording from 02 Visual Perception at City University.



3.2.6 Comparison of paper tasks vs' VDT tasks

Earlier studies that looked at differences in performance between VDT and paper-based tasks tended to find that proof reading tasks result in slower performance times when done using a VDT than with a hard copy (Creed et al, 1987; Wilkinson and Robinshaw, 1987). Gould et al (1987) found no differences in performance between VDTs and a printed document. It must be noted, however, that display screens have improved significantly since the 1980s and more recent studies have shown varied results. Mason et al (2001) and Hallfors et al (2000) were unable to demonstrate any differences between a computer based task and a paper based task although in Hallfors' study, subjects reported that they preferred the computerised task. Mayes et al (2001) asked subjects to read a passage of text on a display screen as well as from a hard copy and answer MCQs at the end of it. They reported that subjects read significantly slower from a display screen. Noyes et al (2004) reported from their work that, whilst they found that comprehension times were similar between computer based tasks and paper tasks, subjects reported higher levels of cognitive workload when using a display screen. They surmised that because subjects found reading from a display screen to be more tiring than from hard copy, this may be contributing to the slower comprehension times as found by Mayes et al (2001). This finding was supported by Wastlund et al (2005).

3.2.7 Types of fonts

Traditionally, fonts can be categorised into two major groups: serif or sans serif.

3.2.7.1 Serif fonts

A serif font is a font where individual letters have extra "curls" typically on ascenders or descenders i.e. 'f' or 'g' compared to 'f' or 'g'. An ascender or descender (Oxford English Dictionary online, 2007) may be defined as the extra stroke that lies outwith the main body of the letter such as the loop of the 'g' with the main body of this letter being the 'o' part. Examples of serif fonts include:

- **Times New Roman**
- **Times**
- **Bookman Oldstyle**
- **Courier New**
- **Palatino**
- **Georgia**

As can be seen from Figure 28, the ascenders or descenders are particularly curly when compared with a sans serif font (see the 'g' as illustrated in red):

Figure 28 – Serif vs' sans serif

Teal is a big dog. He is a golden retriever (Times New Roman - serif).

Teal is a big dog. He is a golden retriever (Comic Sans - sans serif).

3.2.7.2 Sans serif fonts

A sans serif font is a font without serifs (see Figure 28). Examples of sans serif fonts include:

- **Arial**
- **Helvetica**
- **Verdana**
- **Century Gothic**
- **Comic Sans MS**
- **Trebuchet MS**

3.2.7.3 *Proportionally spaced fonts*

With a proportionally spaced font, the amount of space taken up by each letter is determined by the width of that particular letter. For example, an 'l' is narrower than a 'w' and so, proportionally, takes up less space (see Figure 29). Examples of proportionally spaced fonts include:

- **Comics Sans**
- **Arial**
- **Helvetica**

3.2.7.4 *Mono spaced fonts*

A mono-spaced font is a font whereby each letter is the same width (see Figure 29). Examples of a mono-spaced font include:

- `Courier New`

Figure 29 - Proportionally spaced vs' mono spaced fonts

Teal is a big dog. He is a golden retriever (Comic Sans).

```
Teal is a big dog. He is a golden retriever (Courier
New).
```

As can be seen from Figure 29, the proportionally spaced font (i.e. Comic Sans) takes up less space than the mono-spaced font (i.e. Courier New) irrespective of the left justification used.

3.2.7.5 *Size of a font*

According to the Cascading Style Sheets, level 2 CSS2 Specification (1998), the size of a font is depicted by the height of each letter which is measured in points. One point is 0.0139 per inch and is also known as a pica. A 12 point font is, therefore, 0.0139 x 12 = 0.1656 inches tall i.e. 1/72 of an inch with a 72 point font measuring one inch. The height is determined by the main body of the letter and is referred to as the x-height (see Figure 30). Alternatively, Knuth makes the assertion that the point size of a font is a relative measurement with different fonts being scaled accordingly. He states that: "a more-or-less arbitrary number that reflects the size of type [a font] is intended to blend with" (Ricker, 1992). Other ways of determining the point size of a font is to measure the distance from the baseline of one line to the baseline of the line below this.

Figure 30 – Figure showing x-height



After: http://en.wikipedia.org/wiki/Typeface

A number of studies have investigated the 'readability' of various fonts, i.e. how easy a particular font is to read both with subjective and objective measurements (Scharff, 2002; Bernard et al, 2001; Bernard & Mills, 2000). Subjectively, Bernard et al. (2001) reported that subjects rated Times New Roman and Comic Sans MS as being easier to read than others used in their research. Hill and Scharff (2002) compared reading speed of subjects using Times New Roman and Arial. They used out of place words (circle, triangle, square) embedded in a passage of text and found that subjects read faster with Times New Roman than Arial. In contrast to this finding, Bernard and Mills (2000) found no significant differences between these two fonts when they measured reading speed and accuracy on a computer screen. This is also in contrast to the work by Sheedy et al (2005) who showed that Verdana and Arial were deemed more legible than Times New Roman and Franklin.

Hoffman et al. (2002) recruited 146 graduates and presented them with ten pairs of different paragraphs so that each pair was presented simultaneously and subjects selected the paragraph that was "easiest to read". The results indicated that subjects chose the two fonts that were specifically designed for use with computers (Verdana and Trebuchet) over Arial and Times as the most readable. Out of the remaining three fonts that were not designed specifically for computer use, subjects preferred Arial to Times and Helvetica. In this experiment, all five fonts were set to size 3 in the web browser. However, due to differences in the x-height dimension of each font, there were noticeable differences in font height which could have contributed to the results. As a direct consequence, Hoffman et al. (2002) designed a second experiment to control for these factors. In this experiment, relative font size was adjusted to make all fonts relatively uniform. This was done by displaying the paragraphs as bit-mapped images. Two hundred and twenty eight subjects were recruited and the same experiment was conducted as before (with controlled letter height) was conducted. Results showed that subjects still preferred the fonts designed specifically for computer use, i.e. Trebuchet and Verdana. However, interestingly, Times New Roman which had been rated the least legible font along with Helvetica in the previous experiment, was now rated the same as Arial in terms of legibility and more readable than

Helvetica. This is particularly interesting as Times was the font that appeared the smallest in the original experiment.

Using the same out-of-place word search task as Hill and Scharff, Hoffman conducted a third experiment to provide an objective measurement of font readability. In this experiment, he found that the differences in reading speed were very small between the fonts (10.80 secs for Helvetica to 11.98 secs for the slowest font, Arial). These results were not significant.

Mansfield et al. (1996) used two MNRead charts each with a different font to investigate the effects of fonts. Fifty participants with normal vision and 42 subjects with a form of visual impairment were examined. The latter group peformed better with Courier-bold font, reading up to twice as fast than with TNR with average font size. This difference was inversely proportional to the reading speed of the subject (i.e. greater for subjects with slower reading speeds). The study did however, demonstrate that normal readers read faster with Courier when the text is smaller than the critical print size. It was suggested that this may be because the individual Courier characters required 40% more space than the corresponding TNR one and, therefore, was likely to be easier to read below critical print size (CPS).

Arditi & Cho (2005) investigated whether presence/ absence of serifs had any effect on reading. They designed nine different artificial fonts from three different serif sizes (0, 5 and 10% of the capital letter height of the font) and three different inter-letter spacings (0, 10 and 40% of the capital letter height). They demonstrated that the closer the letters are placed together (i.e crowded), the harder they are to read. The presence of a serif on presentation of a single word had an effect but was not significant. No other effects were found for size threshold, or when reading jumbled sentences.

The literature suggests that font selection is a subjective preference which is affected by the size of a font. For example, an Arial size 12 font is proportionally larger than a Times New Roman despite being the same nominal font size. This would appear to be a factor when selecting fonts. This chapter will examine whether or not this is true.

A number of studies have investigated the readability of various alternative character sets such as Chinese and Arabic. These studies are difficult to compare as the language and reading style between Chinese characters and Arabic characters differ markedly. This is primarily because Arabic characters are read from left to right in horizontal rows whilst Chinese characters are read from right to left in vertical columns from top to bottom. Reading Chinese characters has been shown to be a more complex task than reading Arabic letters (Zhang et al, 2007). Chien-Hsiung and Yo-Hung (2005) showed that Chinese

typography and font size did not impact upon reading comprehension. Perhaps unsurprisingly, they found that comprehension was affected by speed of presentation; the faster the presentation, the lower the comprehension.

3.3 Font selection and scaling

The aim of the studies described in this chapter was to rate a variety of common screen fonts in terms of subjective preference and "efficiency".

Despite the availability of literally thousands of fonts, a few fonts have emerged as the most popular. In the studies described below, eight fonts were selected for the following reasons. Times New Roman and Arial were selected as they are the most commonly-used fonts with many computers having them set as the default font. Georgia and Trebuchet were chosen because they were designed specifically for use with computers. Courier was included because it was used in the original MNRead test and Comic and Lucida were included as extreme examples of each type of font.

Four of these fonts can be described as "serif" fonts. They were as follows:

- Times New Roman (designed by Microsoft Typography Group for Microsoft)
- Georgia (designed by Matthew Carter for Microsoft)
- Courier New (designed by Microsoft Typography Group for Microsoft)
- *Lucida Handwriting* (designed by Charles Bigelow and Kris Holmes, 1985)

The other four fonts can be described as "sans serif" fonts. They were as follows:

- Arial (designed by Microsoft Typography Group for Microsoft)
- Verdana (designed by Matthew Carter for Microsoft)
- Comic Sans MS (designed by Vincent Connare for Microsoft)
- Trebuchet MS (designed by Vincent Connare for Microsoft)

Comparing fonts is fraught with difficulties. Different fonts not only have different "styles" but also vary in letter height, stroke width, letter spacing and row spacing, all of which is likely to affect the legibility of the text. It is these factors which contribute to each font's distinctive appearance and, as a result, it would be futile to try and equalise each of these factors before comparison.

However, it was considered important for all fonts to be the same "size" to allow a meaningful comparison. Even this is not straightforward as a decision has to be made about whether to equalise horizontal or vertical size. After some debate, it was decided to equalise the x-height of the letters as subjectively this gave the best perceived match. This was achieved by measuring the x-height of each letter and working out a scaling factor for each font relative to Arial. This is shown in Table 4 as X1 signifying 1 unit. Because Comic Sans is naturally larger with the x-height of this font measuring 14mm, this font was

multiplied by 0.93 to make it the same height as the equivalent Arial font. Table 6 shows the adjustments that were made to each font using a size 12 font as the baseline.

Table 6 – Table demonstrating adjustments made for height

Font	X height	13/value	Ascenders/descenders	23/value
Arial	**13mm**	**X1**	**23mm**	**X1**
Comic sans	14mm	X0.93	27mm	X0.852
Courier new	11mm	X1.18	21mm	X1.095
Georgia	12.5mm	X1.04	25mm	X0.92
Lucida handwriting	16mm	X0.81	30mm	X0.77
Times New Roman	12mm	X1.08	23mm	X1
Trebuchet MS	13.5mm	X0.96	24mm	X0.958
Verdana	14mm	X0.93	24mm	X0.958

3.4 Methods

3.4.1 Subjects

Twenty six male and 15 female undergraduate optometry students and staff at City University aged 18-46 yrs (mean 23 yrs) took part. All participants had near vision/ visual acuity of N5. Eighteen subjects (41.0%) wore appropriate contact lenses or spectacle correction for the experiments. These subjects took part in experiments 1-4. Some observers participated in more than one experiment but practical constraints meant that different "normal" observers were recruited for each experiment.

3.4.2 Apparatus

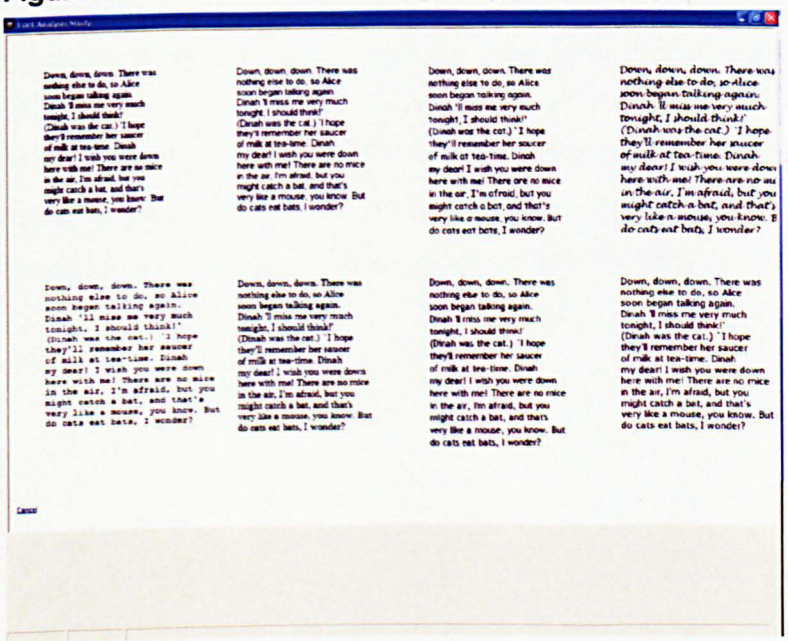
The same equipment as used in Chapter 2 was used for all the experiments described below.

3.4.3 Experiment 1: Subjective rating of different fonts (ranking test): Methods

The aim of the first experiment was to obtain a simple rank order for the eight fonts in terms of subjective opinion of their legibility. Eight identical passages of text were displayed simultaneously on the screen in the eight fonts (see Figure 31). The text was displayed in 11 point font and was scaled as above. They were presented as black text on a white background (mean luminance 212 cdm^{-2}). Observers were instructed to study each passage carefully and click on the font which was the easiest to read. This passage was then removed and the observer clicked on the preferred font from the remaining seven. This was repeated until a single font remained.

The computer program recorded the order of preference for each subject.

Figure 31 – Screenshot showing subjective rating of different fonts (ranking test)



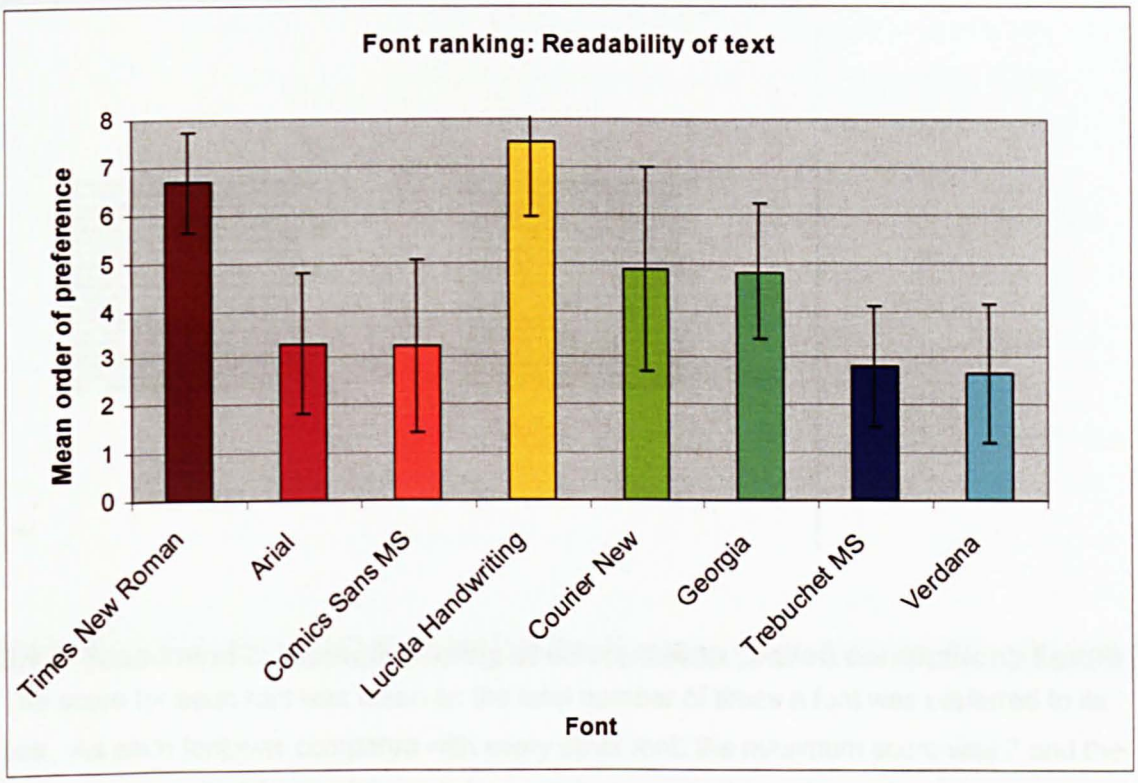
3.4.4 Experiment 1: Subjective rating of different fonts (ranking test): Results

The average ranking for each font is shown in Figure 32. The rank order was Verdana, Trebuchet, Comic Sans, Arial, Georgia, Courier New, Times New Roman with Lucida Handwriting judged to be the least readable.

Overall, the sans serif fonts were judged to be more readable than the serif fonts (sans serif = 2.95 vs' serif = 6.03; $p < 0.001$).

Figure 32 shows the subjective rating of each individual font in terms of readability. The higher the bar, the more readable the font was rated.

Figure 32 – Histogram showing the results for 'font ranking': 1= difficult, 8 = easiest. The error bars represent +/- 1 standard deviation

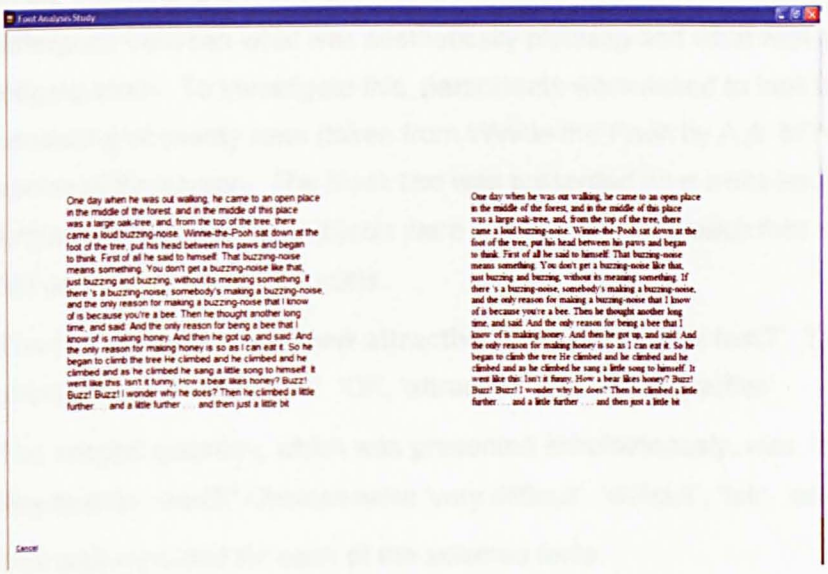


3.4.5 Experiment 2: Subjective rating of fonts (paired comparison): Methods

This second experiment was designed to determine the rank order for the fonts in terms of subjective legibility. Two passages of text (taken from Winnie-the-Pooh) were displayed in 12 point and were scaled so that their x-heights were the same (black on white background, mean luminance 212 cdm^{-2}) on either side of the midline of the screen. The two passages were displayed in different fonts and the text was arranged such that there was the same number of words per line, with each row being of equal length of words (see Figure 33.

Each of the eight fonts was presented with every other font and participants were instructed to click on whichever font was judged to be the "easier to read". The order of presentation and the position of the paragraph (left or right) was randomised to avoid any bias.

Figure 33 – Screenshot showing subjective rating of different fonts (paired comparison)



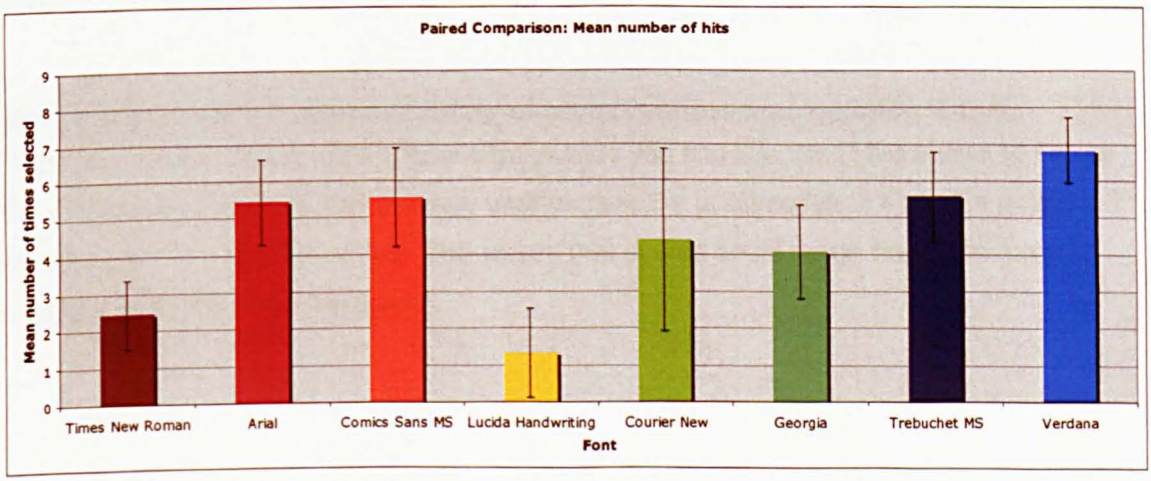
3.4.6 Experiment 2: Subjective rating of different fonts (paired comparison): Results

The score for each font was taken as the total number of times a font was preferred to its pair. As each font was compared with every other font, the maximum score was 7 and the minimum score 0. The mean scores for each font are shown in Figure 34.

The rank order for the fonts was Verdana, Trebuchet, Comic Sans, Arial, Courier New, Georgia, Times New Roman with Lucida Handwriting receiving the poorest rating.

Sans serif fonts were perceived as being significantly easier to read than serif fonts ($p < 0.001$).

Figure 34 – Histogram showing the results of the paired comparison test. The error bars represent +/- 1 standard deviation



3.4.7 Experiment 3: Subjective rating of attractiveness and legibility: Methods

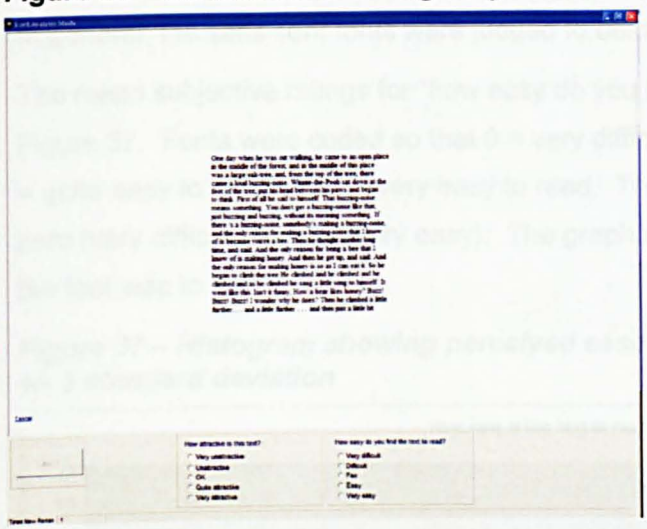
In the course of the first experiment, a number of observers suggested that there was a difference between what was aesthetically pleasing and what was easy to read when judging fonts. To investigate this, participants were asked to look at a passage of text consisting of twenty rows (taken from Winnie the Pooh by A.A. Milne), presented in the centre of the screen. The black text was presented on a white background (mean luminance 212 cdm^{-2}). Subjects were instructed to rate each font in two ways (see Figure 35) using a 5-point Likert scale.

The first question was: "**How attractive do you find this text?**" The choices were: 'very unattractive', 'unattractive', 'OK, 'attractive' and 'very attractive'.

The second question, which was presented simultaneously, was: "**How easy do you find this text to read?"** Choices were 'very difficult', 'difficult', 'fair', 'easy', and 'very easy'.

This was repeated for each of the selected fonts.

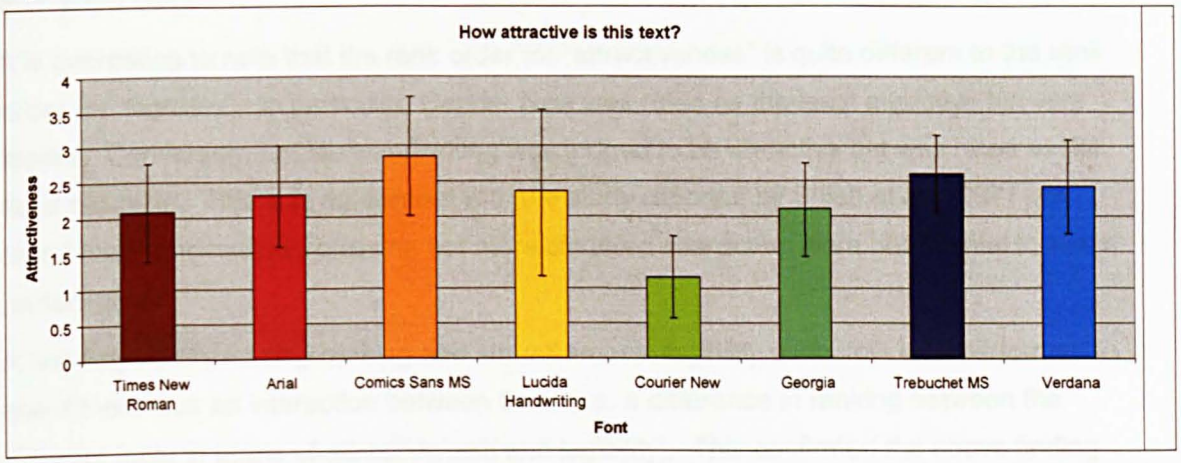
Figure 35 – Screenshot showing subjective rating of different fonts



3.4.8 Experiment 3: Subjective rating of attractiveness and legibility: Results

The mean subjective ratings for "how attractive do you find this text?" are shown in Figure 36. Fonts were coded so that 0 = very unattractive, 1 = unattractive, 2 = ok, 3 = quite attractive and 4 = very attractive. This meant that scores could range from zero (very unattractive to four (very attractive).

Figure 36 – Graph showing subjective rating for 'attractiveness'. The error bars represent +/- 1 standard deviation

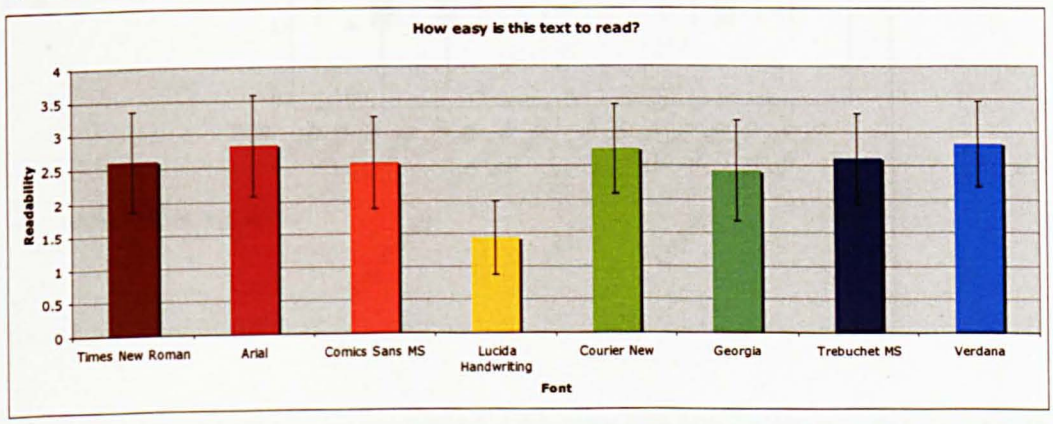


The rank order was Comic Sans, Trebuchet, Verdana, Lucida, Arial, Georgia, Times New Roman with Courier being ranked as the least attractive. The difference between Courier and all other fonts was significant (paired t-test, $p<0.001$).

In general, the sans serif fonts were judged to be more attractive (paired t-test, $p < 0.001$).

The mean subjective ratings for "how easy do you find this text to read?" are shown in Figure 37. Fonts were coded so that 0 = very difficult to read, 1 = difficult to read, 2 = ok, 3 = quite easy to read and 4 = very easy to read. This meant that scores could range from zero (very difficult) to four (very easy). The graph shows that the higher the bar, the easier the font was to read.

Figure 37 – Histogram showing perceived ease of reading. The error bars represent +/- 1 standard deviation



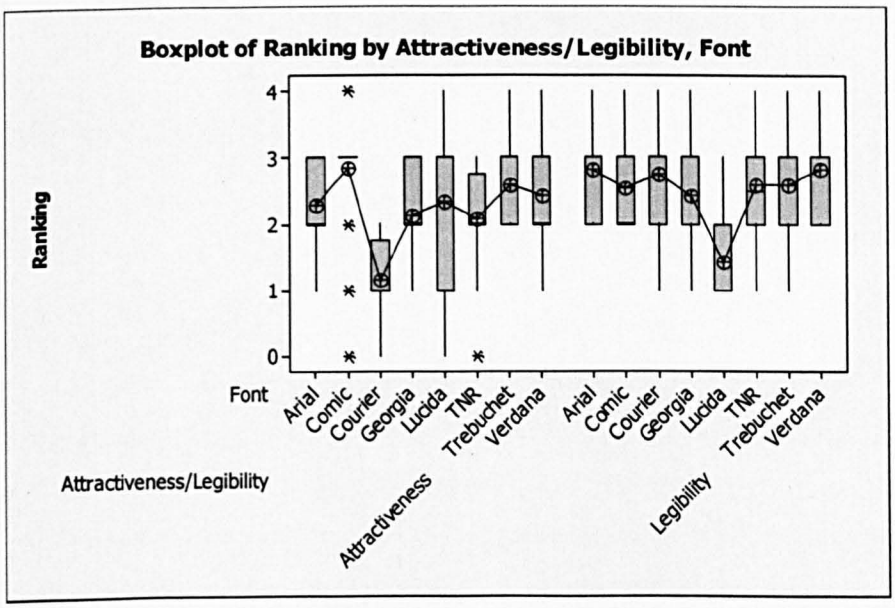
The rank order was Verdana, Arial, Courier New, Times New Roman, Trebuchet, Comic Sans, Georgia with Lucida Handwriting judged to be the most difficult to read.

Overall, sans serif fonts were rated as 'easier to read' than their serif counterparts (paired t-test, $p < 0.001$).

It is interesting to note that the rank order for "attractiveness" is quite different to the rank order for "legibility". In particular, Courier New was rated as the least attractive but very legible. Conversely, Lucida Handwriting was judged to be attractive but was rated as the least readable. This is in agreement with the study reported by Shieh et al (1997) who found that: "aesthetically pleasing but more cluttered characters were detrimental to visual performance".

A two way ANOVA using ranking and attractiveness/ legibility as factors was performed to see if there was an interaction between them (i.e. a difference in ranking between the different fonts in terms of attractiveness and legibility). This confirmed the above finding that Courier New was found to be the least attractive font whilst Lucida Handwriting was judged as the least readable. This was significant (see Figure 38).

Figure 38 – Boxplot of ranking by attractiveness/legibility vs' font. The boxes for each of the letter sizes represent the central 50% of the data whilst the lines at either end of the boxes indicate the remainder of the data showing the full range. The horizontal central line in each box marks the median for each letter size. The asterisk demonstrates any outliers in the data.



3.4.9 Experiment 4: Word Search Speed with different fonts (word search): Methods

Experiments 1-3 simply required participants to rate the perceived legibility / attractiveness of the fonts. The following series of experiments were designed to assess if there were any differences in the ability to access the information presented in different fonts.

In the first experiment in this series, participants were required to locate a particular misplaced word (vine, wine or dine) embedded within a paragraph of text, taken from an Agatha Christie novel. This required participants to read the text as quickly and accurately as possible (see Figure 39). This task was designed to replicate proofreading as Buchner and Baumgartner (2007) demonstrated that proofreading using dark text on a light background as is used in this experiment was better than when performed with light text on a dark background. Subjects were encouraged to simply read the text from top to bottom until they encountered the target word. However, it must be acknowledged that a number of strategies could be used to complete this task including skimming, proofreading or searching.

The three search words were randomised using a random number generator (www.random.org) so that 'vine' appeared fourteen times, 'wine' fourteen times and 'dine' twelve times respectively. Each font was presented five times and the search words were positioned in different parts of the text in each trial. However, the position was varied so that over the five trials, there were 500 words before the search word (average of 100 words/ presentation). Each passage of text was 200 words in length. Table 7 shows the order of insertion and the search word.

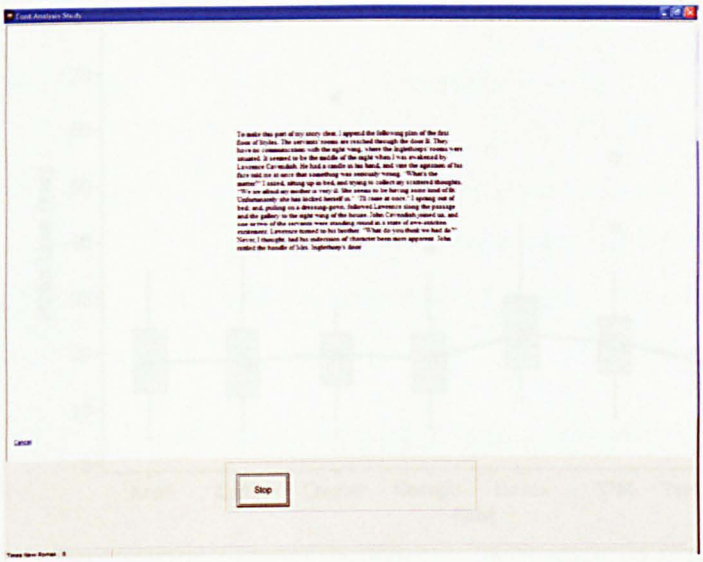
Table 7 - Order of insertion

Height / Font	Word 1	Word 2	Word 3	Word 4	Word 5	Mean
Times	67	37	163	93	140	100
	1	3	2	2	1	
	vine	dine	wine	wine	vine	
Arial	88	50	46	192	124	100
	1	2	3	1	2	
	vine	wine	dine	vine	wine	
Comic	62	50	118	198	72	100
	3	2	1	3	1	
	dine	wine	vine	dine	vine	
Lucida	160	94	124	66	56	100
	2	3	3	3	2	
	wine	dine	dine	dine	wine	
Courier	157	148	99	65	31	100
	1	2	2	2	3	
	vine	wine	wine	wine	dine	
Georgia	78	91	170	83	78	100
	2	2	1	2	1	
	wine	wine	vine	wine	vine	
Trebuchet	62	71	54	154	159	100
	1	3	3	3	1	
	vine	dine	dine	dine	vine	
Verdana	144	70	89	155	42	100
	3	2	1	1	1	
	dine	wine	vine	vine	vine	

Each subject was given a practice trial to minimise any learning effects. When the subject was ready, they were instructed to click on the 'start' button at the bottom of the screen, which started a software timer. The instruction was to read the passage of text given, quickly and accurately, and to locate one of three possible words: 'vine', 'dine' or 'wine'. There was no indication given to the subject if this word would appear singly or on multiple occasions. When the inserted word was located, the subject was instructed to click on the stop icon. This would stop the clock and the program would then calculate their reading speed. At this point, the text would vanish from the screen and subjects would be presented with the three choices of word: 'wine', 'vine' or 'dine'. Subjects were required to click on the correct inserted word. When this was done, the next passage of text would be presented. This was repeated 40 times so that each font was presented a total of five times and the

computer recorded whether the subject was correct in their selection of the word. The order of presentation was randomised to balance for order effects.

Figure 39 – Screenshot showing the word search task



3.4.10 Experiment 4: Word Search Speed with different fonts (word search): Results

The mean search time for each font is shown in Figure 40 and as a boxplot in Figure 41. The rank order is shown in Table 8.

Figure 40 - Histogram showing the mean search time for each font in the word search task. The error bars represent +/- 1 standard deviation.

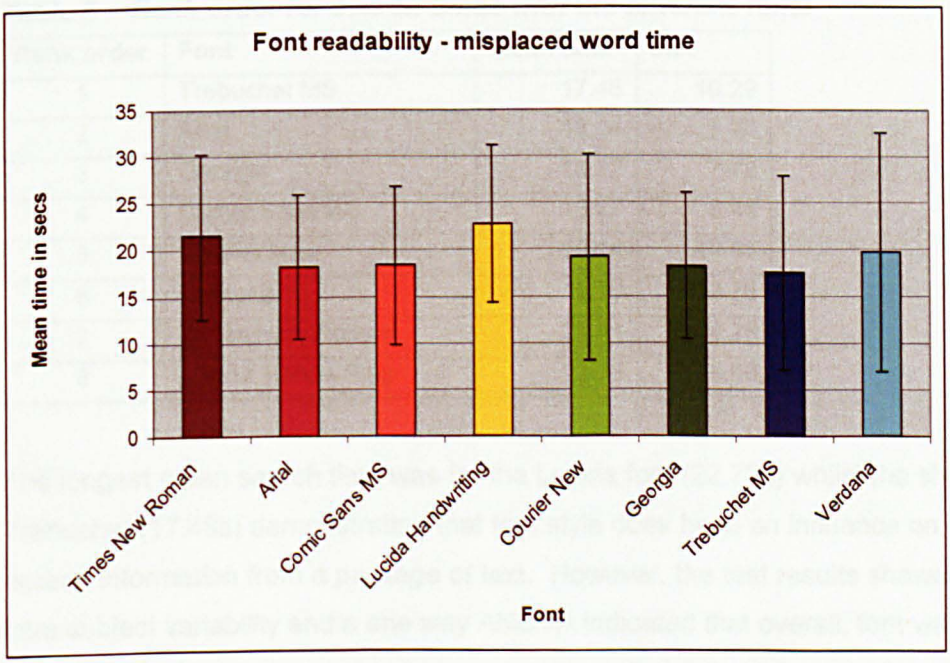
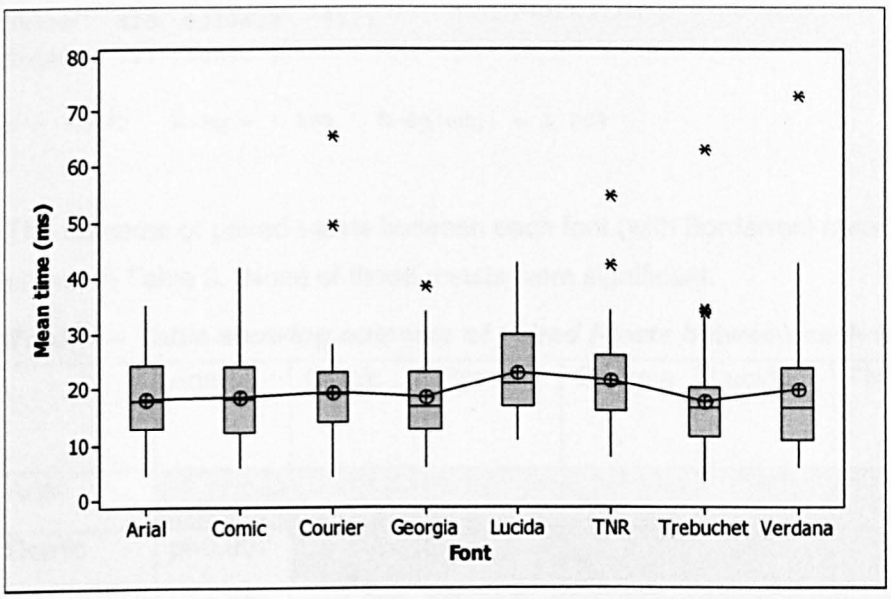


Figure 41 – Boxplot of mean search time for each font. The boxes for each of the fonts represent the central 50% of the data whilst the lines at either end of the boxes

indicate the remainder of the data showing the full range. The horizontal central line in each box marks the median for each font. The asterisk demonstrates any outliers in the data



Re-examination of the outliers indicated that these were mainly attributable to one subject who seemed to have particular difficulties with this task. It is indeed odd that this subject had particular difficulties with certain fonts and it is likely that given the nature of the task, this was a chance observation.

The rank order for the search times is shown below.

Table 8 – Rank order for search times with the different fonts

Rank order	Font	Mean time	s.d.
1	Trebuchet MS	17.48	10.29
2	Arial	18.14	7.70
3	Georgia	18.22	7.72
4	Comic Sans MS	18.27	8.44
5	Courier New	19.15	10.98
6	Verdana	19.70	12.75
7	Times New Roman	21.41	8.76
8	Lucida Handwriting	22.73	8.45

The longest mean search time was for the Lucida font (22.73s) whilst the shortest was for Trebuchet (17.48s) demonstrating that font style does have an influence on the ability to access information from a passage of text. However, the test results showed large inter and intra subject variability and a one way ANOVA indicated that overall, font was not a significant factor.

One-way ANOVA: Mean time (ms) versus Font

```
Source   DF       SS      MS     F      P
Font      7    952.0   136.0  1.49  0.169
Error   320  29138.3    91.1
Total   327  30090.3

S = 9.542   R-Sq = 3.16%   R-Sq(adj) = 1.05%
```

The outcome of paired t-tests between each font (with Bonferroni correction applied) is shown in Table 9. None of these results were significant.

Table 9 – Table showing outcome of paired t-tests between each font

	Arial	Comic	Courier	Georgia	Lucida	TNR	Trebuchet	Verdana
Arial								
Comic	p=0.907							
Courier	p=0.520	p=0.558						
Georgia	p=0.939	p=0.972	p=0.577					
Lucida	p=0.004	p=0.009	p=0.087	p=0.004				
TNR	p=0.014	p=0.038	p=0.228	p=0.008	p=0.375			
Trebuchet	p=0.647	p=0.624	p=0.382	p=0.556	p=0.012	p=0.014		
Verdana	p=0.388	p=0.283	p=0.778	p=0.436	p=0.154	P=0.341	p=0.292	

Sans serif fonts were read marginally quicker than serif fonts although this was not significant (21.9 secs vs' 20.6 secs; p = 0.04, NS).

3.4.11 Experiment 5: MNRead test with different fonts: Methods

For the final experiment in this series, the computer-based MNRead test described in Section 2.2.1 was adapted to give a direct measure of reading speed for each font.

Reading speeds were measured using the modified MNRead as described in Section 2.2.1.

Twenty subjects (M:F = 9:11) with vision or visual acuites of 0.22 logMAR or better and near vision/ visual acuities of N5 and no ocular pathologies participated in this study. The mean age was 41.9 yrs (range 21 – 73yrs).

The MNRead sentences as described in Section 2.2.1 were presented at ten font sizes corresponding to logMAR values of 0.1 to 1.5. Font sizes were presented in ascending and descending order in different trials to balance for order effects.

Due to the number of trials required for this study, the font selection was constrained to Arial, Times New Roman and Tiresias. The first two fonts are probably the most commonly used and are good examples of a serif and sans serif font. Tiresias is a font that has been developed specifically for the visually-impaired and was included in this study to provide control data for the experiments described in Chapter 5.

3.4.12 Experiment 5: MNRead test with different fonts: Results

The mean reading time for all subjects is shown as a function of letter size for all fonts in Figure 42 and as a box plot in Figure 43. This graph shows the familiar change in reading time with font size but no apparent difference between the three fonts. This was confirmed by a two way ANOVA which showed that font size was a significant factor but font style was not and that there was no significant interaction between font size and font style.

Figure 42 – Reading time as a function of font size for three different fonts for all normal subjects

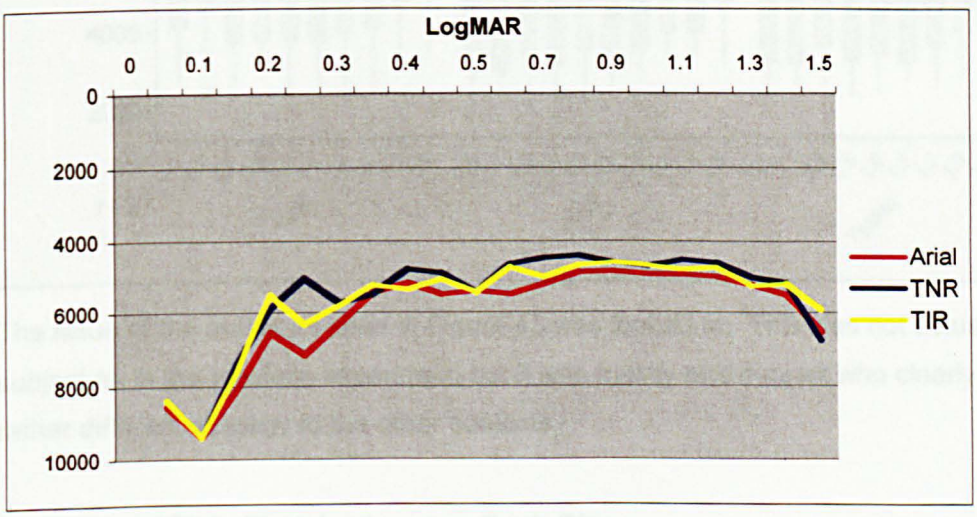
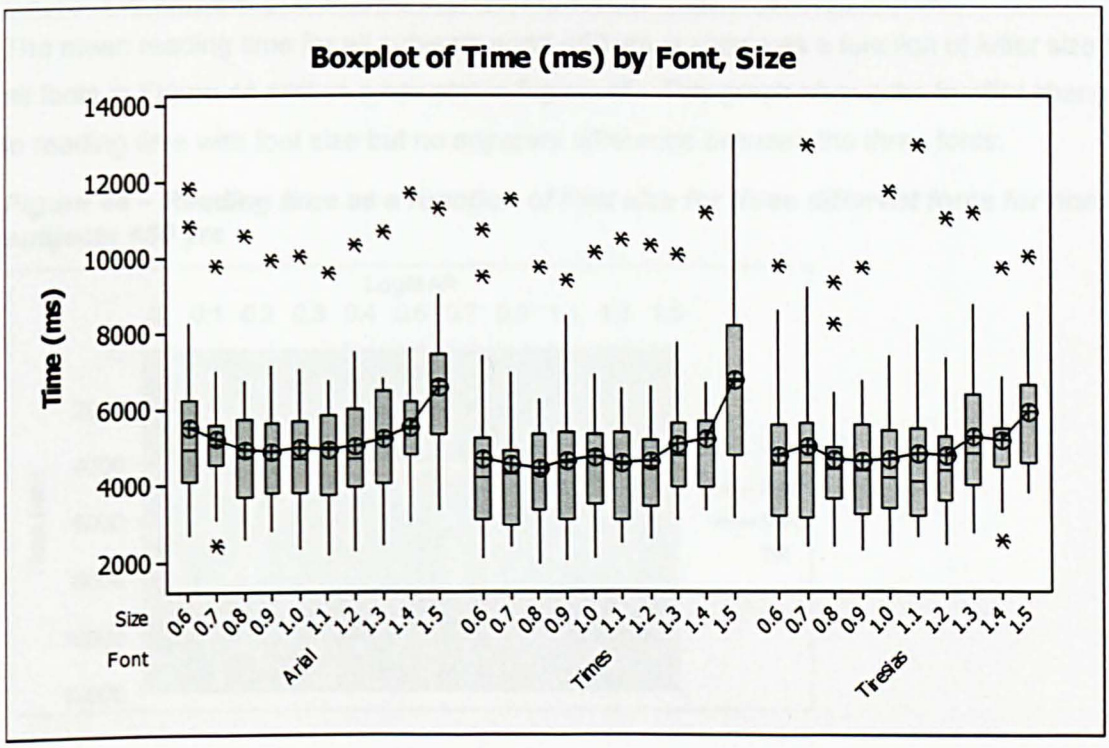


Figure 43 - *Boxplot of mean reading time as a function of font size for three different fonts. The boxes for each of the letter sizes represent the central 50% of the data whilst the lines at either end of the boxes indicate the remainder of the data showing the full range. The horizontal central line in each box marks the median for each letter size. The asterisk demonstrates any outliers in the data*



The issue of the outlier as seen in Figure 43 was looked at. This was not actually the same subject as in the previous experiment but it was mainly one subject who clearly adopted a rather different strategy to the other subjects.

Two-way ANOVA: Time (ms) versus Font, Size

Source	DF	SS	MS	F	P
Font	2	15080187	7540093	2.07	0.128
Size	9	145328052	16147561	4.43	0.000
Interaction	18	16226635	901480	0.25	0.999
Error	570	2079680433	3648562		
Total	599	2256315306			

S = 1910 R-Sq = 7.83% R-Sq(adj) = 3.14%

A closer look at the data suggested that there may be some differences with age. Consequently, a post-hoc analysis sub-divided the subjects into those aged <50 yrs and those aged >=50 yrs. The younger group, therefore, comprised of ten subjects (M:F = 5:5) aged between 21 and 25 years (mean 22.7) with vision or visual acuites of 0.0 logMAR or

better and no ocular pathologies. The older group also consisted of ten subjects, (M:F = 5:5) aged between 51 an 73 years (mean 61.2 years) with vision or visual acuites of 0.22 logMAR or better and no ocular pathologies.

3.4.13 Experiment 5: MNRead test with different fonts: Post-hoc results

The mean reading time for all subjects aged <50 yrs is shown as a function of letter size for all fonts in Figure 44 and as a box plot in Figure 45. This graph shows the familiar change in reading time with font size but no apparent difference between the three fonts.

Figure 44 – Reading time as a function of font size for three different fonts for normal subjects <50 yrs

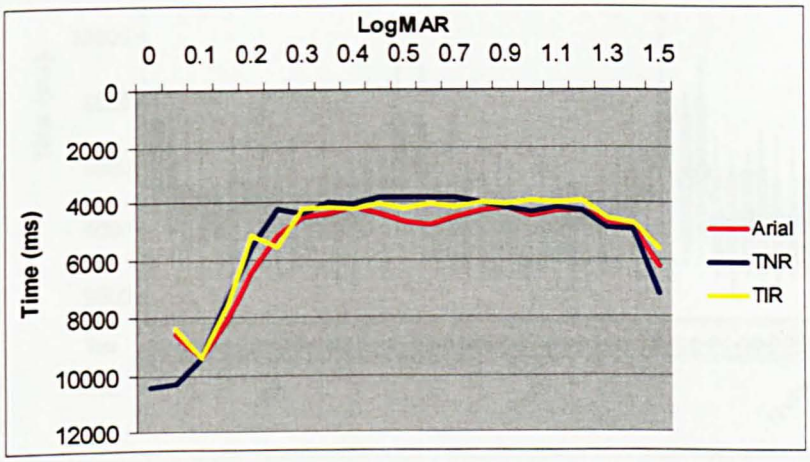
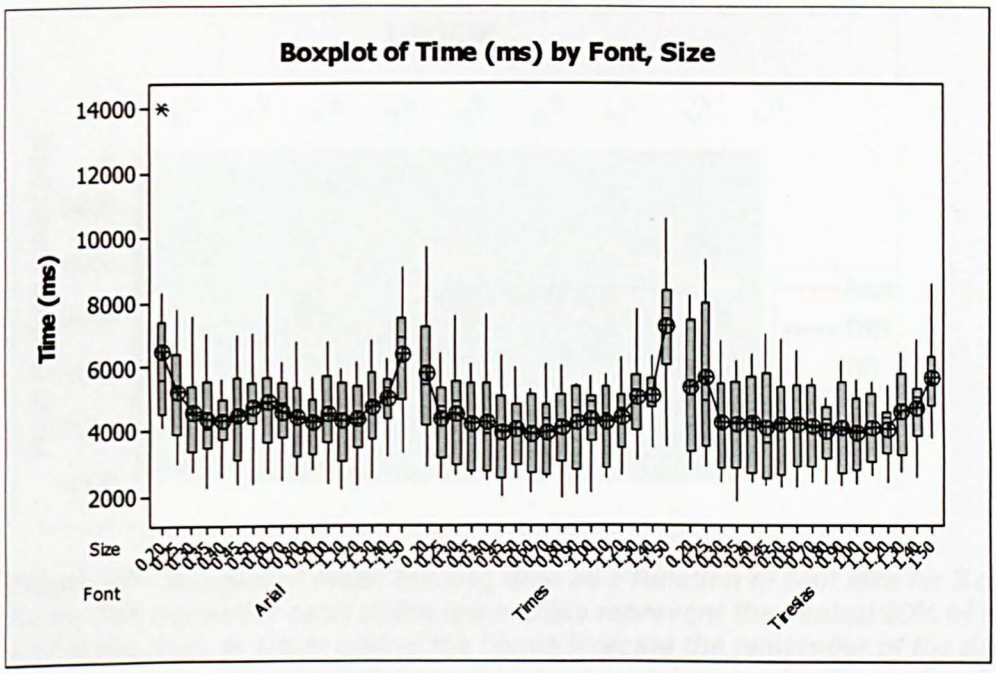


Figure 45 – Boxplot of mean reading time as a function of font size for three different fonts. The boxes for each of the letter sizes represent the central 50% of the data whilst the lines at either end of the boxes indicate the remainder of the data showing the full range. The horizontal central line in each box marks the median for each letter size. The asterisk demonstrates any outliers in the data



This was confirmed by a two way ANOVA which showed that font size was a significant factor but font style was not and that there was no significant interaction between font size and font style.

Two-way ANOVA: Time (ms) versus Font, Size

Source	DF	SS	MS	F	P
Font	2	10109289	5054644	2.40	0.092
Size	16	207581484	12973843	6.17	0.000
Interaction	32	35372925	1105404	0.53	0.986
Error	459	965411687	2103293		
Total	509	1218475385			

S = 1450 R-Sq = 20.77% R-Sq(adj) = 12.14%

The mean reading time for the subjects aged >=50 yrs is shown as a function of letter size for all fonts in Figure 46 and as a box plot in Figure 47. The mean reading times for this group were longer than for the younger group presumably reflecting a combination of poorer

vision and a decline in the speed of cognitive processing. It is also interesting to note that the reading times for the Tiresias was on average shorter for all font sizes than the other two fonts and the optimum reading speed faster.

Figure 46 – Reading speed as a function of font size for 3 fonts for normal subjects >=50 yrs

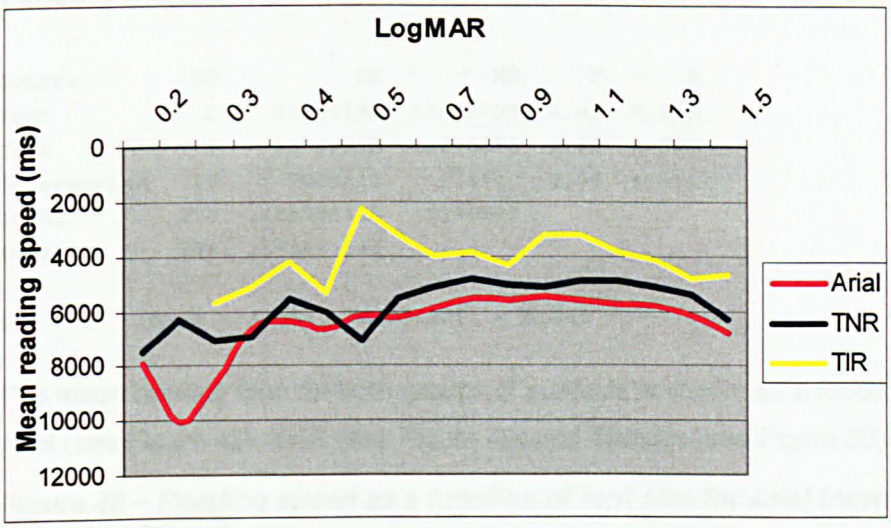
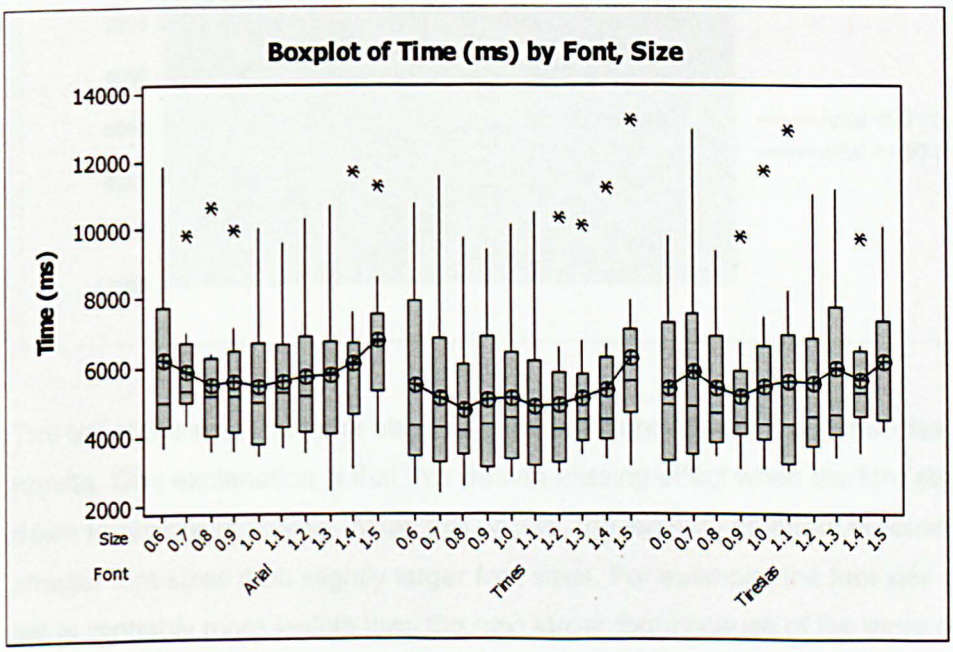


Figure 47 – Boxplot of mean reading time as a function of font size for 3 different fonts. The boxes for each of the letter sizes represent the central 50% of the data whilst the lines at either end of the boxes indicate the remainder of the data showing the full range. The horizontal central line in each box marks the median for each letter size. The asterisk demonstrates any outliers in the data.



Whilst some subjects read as small as 0.05 logMAR (two subjects for Arial, two for TNR and one subject for Tiresias), ANOVA requires equal data sets for analysis and so, the smallest

font that could be read by all subjects for all three fonts was used. This restricted the analysis to between 0.6 and 1.5 logMAR.

With this data set, neither font size nor style were found to be significant factors and there was no significant interaction between them.

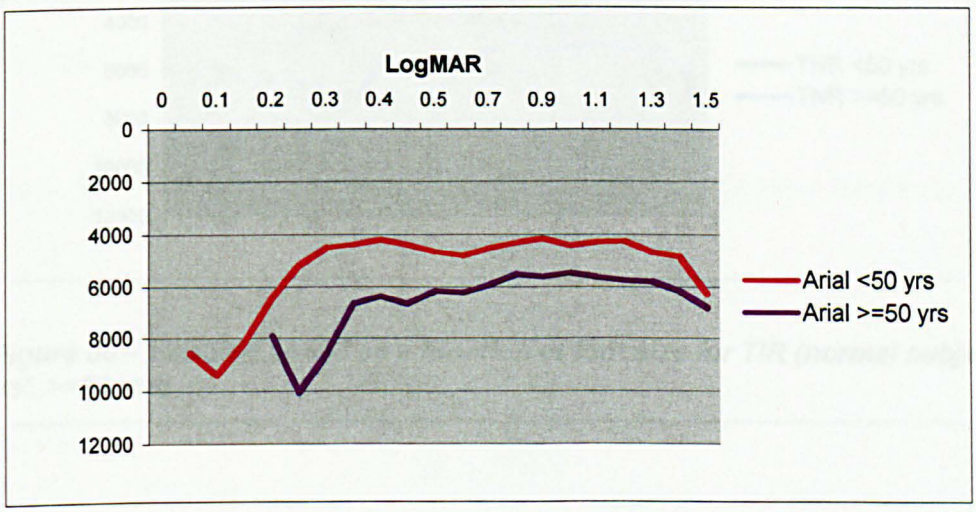
Two-way ANOVA: Time (ms) versus Font, Size

Source	DF	SS	MS	F	P
Font	2	21680198	10840099	2.03	0.133
Size	9	32762512	3640279	0.68	0.725
Interaction	18	7663311	425740	0.08	1.000
Error	270	1440935125	5336797		
Total	299	1503041146			

S = 2310 R-Sq = 4.13% R-Sq(adj) = 0.00%

The mean reading time for both groups of subjects is shown as a function of letter size for Arial (see Figure 48), TNR (see Figure 49) and Tiresias (see Figure 50).

Figure 48 – Reading speed as a function of font size for Arial (normal subjects: <50 yrs vs' >=50 yrs)



The tail at the smallest letter sizes as seen in Figure 48 was a common feature of the results. One explanation is that this was an aliasing effect when the font size started to get down to ten pixels or less. When this occurs, the legibility of letters is sometimes better at smaller font sizes than slightly larger font sizes. For example, the font size second from the left is probably more legible than the next larger font because of the more even distribution of its components.

However, the same phenomenon is seen on some occasions even when the font size is much larger and beyond the size where aliasing is likely to be a factor.

An alternative explanation is that this is an artefact which occurs when the data for a number of subjects is averaged. Those with slightly poorer acuity are unable to see the smallest letters and are, therefore, excluded from the mean. Therefore, the first point often includes data for only those subjects with better acuity who may also be slightly faster readers for a given font size.

Figure 49 – Reading speed as a function of font size for TNR (normal subjects: <50 yrs vs' >=50 yrs)

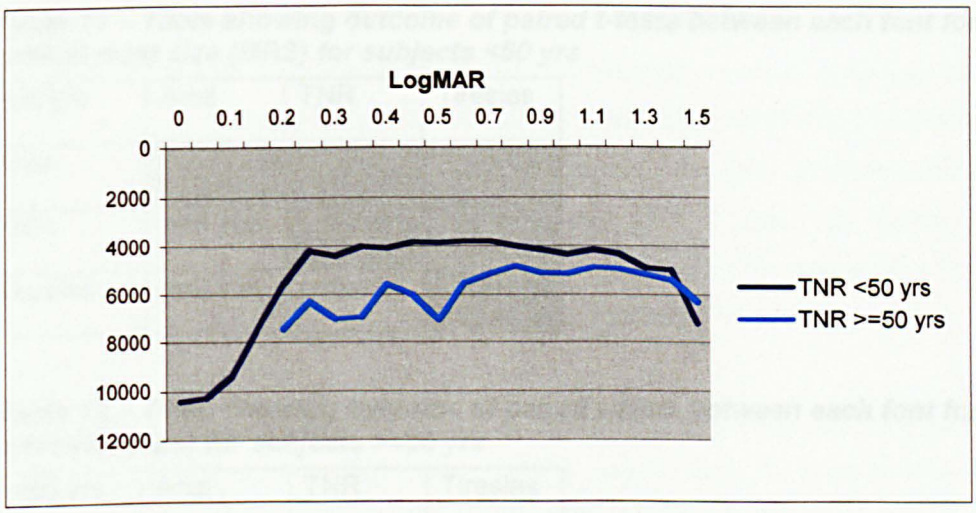
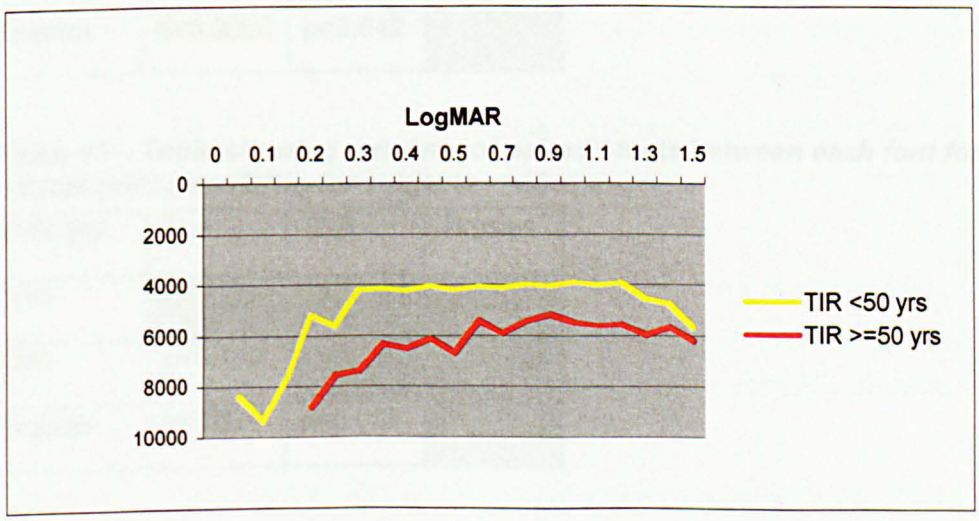


Figure 50 – Reading speed as a function of font size for TIR (normal subjects: <50 yrs vs' >=50 yrs)



The outcome of paired t-tests between each font for critical print size and the mean critical print size (MRS) is shown in Tables 10 – 13. There was a significant difference in critical print size for the older subjects with Arial having a cps of 0.44 and Tiresias having a cps of 0.37 (p=0.0005).

Table 10 – Table showing outcome of paired t-tests between each font for critical print size (cps) for subjects <50 yrs

<50 yrs	Arial	TNR	Tiresias
Arial			
TNR	p=0.032		
Tiresias	p=0.604	p=0.044	

Table 11 – Table showing outcome of paired t-tests between each font for the mean critical print size (MRS) for subjects <50 yrs

<50 yrs	Arial	TNR	Tiresias
Arial			
TNR	p=0.703		
Tiresias	p=0.134	p=0.424	

Table 12 – Table showing outcome of paired t-tests between each font for critical print size (cps) for subjects >=50 yrs

>=50 yrs	Arial	TNR	Tiresias
Arial			
TNR	p=0.024		
Tiresias	p=0.0005	p=0.642	

Table 13 – Table showing outcome of paired t-tests between each font for the mean critical print size (MRS) for subjects >=50 yrs

>=50 yrs	Arial	TNR	Tiresias
Arial			
TNR	p=0.102		
Tiresias	p=0.676	p=0.058	

3.5 The legibility, readability and visual efficiency of fonts: Conclusions

Reading is a complex task and fonts are complex visual stimuli. It is not surprising, therefore, that determining the optimum font for reading from computer displays is not straightforward. A number of approaches have been adopted in the experiments described in this chapter in order to gain some insight into the factors that might determine the acceptability and efficiency of different fonts.

In the first experiment, subjects viewed eight passages of text in different fonts displayed simultaneously on the screen and were simply asked to rank them in terms of how easy they were to read. The rank order was Verdana, Trebuchet, Comic Sans, Arial, Georgia, Courier New, Times New Roman with Lucida Handwriting judged to be the least readable. Overall, the sans serif fonts were judged to be significantly more readable than the serif fonts (sans serif = 2.95 vs' serif = 6.03; $p < 0.001$).

Subjects found this ranking procedure rather difficult so the experiment was redesigned so that fonts were presented in pairs and each font was compared with every other font. A score was calculated on the basis of the number of times each font was preferred in the paired comparison. The rank order was Verdana, Arial, Courier New, Times New Roman, Trebuchet, Comic Sans, Georgia with Lucida Handwriting judged to be the most difficult to read. Overall, sans serif fonts were rated as significantly 'easier to read' than their serif counterparts ($p < 0.001$).

In the course of this experiment, a number of subjects remarked that they found some of the fonts aesthetically pleasing but not necessarily easy to read. In order to differentiate between perceived "attractiveness" and "legibility / readability", a third experiment was carried out where subjects had to simply rate "attractiveness" and "readability" of each font using a five point Likert scale. The rank order for attractiveness was Comic Sans, Trebuchet, Verdana, Lucida, Arial, Georgia, Times New Roman with Courier being ranked as the least attractive. The rank order for readability was Verdana, Arial, Courier New, Times New Roman, Trebuchet, Comic Sans, Georgia with Lucida Handwriting judged to be the most difficult to read. Overall, sans serif fonts were rated as significantly 'easier to read' than their serif counterparts ($p < 0.001$).

It is interesting to note that the rank order for "attractiveness" is quite different to the rank order for "legibility". In particular, Courier New was rated as the least attractive but very legible. Conversely, Lucida Handwriting was judged to be attractive but was rated as the least readable.

A second series of experiments was designed in a bid to measure the accuracy and speed of reading with different fonts. In the first experiment in this series, subjects were required

to search for specific words within a passage of text. This was, therefore, a test of reading speed and accuracy. Although individual differences between fonts were apparent, overall, font style was not found to be a significant factor in performing this task.

In the final experiment in this section, reading speed for each three fonts was measured using a modified MNRead test. Reading speed was found to vary in the characteristic manner with font size, but overall, font style was not found to be a significant factor in determining reading speed. The outcome of paired t-tests between each font for critical print size and the mean critical print size (MRS) is shown in Tables 10 – 13. There was a significant difference in critical print size for the older subjects with Arial having a cps of 0.44 and Tiresias having a cps of 0.37 ($p=0.0005$).

It can be seen in Figures 43 and 47, that there is an outlier in the data. Examination of the data revealed that this was the same participant in all cases.

We may conclude the following:

- Fonts that are aesthetically pleasing are not necessarily the most readable.
- Sans serif fonts are generally perceived to be the most readable.
- Whilst there are surprisingly large individual differences in reading speed and accuracy with different fonts, overall there are no significant differences in these metrics for the eight fonts tested.

3.6 The effect of character spacing on reading speed

Chung (2002) investigated the effect of character / word spacing on reading speed and accuracy. He looked at central and peripheral vision using the rapid serial visual presentation (RSVP) method. The RSVP shows words singly one after another to give a final sentence. The results showed that reading speed increased from zero spacing up to a critical spacing. The critical spacing was found to be close to standard character spacing after which no further increase in maximum reading speed was elicited.

Chien-Hsiung and Yo-Hung (2005) showed that Chinese typography and font size did not impact upon reading comprehension. Perhaps unsurprisingly, they found that comprehension was affected by speed of presentation; the faster the presentation, the lower the comprehension.

Epelboim et al (1997) looked at the effects of removing spacing on reading speed. They found it slowed reading by between 10-20%.

It can be argued that the RSVP method employed by Chung (2002) was rather different to normal reading. To investigate the effects of character spacing on a more normal reading task, the following experiment was conducted.

3.6.1 Methods

A font editor program, "Font Creator", was used to modify the Arial font so that characters had the following spacing:

- Level 1 = no spacing
- Level 2 = half the normal spacing
- Level 3 = normal spacing
- Level 4 = 1.5 times the normal spacing
- Level 5 = twice the normal spacing

Using the same display screen and set up as described above in section 2.2.2.1, the same ten normal subjects (see Section 2.3.1) were required to read randomized sentences of the modified MNRead at the five different character spacings at a viewing distance of 40cm. Subjects had a practice trial to minimise learning effects.

The character spacings and order of presentation (i.e. whether the font started large (1.5 logMAR) and decreased in size or whether it started small (0.0 logMAR) and increased), were randomised for each subject using a random number generator (www.random.org) to ensure that there were no order effects. The sentences from the modified MNRead were also generated randomly by the computer. This ensured that all subjects performed the test in different sequences to each other and consequently, balanced out for any learning

effects. In keeping with the original MNRead, any incompletely read sentences were discarded.

Subjects were required to click on the '*start*' button at the bottom of the screen. This automatically started a software timer as well as bringing up the pair of randomised sentences. Subjects were required to read every word in every sentence and stop the clock by clicking the '*stop*' button at the bottom of the screen.

3.6.2 Results

The mean reading time for the ten subjects is shown as a function of font size for text incorporating the five different character spacings in Figure 51 and as a boxplot in Figure 52.

Figure 51 - Graph showing reading time as a function of font size for text incorporating the 5 character spacings.

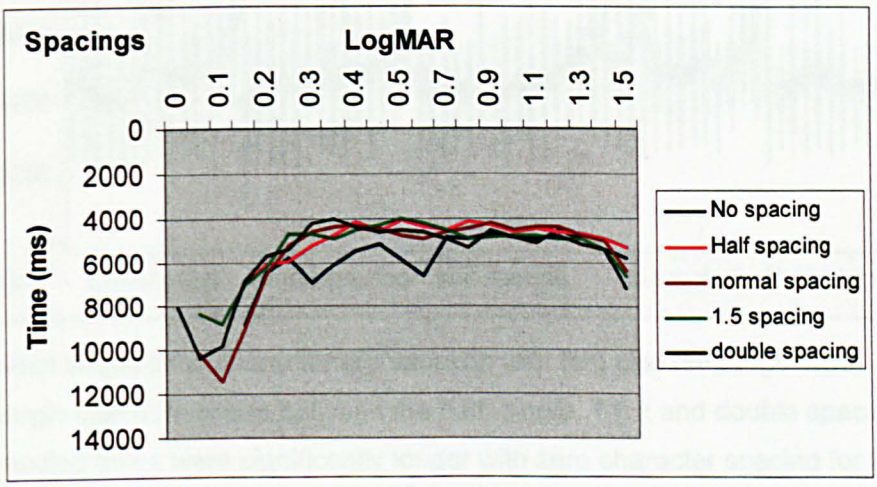
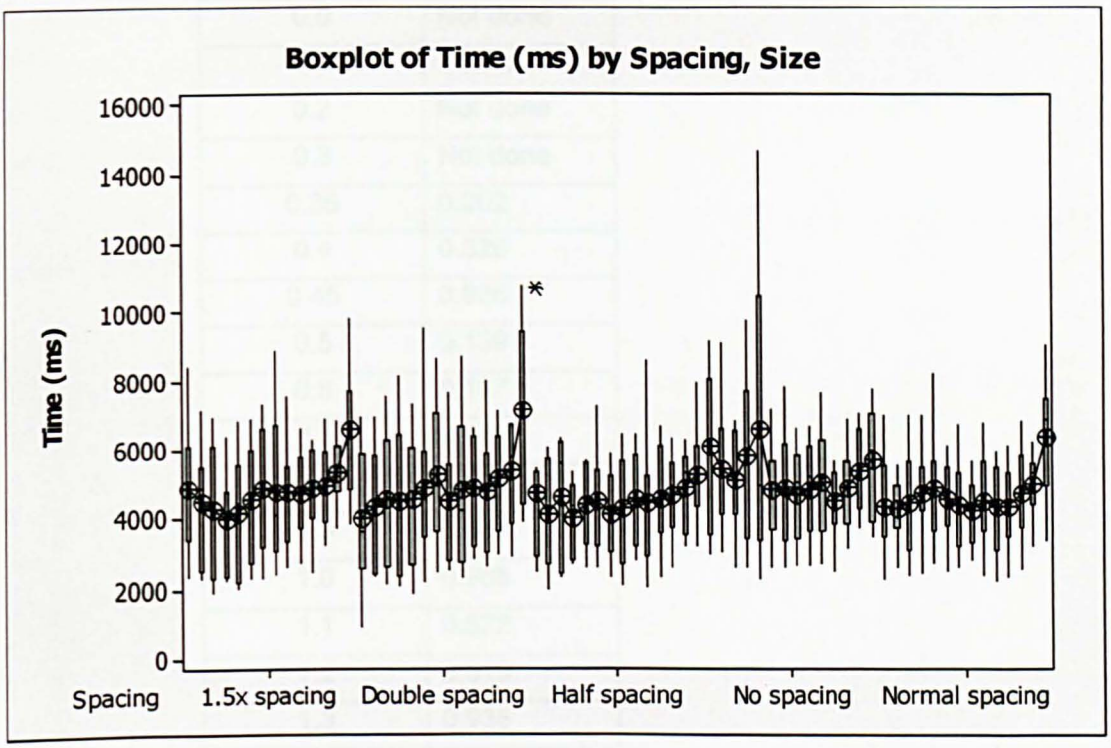


Figure 52 – Boxplot of reading time (ms) as a function of font size for 5 different character spacings. The boxes for each of the letter sizes represent the central 50% of the data whilst the lines at either end of the boxes indicate the remainder of the data showing the full range. The horizontal central line in each box marks the median for each letter size. The asterisk demonstrates any outliers in the data.



Reading speed showed the characteristic variation with font size (see Figure 52). There was surprisingly little differences between the half, single, 1.5 x and double spacing. However, reading times were significantly longer with zero character spacing for the intermediate font sizes.

A two way ANOVA demonstrated that overall, font size and character spacing were both significant factors but there was no significant interaction between them.

Two-way ANOVA: Time (ms) versus Spacing, Size

Source	DF	SS	MS	F	P
Spacing	4	45858890	11464723	4.14	0.003
Size	13	125134695	9625746	3.47	0.000
Interaction	52	95695763	1840303	0.66	0.967
Error	630	1745700172	2770953		
Total	699	2012389520			

S = 1665 R-Sq = 13.25% R-Sq(adj) = 3.75%

The results of a one way ANOVA for each font size are shown in Table 14.

Table 14 – Table showing results for one way ANOVA for each font size

LogMAR	P value
0.0	Not done
0.1	Not done
0.2	Not done
0.3	Not done
0.35	0.202
0.4	0.326
0.45	0.866
0.5	0.139
0.6	0.147
0.7	0.979
0.8	0.592
0.9	0.922
1.0	0.985
1.1	0.822
1.2	0.919
1.3	0.935
1.4	0.804
1.5	0.181

3.6.3 Conclusions

At sizes greater than 1.0 logMAR, subjects read slower with 'no spaces'. Presumably this reflected the fact that words took up the whole screen and, in order to maintain meaning, subjects needed to scan the words and decide where each one finished.

3.7 The effects of anti-aliasing

A computer screen consists of a two dimensional array of pixels. Images are displayed on the screen by varying the luminance of the pixels. Under most circumstances, the pixels are too small to be resolved and the observer perceives patterns constructed from a group of pixels.

The pixels are arranged in a grid and, therefore, if a row or a column of pixels is turned on, a "perfect" horizontal or vertical line is perceived.

However, if a diagonal line is presented, some "staircasing" of the line may be apparent as shown in Figure 53.

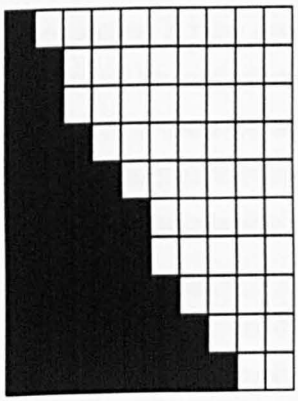
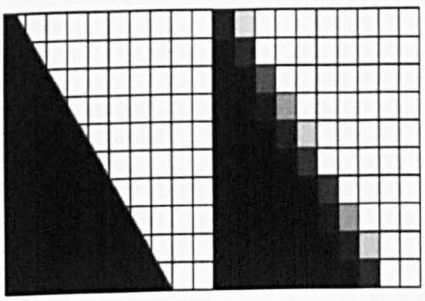


Figure 53 – *A diagonal line presented on an array of pixels causes aliasing and staircasing becomes apparent.*

To overcome this, a technique known as anti-aliasing may be employed (Dillon et al., 1988). A number of algorithms have been devised to achieve this but in essence they work like this. The diagonal line is drawn across the pixel array as shown in Figure 54) and the area of each pixel that is covered by the line is calculated. A grey level is then assigned to the pixel which relates to the area covered. For example, if the diagonal line bisected a pixel, that pixel would be assigned a 50% grey level. The result is shown in Figure 55.

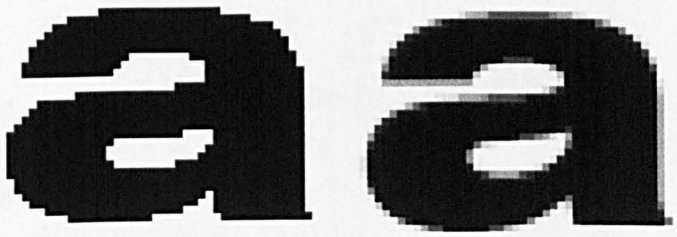
Figure 54 ***Figure 55***



When the anti-aliased line is viewed from a distance, the pixels are "fused" and the observer perceives a smooth line without staircasing.

Most alphanumeric characters contain diagonals and curves and, therefore, anti-aliasing can greatly improve the perceived legibility of the characters. Figure 56 shows a character with and without anti-aliasing applied.

Figure 56 – With and without anti-aliasing



Anti-aliasing is now used on most computer systems. Microsoft Windows contains two algorithms for anti-aliasing text: Standard and Cleartype. Whilst there is no doubt that anti-aliasing improves the appearance of text displayed on a computer display, no studies have been conducted to measure the effect of anti-aliasing on reading speed or to investigate the effects of antii-aliasing at different font sizes.

3.7.1 Methods

The experimental conditions were identical to those described in Section 2.2.2.1. The MNRead test was modified to display the sentences using text that was a) not anti-aliased, b) anti-aliased using Window Standard algorithm and c) anti-aliased using the Microsoft Cleartype algorithm.

Four subjects (M:F = 1:3) with a mean age of 26.8yrs (18 – 41yrs) acted as subjects for this experiment.

3.7.2 Results

The mean reading time for the four subjects is shown as a function of font size for text incorporating the five different character spacings in Figure 57 and as a boxplot in Figure 58.

Figure 57 – Graph showing reading time as a function of font size for the three anti-aliasing conditions.

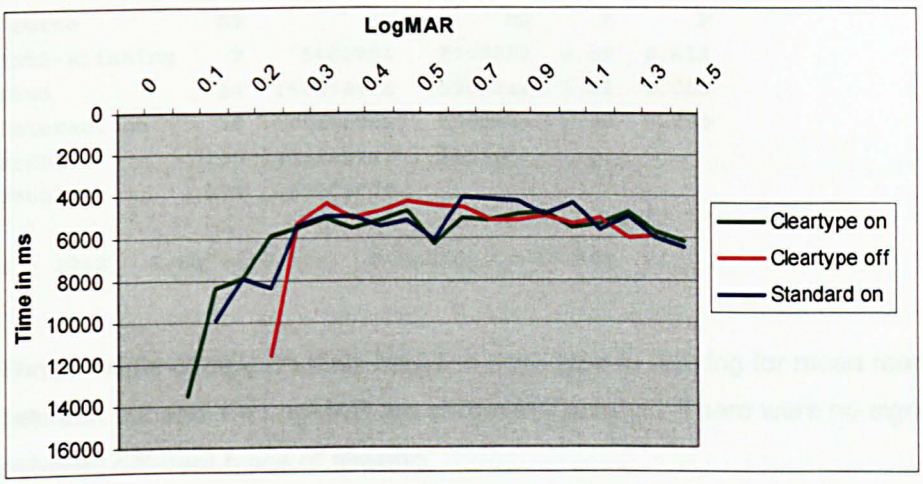
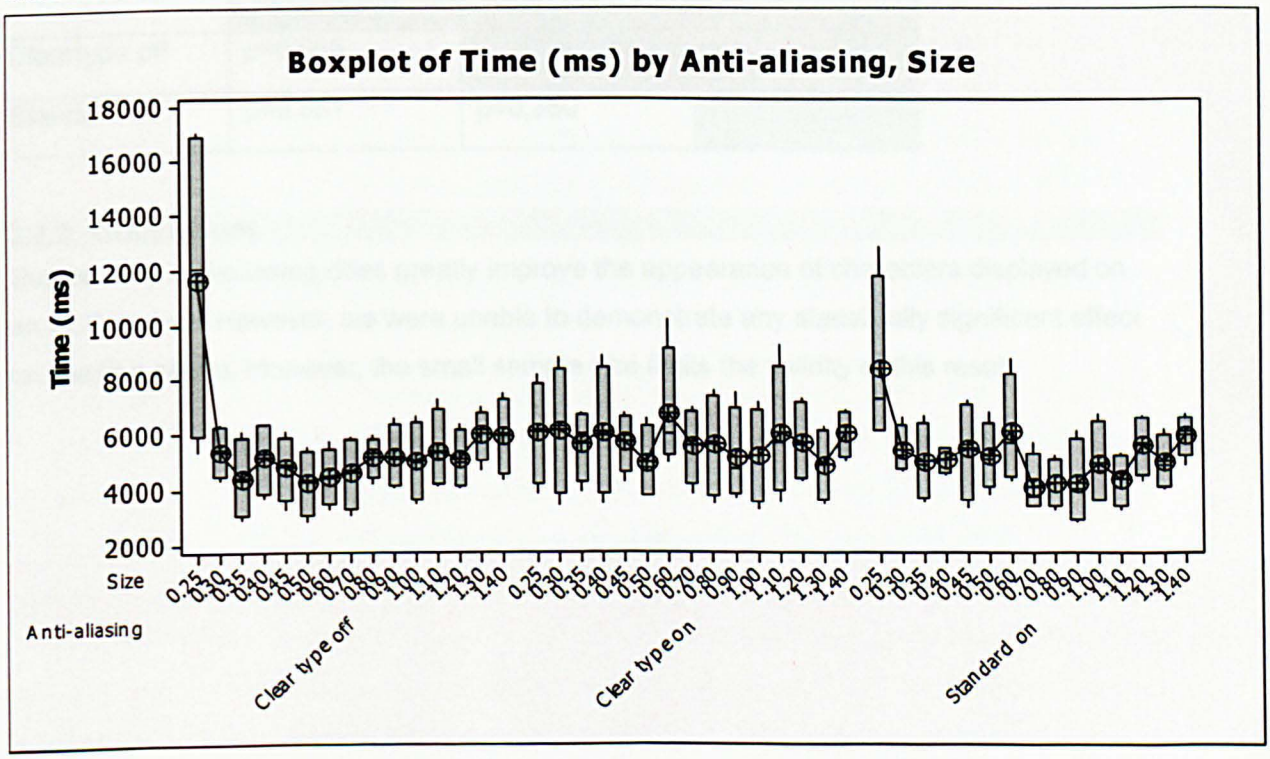


Figure 58 – The boxes for each of the letter sizes represent the central 50% of the data whilst the lines at either end of the boxes indicate the remainder of the data showing the full range. The horizontal central line in each box marks the median for each letter size. The asterisk demonstrates any outliers in the data.



A two way ANOVA demonstrated that overall, font size was a significant factor but the presence of anti-aliasing was not and there was no significant interaction between them.

Two-way ANOVA: Time (ms) versus Anti-aliasing, Size

Source	DF	SS	MS	F	P
Anti-aliasing	2	5400004	2700002	0.89	0.413
Size	14	153538614	10967044	3.61	0.000
Interaction	28	100466908	3588104	1.18	0.260
Error	135	409802243	3035572		
Total	179	669207770			

S = 1742 R-Sq = 38.76% R-Sq(adj) = 18.80%

The outcome of paired t-tests between each type of aliasing for mean reading speed between 0.2 and 1.4 LogMAR are shown in Table 15. There were no significant differences between different types of aliasing.

Table 15 – Table showing outcome of paired t-tests between each type of aliasing for mean reading speed

	Cleartype on	Cleartype off	Standard on
Cleartype on			
Cleartype off	p=0.565		
Standard on	p=0.851	p=0.350	

3.7.3 Conclusions

Subjectively anti-aliasing does greatly improve the appearance of characters displayed on an LCD screen. However, we were unable to demonstrate any statistically significant effect on reading speed. However, the small sample size limits the validity of this result.

4. Optimisation of screen colour: normal subjects

4.1 Introduction

One aspect of the design of the computer user interface that has received surprisingly little attention is the use of colour. The introduction of colour displays has given software engineers enormous scope for using colour coding to enhance the user interface and it is relatively straightforward for users to change their screen colours. However, despite this, the vast majority of computer users tend to retain the normal black on white default for text displays.

There is now good evidence that a significant proportion of the population read printed documents faster when the background colour is other than white (Evans & Joseph, 2002; Wilkins, 2002; Wilkins et al., 2001, Wilkins et al, 1994). Wilkins et al. (2001) reported that 5% of their sample of school children read more than 25% faster when using a coloured overlay in front of the text. Evans & Joseph (2002) found a similar result amongst adults, with 38% of their sample reading more than 5% faster with a coloured overlay. The chromaticity at which reading speed is maximal differs from one individual to another and can be quite specific (Wilkins, 2002). The effects of colour can in certain individuals be surprisingly large; sometimes individuals read more than three times as fast when the background is coloured (Wilkins et al., 2001). This research has carefully controlled for the effects of demand characteristics and placebo effects (Wilkins et al., 2001; Wilkins et al., 1994).

For printed text, colour can be introduced by either placing coloured filters directly over the text (overlays), wearing tinted spectacle lenses or reading under coloured light. There are a variety of testing systems and protocols for determining the optimum colour of overlays and tinted spectacles which are now widely used by optometrists, teachers and other professionals working in this area. It has been established that the colour which is optimal for use in overlays differs from that which is optimal for spectacles (Lightstone, Lightstone & Wilkins, 1999). The reasons for the difference are poorly understood, but may relate to the fact that overlays provide a surface colour, (i.e. the eyes are adapted to white light), whereas coloured lenses have effects similar to those of colouring the light, (i.e. the eyes are adapted to coloured light).

The techniques for assessment of the optimal colour differ in these two contexts. When coloured overlays are assessed and the eyes are adapted to the colour of ambient lighting, two coloured filters can be compared side-by-side (i.e. simultaneous presentation). This is a

simple technique that places no demands on memory. When coloured spectacles are worn the eyes are adapted to coloured light, and the tint prescription must be assessed while the state of colour adaptation is maintained. Small changes of colour are compared one after the other (i.e. successive presentation); a relatively complex procedure requiring memory.

To date, there have been no equivalent studies to investigate if a similar benefit can be obtained by changing the colours displayed on computer screens. If, as seems likely, a similar benefit can be demonstrated, significant improvement in the speed of reading, comprehension and overall productivity may be achievable by simply optimising the screen colours for each user.

Modern computer screens are capable of displaying millions of different colours and shades and, therefore, provide great scope for accommodating individual colour preferences. Furthermore, computer screens offer the possibility of varying the foreground (text) colour as well as the background. One of the aims of this project is to quantify the potential benefits of customising screen colours in terms of reading speed, task efficiency and user comfort in a normal sample of computer users. It will also determine the proportion of computer users who are likely to gain a significant benefit.

Efficient algorithms have been developed to determine the optimum chromaticity of coloured overlays and tinted spectacle lenses and these algorithms will be adapted and developed to guide computer users in the choice of the appropriate chromaticity in such a way that the optimum is rapidly and reliably selected. There are many ways in which colour can be used - as foreground, as background, to highlight etc., and these ways are likely to interact. As a result, it is quite possible that, unless guided, a user may select colour parameters that reflect local optima, but are more generally sub-optimal.

The difference in optimal colours for overlays and lenses is of importance with respect to the selection of optimal colours on a computer screen. Such a screen is usually self-luminous and, depending on surround lighting, may resemble a coloured surface or a coloured light source. Consequently, the optimum colour is likely to vary with the brightness of the screen in relation to that of the surround. The optimal methods of selection are also likely to vary: simultaneous presentation in the case of 'surface colour' and successive presentation, allowing for adaptation, in the case of 'source colour'.

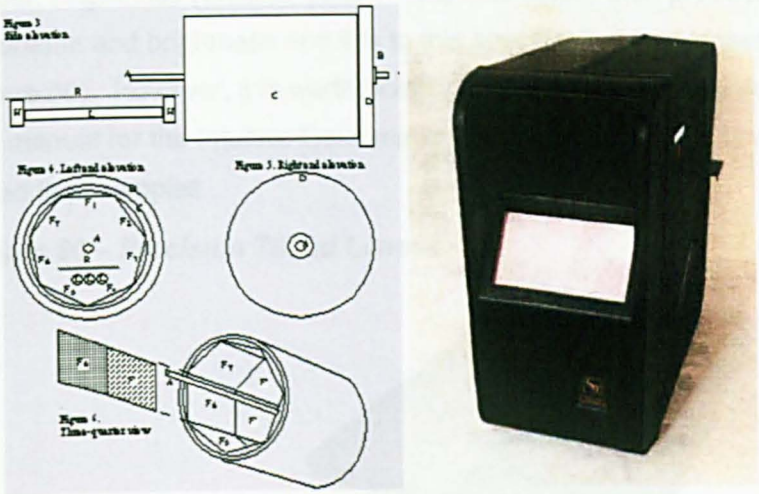
The above issues have been expressed in relation to background colour. In addition, there is a need for experimental studies of the effects of different foreground colours in individuals who show a strong preference for background colour. It is possible that on coloured backgrounds, the optimal foreground colours differ in ways that can be predicted. It is already known that when foreground and background colours have the same luminance,

reading becomes difficult (De Weert et al., 1999) and stereopsis is affected (Simmons & Kingdom, 1995).

4.1.1 Colorimetry

As described in Chapter 1, colour is dependent upon three variables: hue (colour), saturation (strength of the colour) and brightness (relative luminance). Wilkins (2002) and Wilkins, Nimmo-Smith and Jansons (1992) devised a method of controlling these three individual variables with the Intuitive Colorimeter (see Figure 59). This invention was designed along the principals of the Burnham colorimeter and allowed each of the three dimensions of colour to be altered separately, i.e. hue can be varied whilst saturation and brightness are held constant (Wilkins, 2002; Wilkins, Nimmo-Smith, & Jansons, 1992).

Figure 59 – The Intuitive Colorimeter Mark II

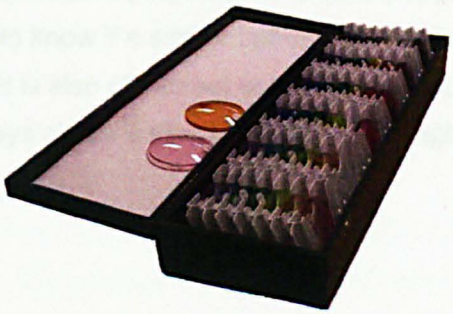


The principal behind the Intuitive Colorimeter is that a transparent disc is sub-divided into seven sections so that each individual sector is then covered with a different filter thereby transmitting a different wavelength of light, i.e. one sector would appear blue thus transmitting a short wavelength, the second sector is green (i.e. intermediate wavelength) and the third, red (i.e. long wavelength). By mixing different amounts of light through this central, transparent disc, different colours are produced.

Subjects are seated in a darkened room thus ensuring that they are dark-adapted. Their head is placed on a chin rest to ensure a constant viewing angle and a passage of text (Rate of Reading test) is viewed through an aperture under different coloured lighting. Subjects systematically view text against twelve different hue angles without an associated change in the saturation and the brightness. The subject initially views the text against a white background (lit by flicker free, white fluorescent lighting) and is asked to describe any distortions experienced. This is then compared against a rose background and the subject

is required to make a subjective assessment on comfort and clarity of text. This process is repeated for the twelve different 'hues'. If at the end, one or more colours are reported as beneficial, these colours are then all investigated further by asking the subject to alter the saturation of that particular hue until the text is at its most comfortable. This process may be applicable for several different hues and the outcome is that these hues are then presented in pairs of forced choice presentation with the subject having to select their optimum colour. One of the obvious disadvantages of this system is that if two colours are not next to each other in the hue circle, then they are not being directly compared as the operator has to rotate the disc through other colours. This involves memory also being included in the process. The final stage in the selection of an optimum tint, is to verify the need for a neutral density filter and this is achieved by adjusting the final dimension of colour; brightness (Wilkins, 2002). This final colour then produces co-ordinates for hue, saturation and brightness and it is to this specification that lenses are now matched (see Figure 60). However, it is worth pointing out that before any tinted spectacles are made up, the manual for the Intuitive Colorimeter advises checking the final colour first using precision tinted lens samples.

Figure 60 – Precision Tinted Lenses



Wilkins asserts that subjects adapt quickly to the surface colour within the colorimeter and consequently, are oblivious to the exact colour chosen. Furthermore, Wilkins claims that due to this adaptation theory, subjects are unable to differentiate between their optimum colour as determined by the colorimeter and a control colour, (i.e. one that is slightly different). This inability to distinguish between colours has been used for double-masked placebo-controlled tests examining the effects of coloured lenses. In these trials, the control colour is matched closely to the optimum colour in terms of hue, saturation and brightness with the defining difference being that the control colour does not reduce symptoms of visual stress.

Wilkins' research with the Intuitive Colorimeter suggests that 82% of subjects suffering from symptoms of visual discomfort benefited from tinted lenses and were still using them almost one year later (Wilkins, 2002). This supports Meares' earlier claims that certain people do

experience distortions in text whilst reading and Irlen's claims that these distortions can be alleviated by colour.

4.1.2 Colour on display screens

Before the advent of colour displays, a number of studies investigated the optimum colour for monochrome displays. Many monochrome displays used green phosphors (mainly on the basis that green is at the peak of the $V\lambda$ function). Because of the chromatic aberration of the eye, the amount of accommodation required to focus on a screen will depend to some extent on the colour - marginally less accommodation being required for blue/ green than red. The difference is small and probably not a major consideration (Neary, 1989).

Studies which have investigated the use of colour on displays have tended to explore the possibility that one colour combination (text and background) may be optimum for all users rather than testing the hypothesis that the optimum colours may be idiosyncratic and vary between individuals (Lightstone et al., 1999). Despite the huge gamut of colours available to users of modern computers, few adopt screen colours other than the default black on white. This may be due to the complexity of achieving this or simply because of the familiarity of the black on white format.

As colour seems to be of benefit to a proportion of the normal population when reading printed text, it is of interest to know if a similar benefit can be demonstrated by customising computer display colours. It is also of interest to know if individuals with visual stress who already use coloured overlays obtain a similar benefit by changing the background colour of a computer display.

4.2 The effect of screen colour on user performance – validation data

4.2.1 Validation of performance tests

The aims of this study were to investigate the effects of customising the background colour of computer displays on the symptomatology and task efficiency of a sample of normal computer users and a sample of individuals who suffer from symptoms of visual stress.

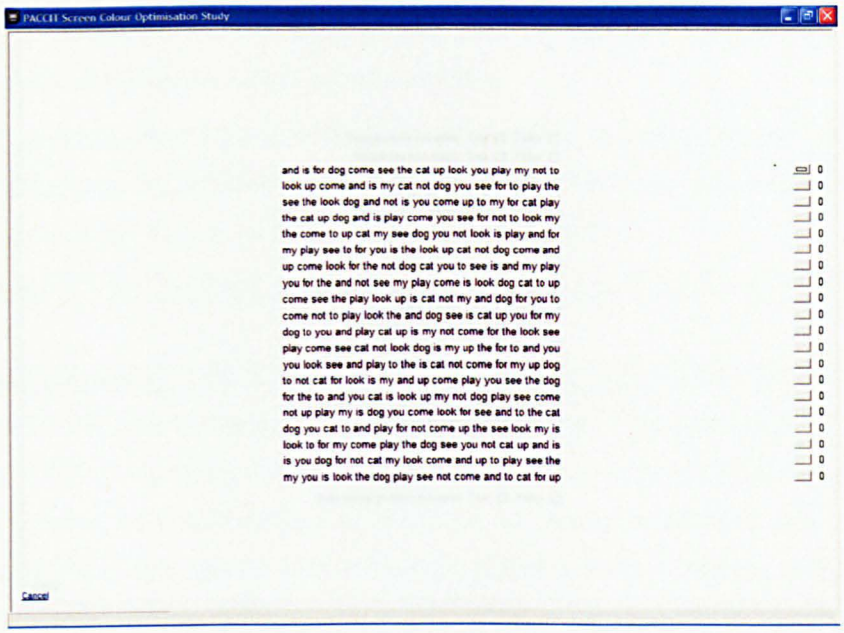
The first stage in testing this hypothesis was to develop a series of visual performance tests that would be a realistic simulation of the tasks carried out by a typical computer user. After careful consideration, it was decided that the main tasks carried out by most computer users are wordprocessing, data entry/ spreadsheets and use of the internet. On this basis, three task performance tests were developed for the study. These were designed to simulate tasks commonly carried out by computer users and thereby quantify any change in performance resulting from the optimisation of screen colour.

4.2.1.1 The Rate of Reading test

This test was based on the Rate of Reading test developed by Wilkins et al. (1996). The conventional test consists of a paragraph of printed text comprising ten lines. Each line has the same fifteen commonly used monosyllabic words in random order. The participant is required to read the words out loud as quickly and accurately as possible whilst the examiner records the number of errors. The time required to complete the paragraph or the number of words read within one minute is used to calculate the rate of reading in words/ minute. This test has been shown to be sensitive to changes in reading performance brought about by the use of colour (Wilkins, 2002).

In the computer adaptation (see Figure 61), the examiner clicked a button to keep a tally of errors and a button to record the completion of each row of text. The rate of reading was calculated automatically.

Figure 61 – Screenshot of the computerised Rate of Reading test

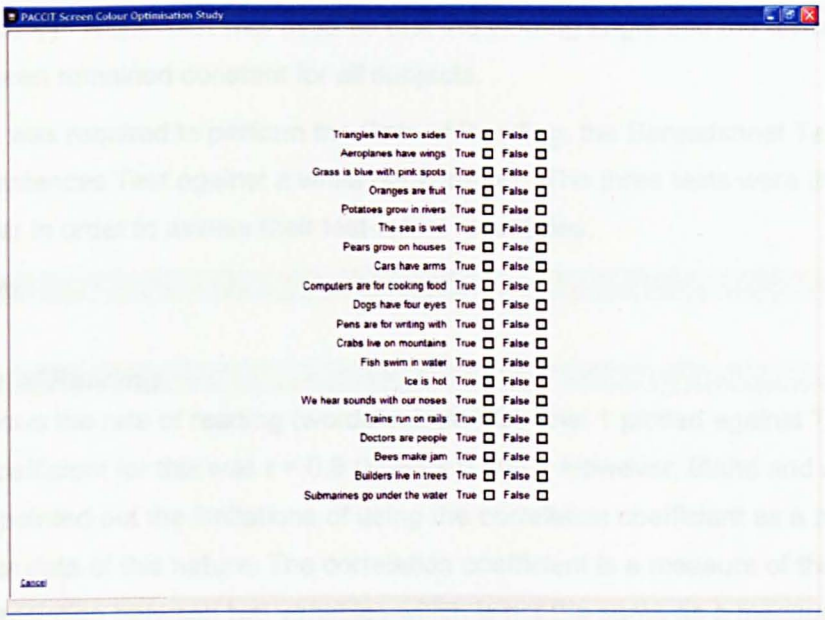


4.2.1.2 Nonsense Sentences Test

This task was based on a test developed by Baddeley, Emslie and Nimmo-Smith (1992), designed to assess reading, comprehension and motor skills. A list of 20 simple sentences (e.g. dogs have six legs) were presented on the screen (see Figure 62). The participant was required to read the sentences silently and classify them as 'true' or 'false' by clicking on the corresponding button at the end of each sentence. There were five versions of this test so no subject read the same sentences more than once. The accuracy of the responses and the time taken to complete the task was recorded.

This test was selected because it combines a series of sensory functions and motor skills in a very similar way to many computer-based tasks.

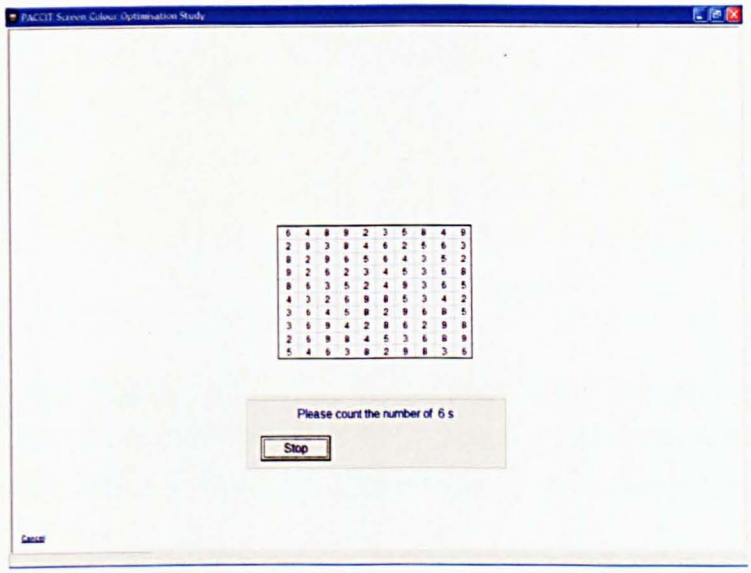
Figure 62 – Screenshot showing the Nonsense Sentences Test



4.2.1.3 Spreadsheet Test

A 10x10 array of single digit random numbers was displayed on the screen (see Figure 63). The participant was required to count the number of occurrences of a given digit in the array. The accuracy of the count and the time taken were recorded. The mean of five trials was calculated.

Figure 63 – Screenshot showing the 'Spreadsheet Task'



4.2.2 Methods

Twenty male and 43 female undergraduate optometry students and staff at City University aged 18-37 yrs (mean = 20.8 yrs) participated in the study. Each participant was seated at

a distance of 40cm from the screen (Flatron 4710B TFT measuring 340mm horizontally by 270mm vertically). A chin rest was used so that the viewing angle and the distance from the computer screen remained constant for all subjects.

Each subject was required to perform the Rate of Reading, the Spreadsheet Test and the Nonsense Sentences Test against a white background. The three tests were then repeated one week later in order to assess their test-retest reliabilities.

4.2.3 Results

4.2.3.1 Rate of Reading

Figure 64 shows the rate of reading (words/ minute) for Trial 1 plotted against Trial 2. The correlation coefficient for this was r = 0.8 (t-test = 0.008). However, Bland and Altman (1986) have pointed out the limitations of using the correlation coefficient as a measure of agreement for data of this nature. The correlation coefficient is a measure of the strength of the linear association between two variables which is not the same as a measure of agreement. Therefore, throughout this thesis the data are are also plotted in a Bland-Altman format where the difference between the first and second measurements are plotted as a function of their mean. Plotted in this way, the mean difference gives an estimate of the average bias, and the standard deviation of the differences gives an estimate of the agreement.

The test-retest repeatability was 24.36s (2 s.e.).

Figure 64 – Graph showing the correlation between test and retest results for the Rate of Reading test.

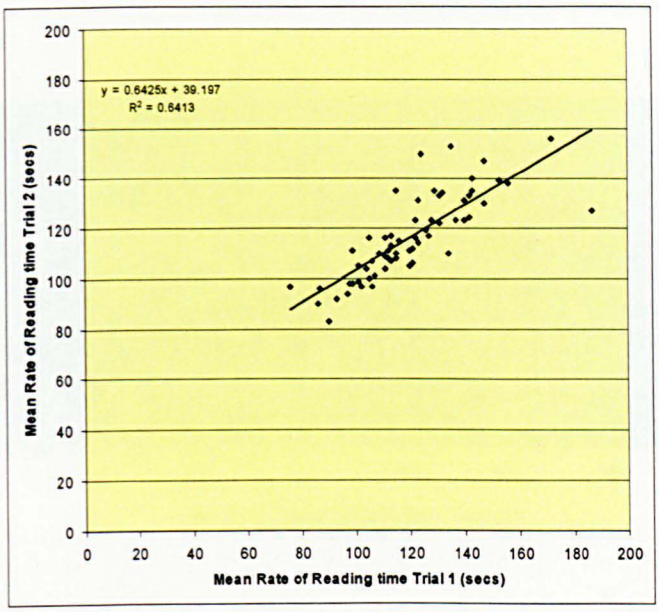
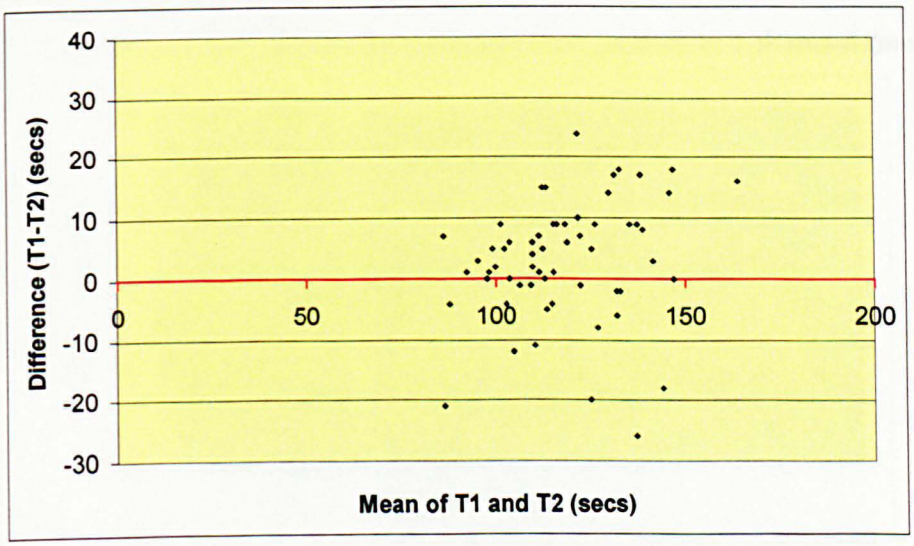


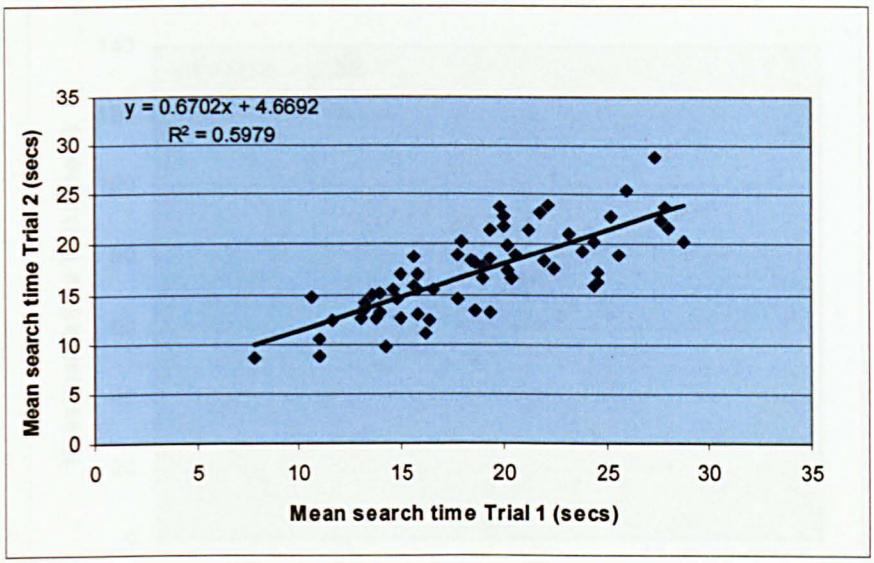
Figure 65 – Bland-Altman plot showing test-retest data for the Rate of Reading test



4.2.3.2 Spreadsheet Test

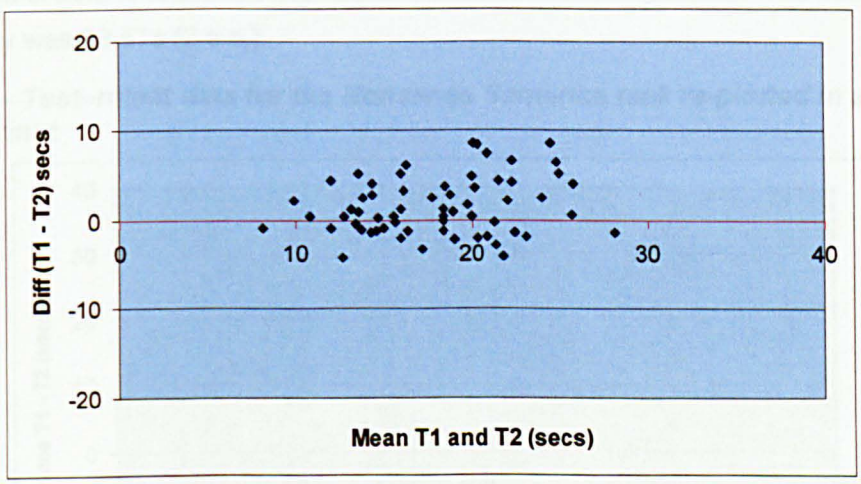
The mean time taken to complete the spreadsheet task (five trials) was calculated for the test and retest and is plotted in Figure 66. The correlation coefficient for this was r = 0.773 (t-test = 0.00017).

Figure 66 – Graph showing correlation between test and retest times to complete the spreadsheet task (63 subjects)



The test-retest data is re-plotted in a Bland-Altman format in Figure 67. The test-retest repeatability was 6.36s (2 s.e.).

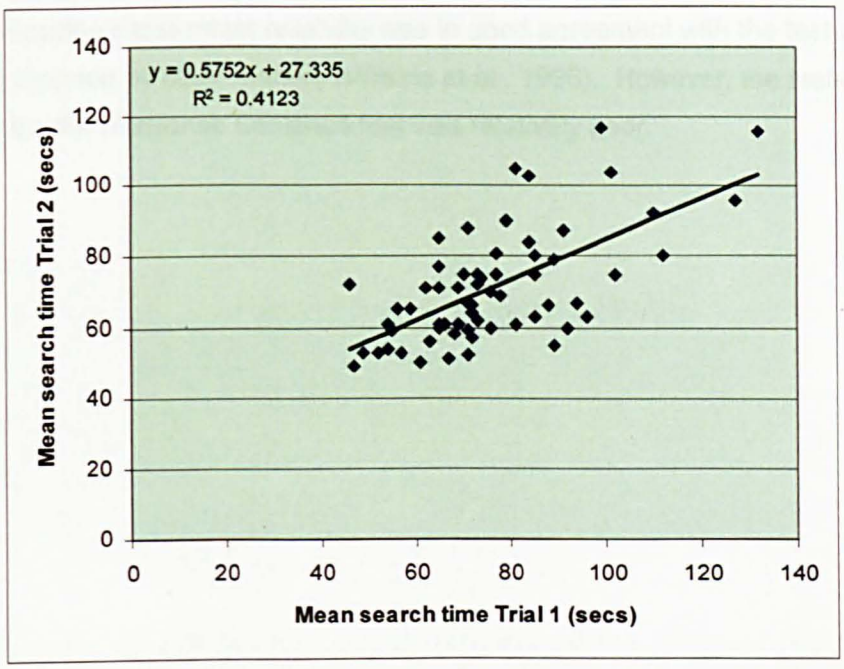
Figure 67 – Test-retest data for the Spreadsheet test plotted in a Bland-Altman format



4.2.3.3 Nonsense Sentences

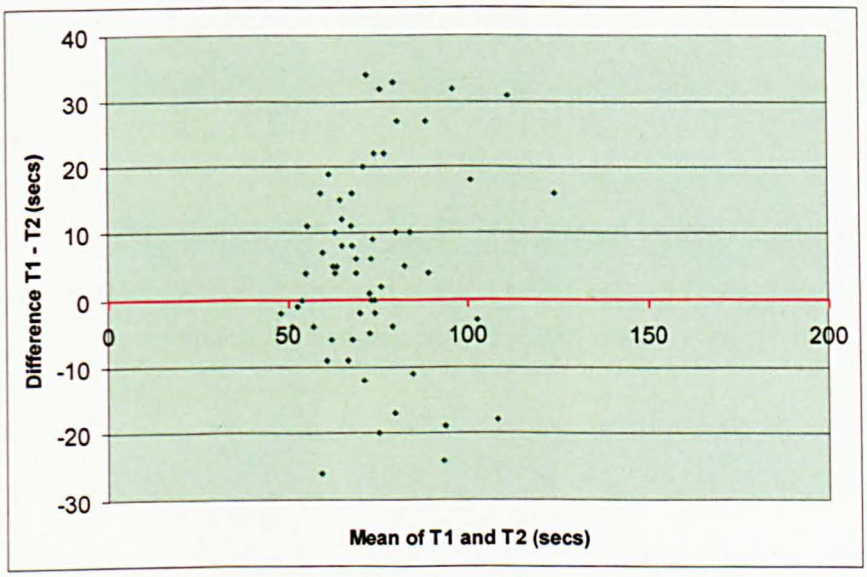
Figure 68 shows the correlation between test and re-test times for the Nonsense Sentence test. The correlation coefficient was r = 0.639 (t-test = 0.0032).

Figure 68 – *Graph showing correlation between test and retest times to complete the Nonsense Sentence task (63 particpants)*



The test-retest data is re-plotted in a Bland-Altman format in Figure 69. The test-retest repeatability was 28.57s (2 s.e.).

Figure 69 – Test–retest data for the Nonsense Sentence task re-plotted in a Bland-Altman format



4.2.4 Discussion

The Rate of Reading and the Spreadsheet Analysis performed reasonably well and indeed, the Rate of Reading's test-retest reliability was in good agreement with the test-retest repeatability reported by other authors (Wilkins et al., 1996). However, the test-retest repeatability for the Nonsense Sentence test was relatively poor.

4.3 Algorithm for choosing colour

The aim of the first study was to investigate the potential benefits of customising screen background colour for a group of normal computer users. To achieve this it was necessary to develop a method to enable users to select their preferred background colour. A pilot study suggested simply giving subjects a free choice of the gamut of colours available using a colour picker (Figure 70) was confusing and provided very variable results.

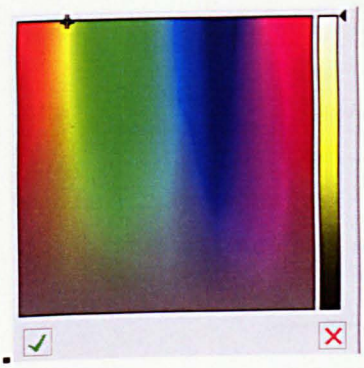


Figure 70 – Colour picker control

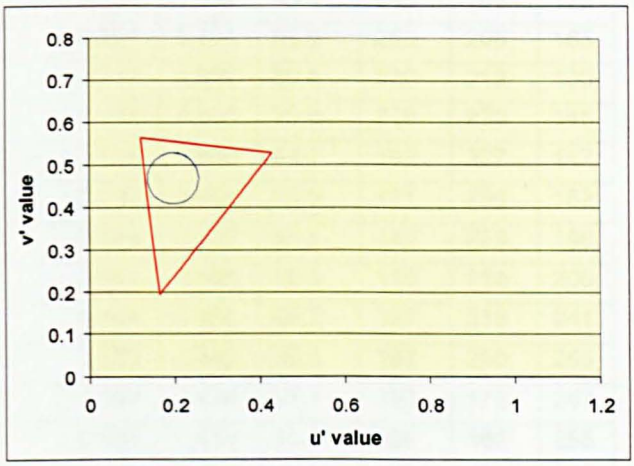
In a bid to make the process more systematic and repeatable, a series of algorithms were developed. This is a significant challenge given the three dimensional nature of colour and the evidence that the optimum of colour can be very specific for some subjects.

Based on the work done by Wilkins and others (2001; 1996) and, Evans and Joseph (2002) with overlays, it was decided to commence the algorithm by presenting a series of de-saturated colours of approximately equal luminance and saturation.

This was achieved by calculating the u', v' co-ordinates (CIE 1976 UCS) of 16 points on a circle of maximum diameter within the triangular colour space available on the display screen (see Figure 71). The circle had a centre with chromaticity u' = 0.1978, v' = 0.4683 (D65) and a radius of 0.0369. In other words, the display could vary in CIE 1976 hue angle (h_{uv}) without an associated change in the CIE 1976 saturation (s_{uv}) and luminance.

In retrospect, the inclusion of a grey of approximately the same luminance as the colours in Phase 1 would have provided some information regarding whether colour was preferred to white simply because it was less bright.

Figure 71 – u'v' coodinates of the red, green and blue pixels on the LCD screen form the apices of the red triangle and, therefore, the triangle bounds the gamut of colours that may be displayed on the screen. The blue circle represents colours of equal saturation around a standard white (u'v' 0.1978, 0.4683). Sixteen points around this circle were selected for the first phase of the algorithm



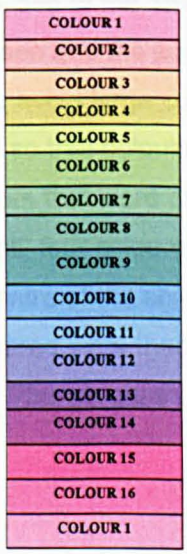
The RGB values required to achieve the desired chromaticities were determined by means of careful calibration using a Minolta Chroma Meter II. As far as possible, the screen luminance was kept constant. This was checked by using the illuminance mode of the Minolta Chroma Meter with the sensor placed directly on the screen (see Table 16). As the experiment was to be carried out in various locations, a laptop computer (Samsung P10) was used for the purpose. The laptop had a high quality TFT screen measuring 28.5cm horizontally by 21.5cm vertically.

Table 16 – u'v' values and corresponding RGB values required to achieve these on the Samsung TFT screen

Colour	A (degs)	u'	v'	Illum	R	G	B
1	0.0	0.235	0.468	54.8	246	171	196
2	22.5	0.232	0.482	56.6	248	183	172
3	45.0	0.224	0.494	65.9	255	208	165
4	67.5	0.212	0.502	59.8	222	212	130
5	90.0	0.198	0.505	70.0	219	229	145
6	112.5	0.184	0.502	63.2	192	227	147
7	135.0	0.172	0.494	69.0	171	239	182
8	157.5	0.164	0.482	62.3	142	228	196
9	180.0	0.161	0.468	55.5	110	219	206
10	202.5	0.164	0.454	60.7	137	215	241
11	225.0	0.172	0.442	56.4	168	200	255
12	247.5	0.184	0.434	51.1	190	179	247
13	270.0	0.198	0.431	51.4	209	162	255
14	292.5	0.212	0.434	52.7	228	149	248
15	315.0	0.224	0.442	57.7	255	149	249
16	337.5	0.232	0.454	50.5	237	149	207
			Mean	60.7			
			Min	50.5			
			Max	77.9			

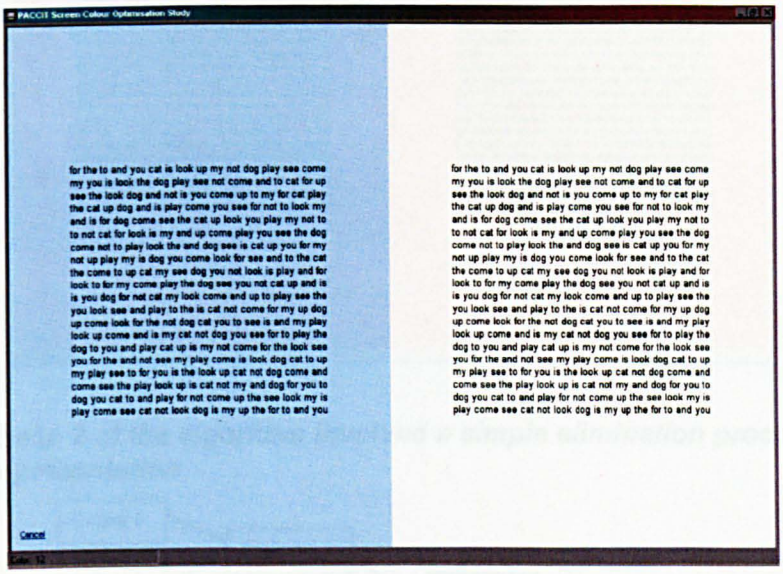
An approximate representation of the colours used are shown in Figure 72.

Figure 72 – Approximate representation of the 16 colours selected for the first phase of the algorithm



In the first stage of the algorithm, the participants were required to look at text (randomly ordered common words displayed in Arial font size 10) on either side of the screen and report if the words were easier/ more comfortable to read with a coloured or white background. The sixteen different colours were presented; the colour appearing on the left or right hand half of the screen at random – see Figure 73.

Figure 73 – Phase 1 of the algorithm



If, at this stage, the participant preferred white to all of the sixteen colours, the program terminated and the participant was not included in the trial.

However, if the participant preferred one of more of the colours to the white, the algorithm entered a second phase. In this phase, two of the 16 colours were presented simultaneously on either half of the screen and the participant was "forced" to declare their preference – see Figure 74. In order to avoid large colour differences and possible adaptation effects, colours were paired so that colours next to each other in the hue circle were compared – see Figure 75. Colours that were chosen in the first round were then compared and the process repeated until four colours remained. At this stage, a single passage of text was displayed in the centre of the screen and the entire screen background was coloured. The colours to be compared were then presented successively, with each colour being presented for 3 seconds. This process was repeated until the "overall winner" was found.

Figure 74 – Screenshot of phase 2 of the algorithm showing simultaneous presentation of two colours

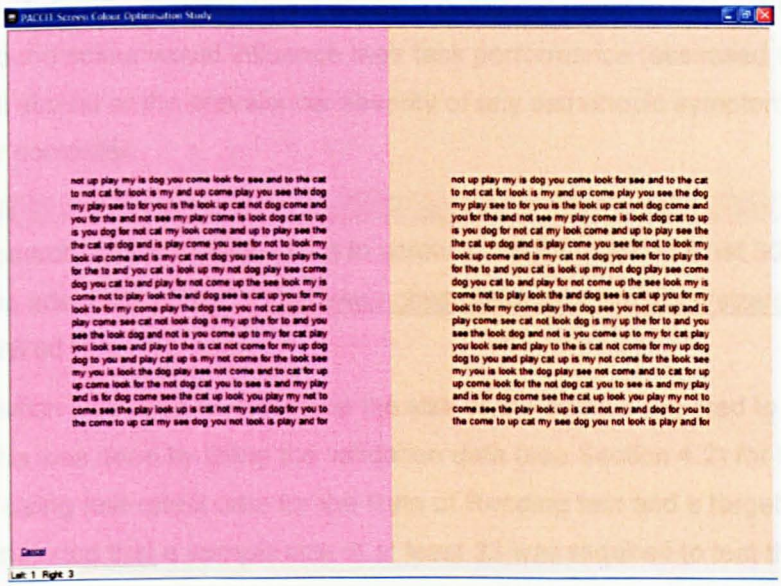
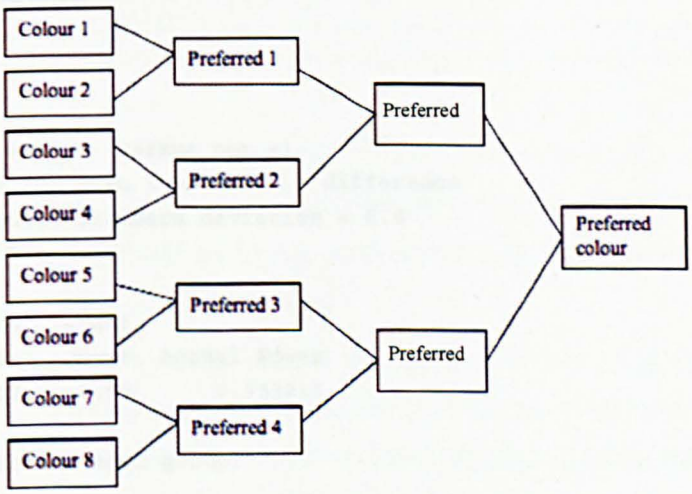


Figure 75 – Phase 2 of the algorithm involved a simple elimination process by simultaneous presentation



For the final phase of the algorithm, the entire screen was presented with the preferred colour in the background and the subject was given the opportunity to vary the saturation and luminance of the chosen colour to optimise the appearance. The RGB values and the corresponding chromaticity were then recorded.

In retrospect, the inclusion of a grey of approximately the same luminance as the colours in phase 1 would have provided some information regarding whether colour was preferred to white simply because it was less bright.

4.4 The effect of screen colour on user performance – normal subjects

The aim of this study was to determine if allowing computer users to select their preferred screen background colour would influence their task performance (assessed using the three tests described above) or the prevalence/ severity of any asthenopic symptoms associated with using their computer.

4.4.1 Methods

"How many research subjects does it take to screw in a light bulb? At least 300 if you want the bulb to have adequate power" (http://www.childrens-mercy.org/stats/size/power.asp, Steve Simon, 25.06.07).

A power calculation was used to determine the size of the sample required to investigate the hypothesis. This was done by using the validation data (see Section 4.2) for the Rate of Reading test. Using test-retest data for the Rate of Reading test and a target power of 95%, it was concluded that a sample size of at least 33 was required to test the hypothesis (see Figure 76). On this basis, a sample size of 40 was used.

Figure 76 - Power calculation

Power and Sample Size

```
2-Sample t Test

Testing mean 1 = mean 2 (versus not =)
Calculating power for mean 1 = mean 2 + difference
Alpha = 0.05  Assumed standard deviation = 6.6


            Sample  Target
Difference    Size   Power  Actual Power
         6      33    0.95      0.953211

The sample size is for each group.
```

Forty office-based computer users (M:F = 15:25) were recruited for this study. Subjects ranged in age from 21-61 years (mean = 32.9 yrs). No data was collected on subjects' ocular status, binocular status or optical correction but all subjects were instructed to use the spectacles or contact lenses (if any) that they normally wore when using their computer. All subjects used desktop computers with LCD screens of a variety of sizes. Whilst the lack of control of these variables could be seen as a weakness of the study, the aim of the study was to sample a typical office workforce and determine if screen colour was beneficial in a typical office environment.

Before commencing the study, each participant was asked a series of questions relating to symptoms which they associated with using their computer. Participants were asked: "over the **last month**, have you suffered from any of the following when using your **computer**?" The list of asthenopic symptoms included: sore eyes, itchy eyes, gritty eyes, burning eyes, dry eyes, tired eyes, eye strain, double vision and headaches. Participants were required to tick: "Never, rarely, sometimes, often or most of the time" to each symptom (see Figure 77).

Figure 77 – Questionnaire to determine prevalence and severity of symptoms associated with using computer screen

Over the last month, have you suffered from any of the following when using your computer? (Please tick the appropriate box).

	Never	Rarely	Sometimes	Often	Most of the time
Sore eyes					
Itchy eyes					
Gritty eyes					
Burning eyes					
Dry eyes					
Tired eyes					
Eye strain					
Double vision					
Headaches					

The tests were conducted in each participant's office and care was taken to minimise influences from the ambient environment such as glare, screen reflections or other distractions. Participants viewed the laptop screen from approximately 40cm and wore their normal spectacles/ contact lenses if required.

The preferred screen colour for each subject was determined using the procedure described above. Participants who showed a preference for at least one colour undertook the task performance tests described above with the screen background colour set to white and their preferred colour. The order of testing (white and coloured background) was balanced to minimise possible order effects. Despite this being a classic ABBA experimental design, it was deemed in hindsight to be a poor way of randomising the trials as subjects could suffer from colour adaptation by doing all three trials with colour and then doing all three trials against a white background.

The background colour of each participant's computer screen was then changed to the colour determined in the test using software developed for the study. Participants were then reassessed between 5 and 15 days later. At the follow-up assessment, participants were asked to complete the symptoms questionnaire used previously and the task performance tests were repeated.

4.4.2 Results

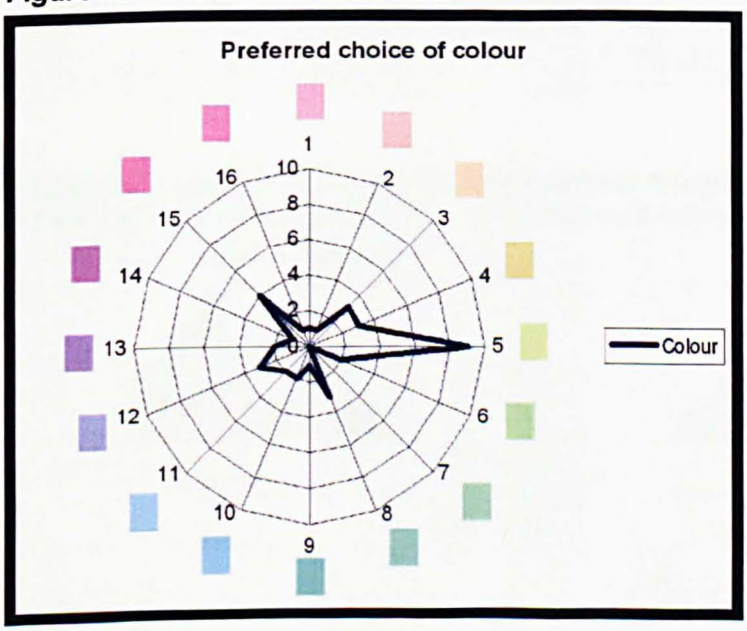
4.4.2.1 Preferred colour

Of the 40 participants tested, only one preferred a white screen to any of the coloured screens. This subject was excluded from the rest of the study. The number of participants choosing each of the 16 colours is shown in Table 17 and graphically in Figure 78.

Table 17 – Table showing the number of participants choosing each of the 16 colours

Colour	Colour on screen	u'	v'	N
1		0.235	0.468	1
2		0.232	0.482	1
3		0.224	0.494	3
4		0.212	0.502	3
5		0.198	0.505	9
6		0.184	0.502	2
7		0.172	0.494	0
8		0.164	0.482	3
9		0.161	0.468	1
10		0.164	0.454	2
11		0.172	0.442	2
12		0.184	0.434	3
13		0.198	0.431	2
14		0.212	0.434	1
15		0.224	0.442	4
16		0.232	0.454	1

Figure 78 – Preference of colours



It can be seen that colour 5 (green) was the most frequently preferred colour (n=9) by some margin.

4.4.2.2 Task performance

Summary data for the three task performance tests are shown in Figures 79 – 81.

Figure 79 - Summary data for the Rate of Reading test for a white background and preferred colour background for initial test and follow-up test

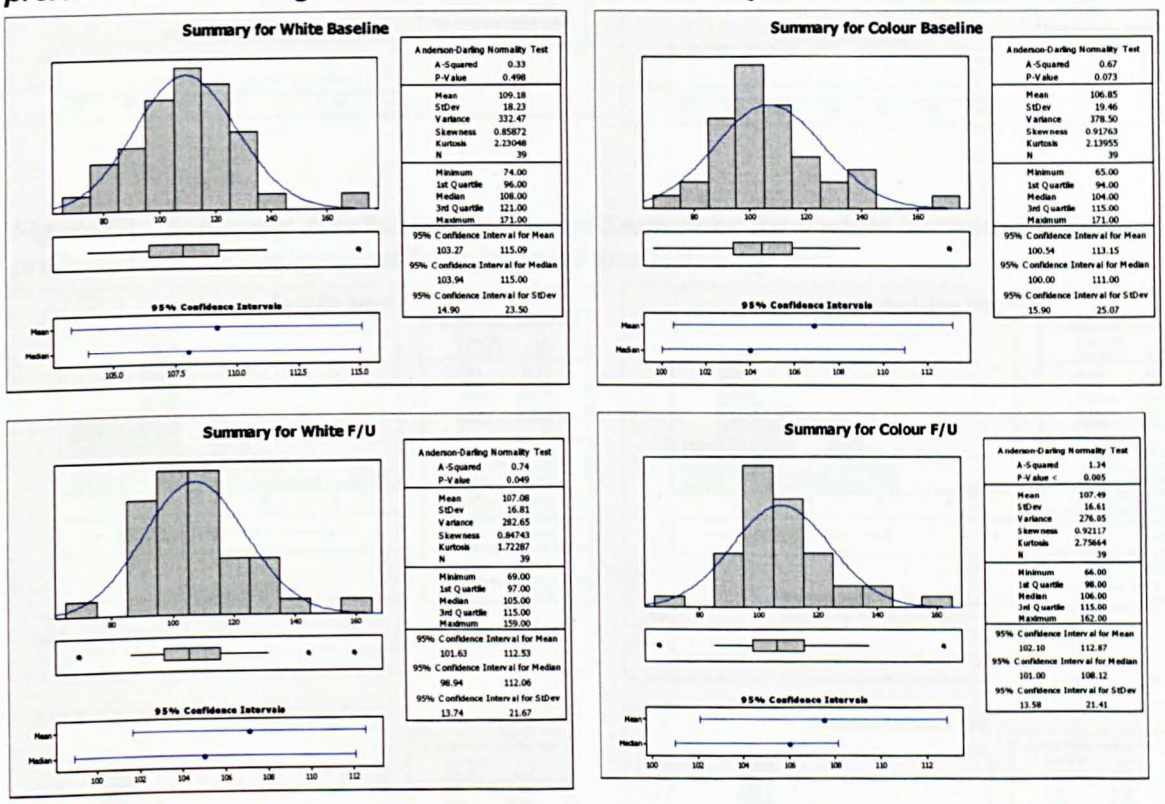
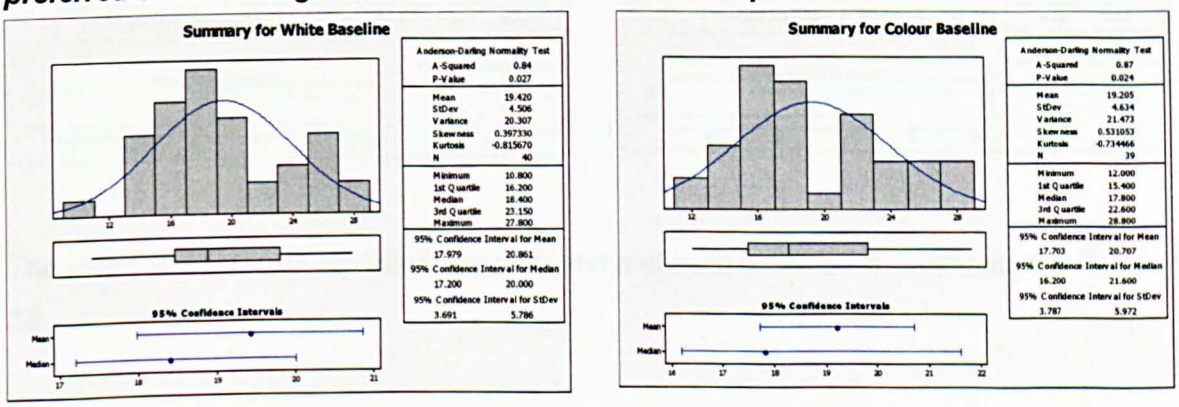
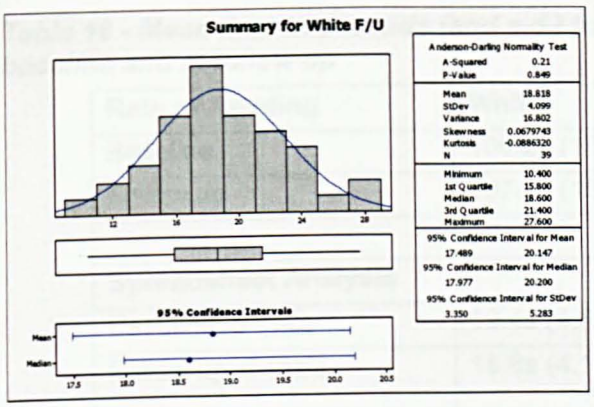


Figure 80 - Summary data for the Spreadsheet Analysis for a white background and preferred colour background for initial test and follow-up test





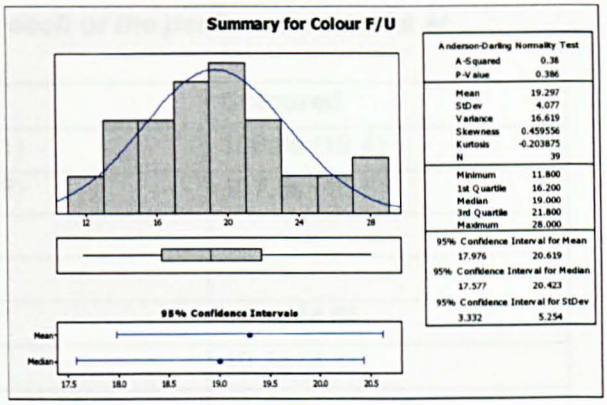
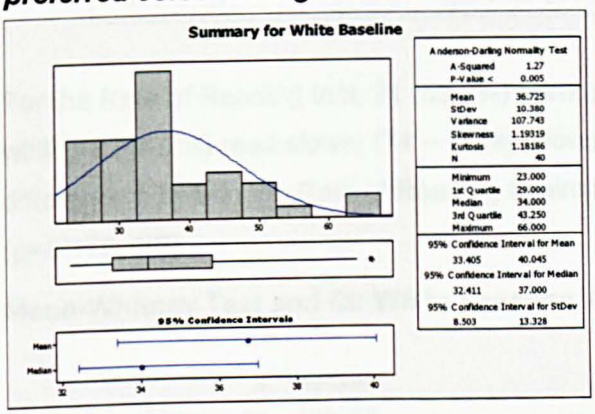
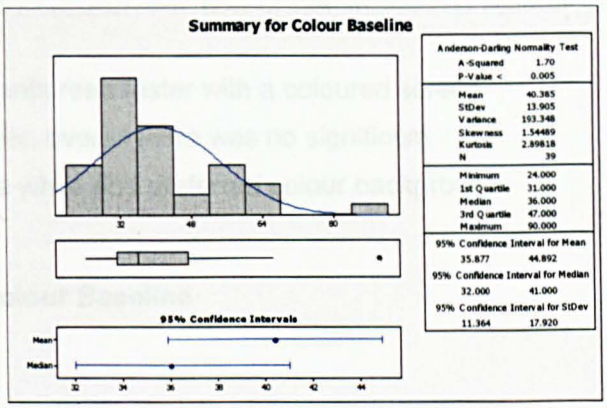
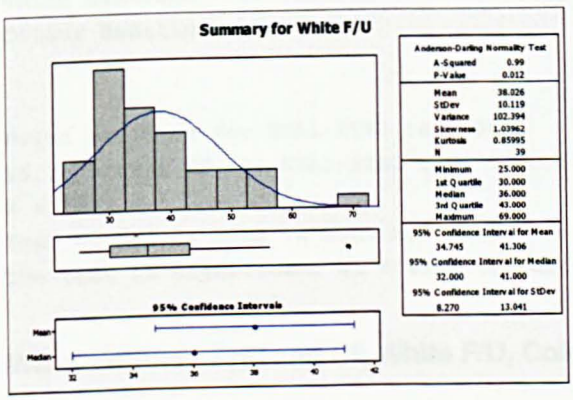
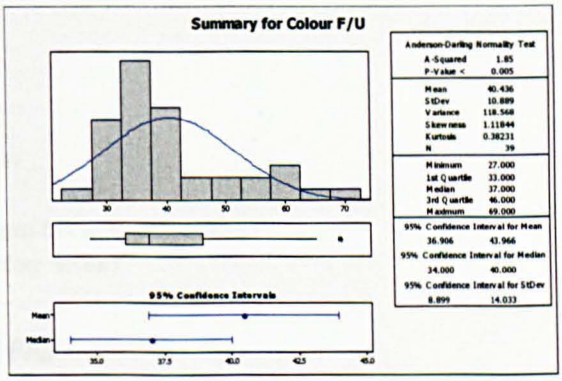


Figure 81 - Summary data for the Nonsense Sentences for a white background and preferred colour background for initial test and follow-up test









The mean and standard deviations for each test and each condition is summarised in Table 18.

Table 18 - Mean time in seconds (and s.d.) for each of the performance tasks at baseline and at follow up

Rate of Reading	White	Coloured
Baseline	109.2s (18.1)	106.8s (19.4)
Follow up	107.1s (16.8)	107.5s (16.6)
Spreadsheet Analysis		
Baseline: 5 trials	19.4s (4.5)	19.2s (4.6)
Follow up: 5 trials	18.8s (4.1)	19.3s (4.1)
Nonsense sentences		
Baseline	36.7s (10.4)	40.4s (13.9)
Follow up	38.0s (10.1)	40.4s (10.9)

For the Rate of Reading test, 21 (53.8%) participants read faster with a coloured screen while 18 (46.2%) read slower (74 – 171s). However, overall there was no significant difference between the Rate of Reading against a white and preferred colour background (p=0.176; NS).

Mann-Whitney Test and CI: White Baseline, Colour Baseline

```
                  N  Median
White Baseline   39  108.00
Colour Baseline  39  104.00


Point estimate for ETA1-ETA2 is 3.00
95.1 Percent CI for ETA1-ETA2 is (-5.00,11.00)
W = 1619.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.4357
The test is significant at 0.4355 (adjusted for ties)
```

Mann-Whitney Test and CI: White F/U, Colour F/U

```
             N  Median
White F/U   39  105.00
Colour F/U  39  106.00


Point estimate for ETA1-ETA2 is -1.00
95.1 Percent CI for ETA1-ETA2 is (-7.00,6.00)
W = 1507.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.7416
The test is significant at 0.7414 (adjusted for ties)
```

Mann-Whitney Test and CI: White Baseline, Colour F/U

```
                 N  Median
White Baseline  39  108.00
Colour F/U      39  106.00


Point estimate for ETA1-ETA2 is 2.00
95.1 Percent CI for ETA1-ETA2 is (-5.00,9.00)
W = 1603.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.5355
The test is significant at 0.5353 (adjusted for ties)
```

For the Spreadsheet Analysis task, 19 (48.7%) participants completed the task faster with a coloured screen while 20 (51.3%) were slower (11.8 – 28.0s). Overall, there was no significant difference in the results for the Spreadsheet Test for the white and preferred colour background (p=0.964; NS).

Mann-Whitney Test and CI: White Baseline, Colour Baseline

```
                  N  Median
White Baseline   39  18.600
Colour Baseline  39  17.800


Point estimate for ETA1-ETA2 is 0.400
95.1 Percent CI for ETA1-ETA2 is (-1.599,2.400)
W = 1583.5
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.6710
The test is significant at 0.6709 (adjusted for ties)
```

Mann-Whitney Test and CI: White F/U, Colour F/U

```
              N  Median
White F/U    39  18.600
Colour F/U   39  19.000


Point estimate for ETA1-ETA2 is -0.400
95.1 Percent CI for ETA1-ETA2 is (-2.200,1.600)
W = 1503.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.7116
The test is significant at 0.7114 (adjusted for ties)
```

Mann-Whitney Test and CI: White Baseline, Colour F/U

```
                 N  Median
White Baseline  39  18.600
Colour F/U      39  19.000


Point estimate for ETA1-ETA2 is -0.000
95.1 Percent CI for ETA1-ETA2 is (-1.800,1.999)
W = 1539.5
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.9960
The test is significant at 0.9960 (adjusted for ties)
```

For the Nonsense Sentences test, 27 subjects performed slower, nine faster and three remained the same. This was not significant with a paired t-test (p=0.137; NS).

Mann-Whitney Test and CI: White Baseline, Colour Baseline

```
                  N  Median
White Baseline   39  34.000
Colour Baseline  39  36.000


Point estimate for ETA1-ETA2 is -2.000
95.1 Percent CI for ETA1-ETA2 is (-6.999,2.004)
W = 1440.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.3176
The test is significant at 0.3172 (adjusted for ties)
```

Mann-Whitney Test and CI: White F/U, Colour F/U

```
             N  Median
White F/U   39  36.000
Colour F/U  39  37.000


Point estimate for ETA1-ETA2 is -2.000
95.1 Percent CI for ETA1-ETA2 is (-6.000,1.997)
W = 1438.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.3080
The test is significant at 0.3075 (adjusted for ties)
```

Mann-Whitney Test and CI: White Baseline, Colour F/U

```
                 N  Median
White Baseline  39  34.000
Colour F/U      39  37.000


Point estimate for ETA1-ETA2 is -3.000
95.1 Percent CI for ETA1-ETA2 is (-7.001,0.002)
W = 1368.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0856
The test is significant at 0.0852 (adjusted for ties)
```

4.4.2.3 Asthenopic symptoms

Table 19 shows the prevalence of each individual symptom at baseline. As can be seen from this table, 'tired eyes' was the commonest symptom (82.5%) with 'sore eyes' (67.5%) and 'itchy eyes' (57.5%) being second and third respectively. Ten per cent of the sample experienced 'diplopia'. Overall, 92.5% of participants reported one or more symptoms associated with using their computer.

Table 19 – Table showing the prevalence of asthenopic symptoms at baseline

Symptom	N = 40	Mean; (s.d.)
Sore eyes	27 (67.5%)	1.31 (1.10)
Itchy eyes	23 (57.5%)	1.07 (1.16)
Gritty eyes	14 (35%)	0.66 (1.02)
Burning eyes	17 (42.5%)	0.74 (1.04)
Dry eyes	20 (50%)	1.08 (1.30)
Tired eyes	33 (82.5%)	1.69 (1.13)
Eyestrain	16 (40%)	0.74 (1.09)
Diplopia	4 (10%)	0.26 (0.86)
Headaches	22 (55%)	1.02 (1.12)

Figure 82 compares the proportion of participants who experienced symptoms with their normal white background and after using their optimum screen colour for a minimum of one week. The maximum score for each subject was used. Only three (7.7%) participants 'never' experienced any symptoms of asthenopia with the white background whereas seven

(17.9%) were asymptomatic with the coloured background. Fifteen (38.5%) participants experienced symptoms of asthenopia 'often' or 'most of the time' at baseline and this reduced to 10 (25.6%) by customising the background colour.

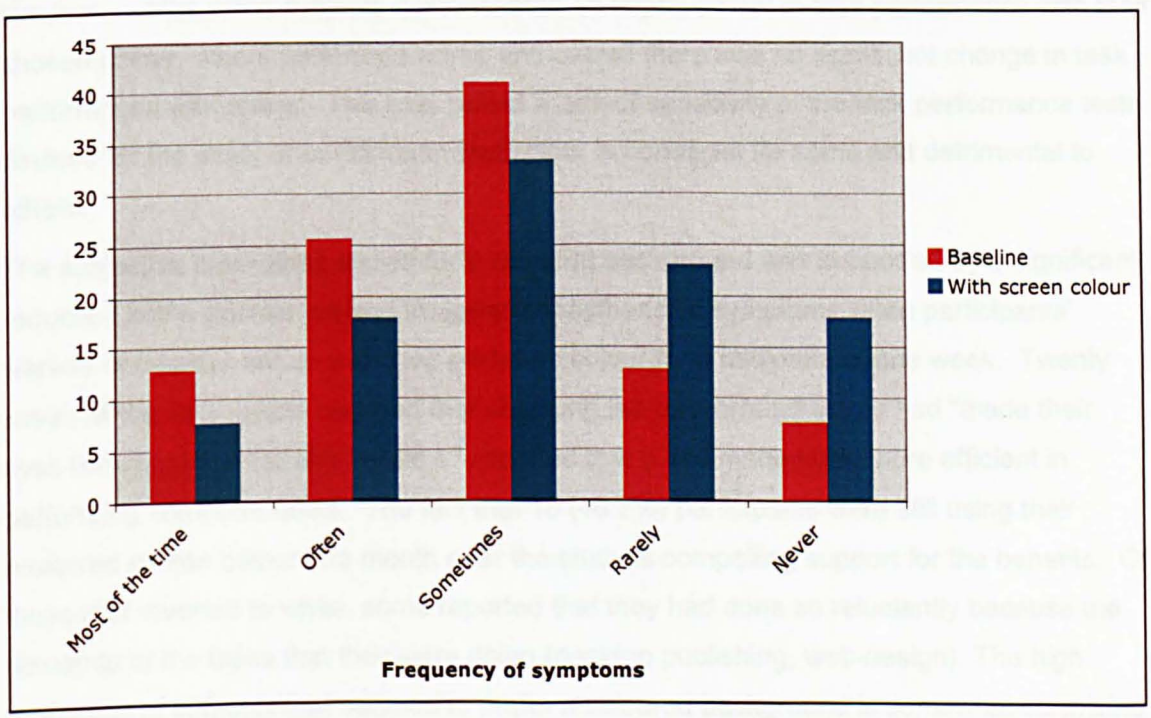
The maximum score obtained for each symptom was recorded for each subject for baseline and follow up results. This could be between 0 ('never') and 4 ('most of the time'). These results were then compared between the two samples. Overall, symptoms improved although this was not significant using a Mann-Whitney U test ($u = 0.073$). As statisticians appear divided on whether data that slightly departs from a normal distribution should be analysed with the t-test or the Mann-Whitney U test, the results were re-analysed using a t-test. With this test the result was statistically significant ($t(38) = 2.47$, $p = 0.018$).

Mann-Whitney Test and CI: Baseline, F/U

```
           N  Median
Baseline  39   2.000
F/U       39   2.000

Point estimate for ETA1-ETA2 is 1.000
95.1 Percent CI for ETA1-ETA2 is (-0.000,1.000)
W = 1720.5
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0728
The test is significant at 0.0628 (adjusted for ties)
```

Figure 82 – Histogram showing distribution of severity of asthenopic symptoms with a white background (Baseline) and the preferred colour at the follow up assessment



In response to the question: "do you feel that your new screen colour has made your eyes feel more comfortable", 27 (69.2%) responded in the affirmative, 10 (25.6%) felt it made no difference and two (5.2%) felt it had made it worse.

In response to the question: "do you feel that your new screen colour has made you more efficient in performing computer tasks", 17 (43.6%) reported that they felt colour did make them more efficient, 20 (51.3%) felt it made no difference and the same two participants (5.2%) felt it had reduced their efficiency.

One month after the follow up appointment, 18 (46.2%) were still using their chosen screen colour. A further five subjects (12.8%) preferred a coloured screen to white but were uncertain whether they would keep their colour because it interfered with other colours in frequently used applications.

4.4.3 Conclusions

There is growing evidence that a proportion of the population read printed text faster when the background is coloured. Consequently, it was not unreasonable to expect a similar benefit if computer users were allowed to customise the background colour of their displays.

Subjectively, 39 out of the 40 participants in the first part of this study expressed a preference for a coloured background over a white background on a computer screen. The choice of colour was idiosyncratic with no clear trends apparent from the data, in agreement to findings for coloured overlays/ spectacles and printed text. A light green background was the most frequently selected colour.

However, whilst some subjects demonstrated an improvement in task performance with their chosen colour, others performed worse and overall there was no significant change in task performance with colour. This may reflect a lack of sensitivity of the task performance tests devised for the study or could mean that colour is beneficial for some and detrimental to others.

The subjective preference shown for a coloured background was supported by a significant reduction in the prevalence and frequency of asthenopic symptoms when participants' worked at displays set up with their preferred colour for a minimum of one week. Twenty seven of the 39 subjects reported that changing the background colour had "made their eyes feel more comfortable" while 17 reported that it had made them more efficient in performing computer tasks. The fact that 18 (46.2%) participants were still using their preferred screen colour one month after the study is compelling support for the benefits. Of those that reverted to white, some reported that they had done so reluctantly because the demands of the tasks that they were doing (desktop publishing, web-design). The high proportion of subjects that seemed to prefer a coloured background is somewhat surprising

among a group of "normal" office workers given that less than 20% might be expected tp have Meares-Irlen syndrome.

This perceived benefit of colour, even if not supported by attempts to quantify the effects, is significant and could have major implications in terms of the prevalence of symptoms and general sense of well-being amongst computer users.

Although the sample size in this study is relatively small, the results suggest that allowing computer users to customise the background colour of their displays may be beneficial in terms of visual comfort and perceived efficiency. Subjects ranged in age from 21-61 years (mean = 32.9 yrs). No data was collected on subjects' ocular status, binocular status or optical correction but all subjects were instructed to use the spectacles or contact lenses (if any) that they normally wore when using their computer. All subjects used desktop computers with LCD screens of a variety of sizes. While the lack of control of these variables could be seen as a weakness of the study, the aim of the study was to sample a typical office workforce and determine if screen colour was beneficial in a typical office environment. The lack of a control group in this study does not allow us to rule out the possibility of a placebo effect. However, there is no evidence for a placebo effect in the visual performance results (although it could be argued that these tests were less susceptible to a placebo effect). Further studies on a larger number of computer users and including a suitable "sham" treatment would be required to confirm these findings.

4.5 The effect of screen colour on user performance – Meares Irlen syndrome

4.5.1 Introduction

The effects of colour seem to be particularly marked for individuals who experience "visual stress" when reading. The term "visual stress" is used to describe a condition in which individuals experience a range of visuo-perceptual distortions when viewing certain patterns including text. Symptoms may include the perception of movement, flicker, "glare" or general discomfort when reading. Such symptoms tend to reduce Word Search Speed and speed and may impact upon educational development and progress (Cole, 2007). The condition is also known as Meares-Irlen Syndrome (MIS). Individuals are often unaware that they are suffering from this condition, assuming that their perception of printed text is entirely normal (Irlen, 1983).

In some cases, these symptoms can be alleviated or eliminated by the use of colour. For reading printed text, this is usually achieved by using coloured overlays or tinted spectacle lenses.

In the study described above (see Section 4.4), some participants in the unselected group seemed to gain a significant benefit from changing the background screen colour whilst others found it made no difference or even made it less comfortable to view. It is possible that this reflected the presence of subjects with "visual stress" within the group.

The aim of this study was to investigate the effects of customising the background colour of computer displays on the symptomatology and task efficiency of a sample of individuals with an established diagnosis of visual stress and a proven benefit of coloured overlays or spectacles.

4.5.2 Methods

Thirty-two participants (16 males and 16 females) were recruited from the orthoptics department at Brighton Hospital, Sussex (mean age = 15 yrs; range = 7 to 40 years). All participants had been previously diagnosed with visual stress and regularly used coloured overlays or coloured spectacles. Prior to entry into the study, all volunteers underwent a full orthoptic assessment which included visual acuity assessment, prism cover test, ocular motility, convergence, prism fusion range and stereopsis. Any participants with significant binocular vision anomalies were excluded from the study. In keeping with the Declaration of Helsinki (2000), ethical approval was obtained from both the City University Research and Ethical Committee and the Local Research Ethics Committee (LREC) for Brighton, Mid Sussex and East Sussex.

The same questionnaire as used in Section 4.4 was used for this sample although an extra set of questions were included. Subjects were asked: "Over the **last month** have you

suffered from any of the following when using your **computer**?" Subjects had to rate "Do the words appear to move, wobble or flicker?", "Do the words go in and out of focus?", "Do the words look too close together?", "Does the page look too bright or dazzling?" and "Does it hurt your eyes when you look at the page?" on a scale of "never, rarely, sometimes, often, most of the time". These were symptoms found by Evans to be indicative of visual stress (Evans et al., 1996).

All participants were assessed using the same tests and protocol described in Section 4.4.

4.5.3 Results

4.5.3.1 Preferred colour

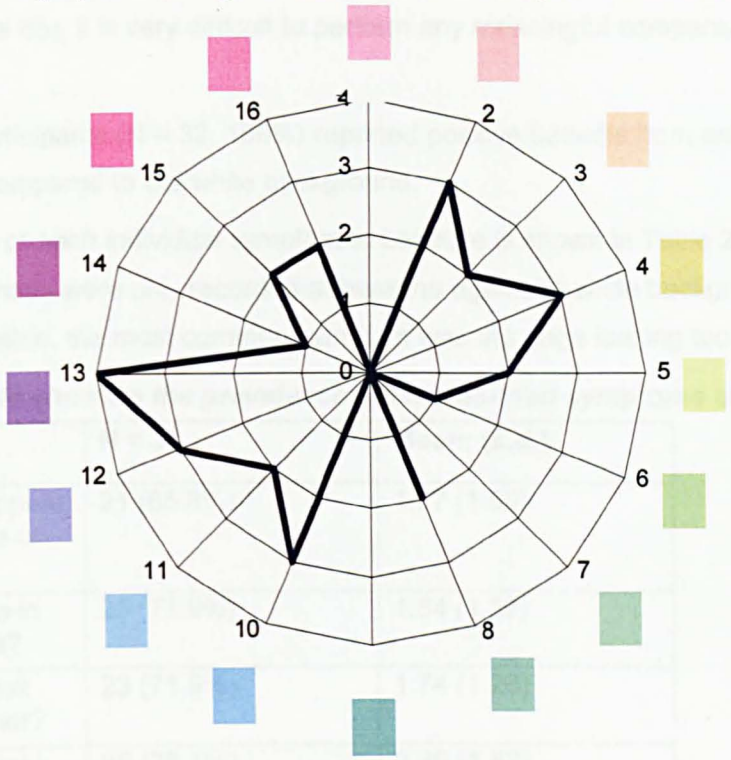
All participants (100%) chose a coloured background compared to a white background in the first phase of the algorithm. Figure 83 shows the number of participants who chose each of the 16 colours.

Figure 83 – Frequency table showing the number of participants choosing each of the 16 colours

Original colours	No. of subjects
COLOUR 1	0
COLOUR 2	3
COLOUR 3	2
COLOUR 4	3
COLOUR 5	2
COLOUR 6	1
COLOUR 7	0
COLOUR 8	2
COLOUR 9	0
COLOUR 10	3
COLOUR 11	2
COLOUR 12	3
COLOUR 13	4
COLOUR 14	1
COLOUR 15	2
COLOUR 16	2
COLOUR 1	0

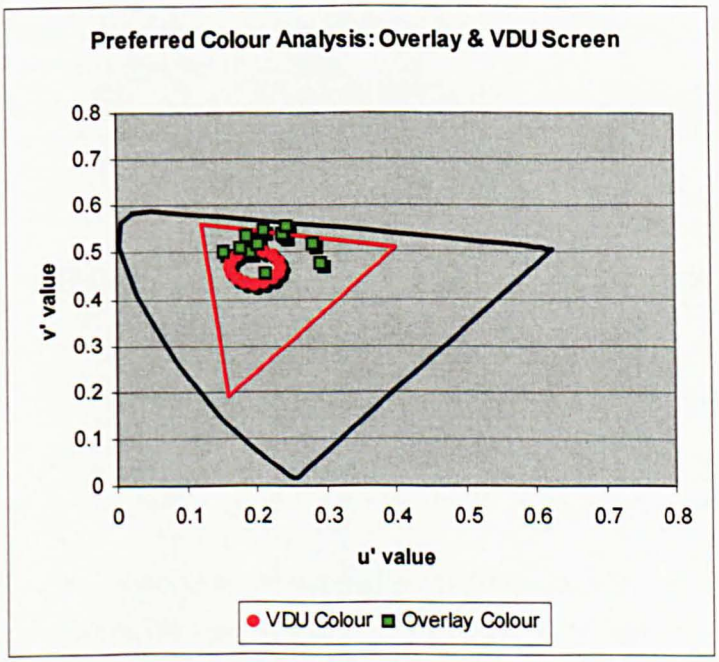
These data are re-plotted as a polar graph in Figure 84.

Figure 84 – Polar graph showing the distribution of the preferred colour



The u'v' values for the Irlen overlays, and the u'v' values for the colours chosen by the subjects on the computer screen and plotted on a CIE u'v' diagram are shown in Figure 85.

Figure 85 – u'v' values of paticipant's Irlen overlay colour and the preferred computer colour plotted in CIE UCS



As the colours of the Irlen filters used by the participants were not uniformly distributed in UCS (see Figure 85), it is very difficult to perform any meaningful comparison of screen and overlay colours.

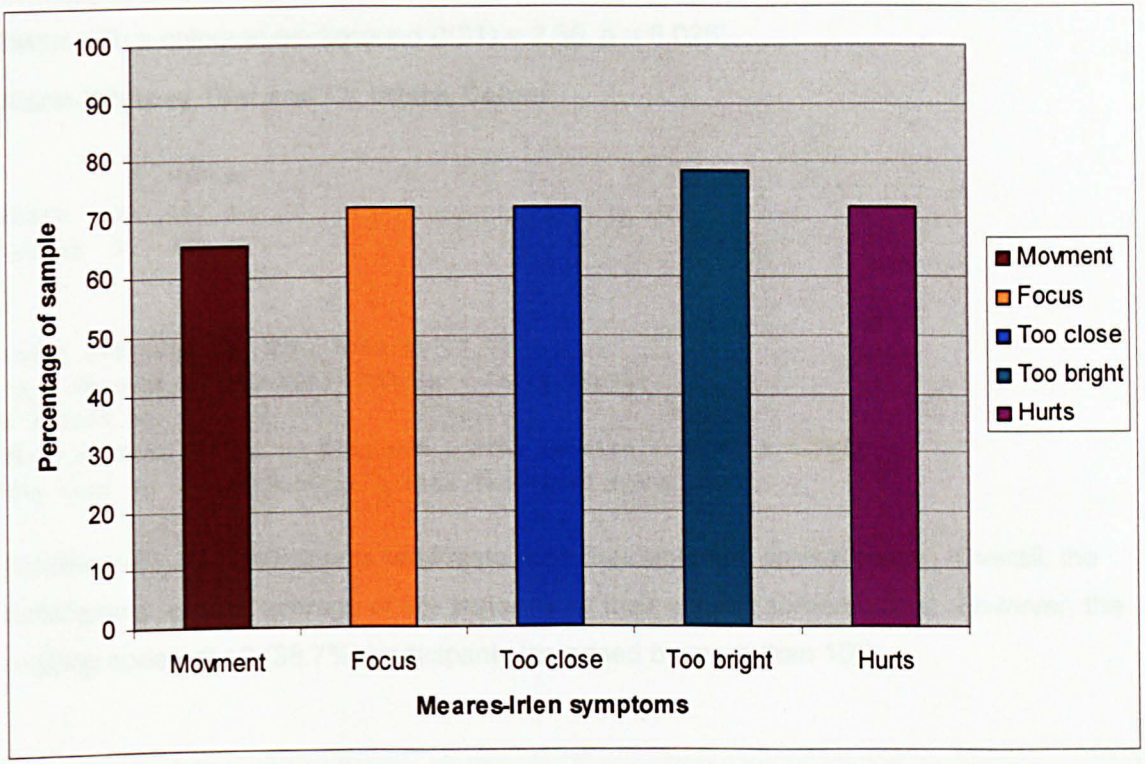
However, all participants (N = 32, 100%) reported positive benefits from using their optimum screen colour compared to the white background.

The prevalence of each individual symptom at baseline is shown in Table 20 and graphically in Figure 86. These were only recorded at baseline against a white background. As can be seen from this table, the most common symptom was the page looking too bright (78.1%).

Table 20 – Table showing the prevalence of Meares-Irlen symptoms at baseline

Symptom	**N = 31**	**Mean; (s.d.)**
Do the words appear to move, wobble or flicker?	21 (65.6%)	1.77 (1.50)
Do the words go in and out of focus?	23 (71.9%)	1.84 (1.37)
Do the words look too close together?	23 (71.9%)	1.74 (1.26)
Does the page look too bright or dazzling?	25 (78.1%)	2.39 (1.52)
Does it hurt your eyes when you look at the page?	23 (71.9%)	1.87 (1.50)

Figure 86 – Histogram showing frequency of visual stress symptoms in response to the questionnaire



4.5.3.2 Task performance

A summary of the results for the Rate of Reading test with a white background and with the preferred colour is shown in Figure 87. The Anderson Darling test indicates that these data are not normally distributed.

Figure 87 – Summary of the data for the Rate of Reading test against a white background and with the preferred colour

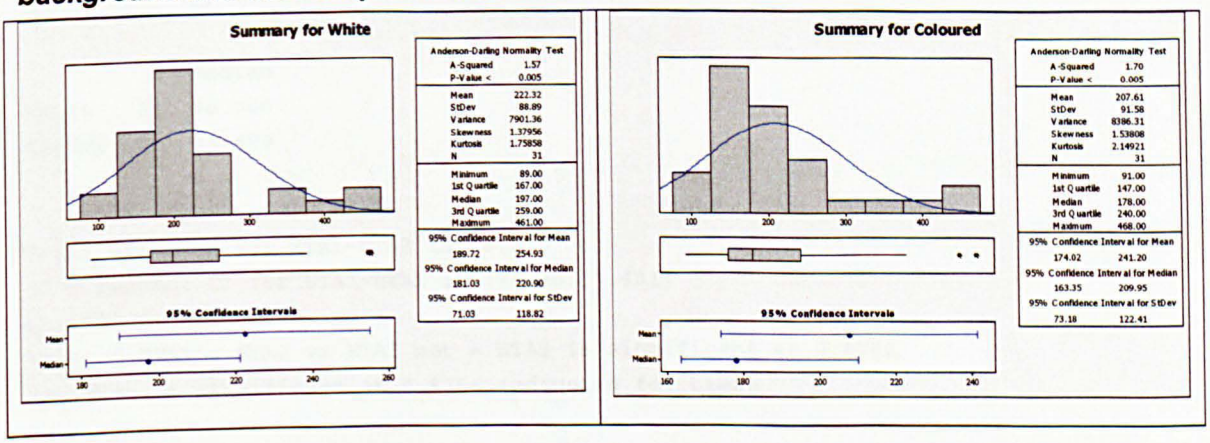


Figure 87 shows that the mean time for participants to complete the computerised Rate of Reading test against a white background was 222.32s (s.d. = 89.89s) and against the optimum coloured background, 207.61s (s.d. = 91.58s). Using a Mann-Whitney 'U' test, this was not significant (u = 0.245; NS). As statisticians appear divided on whether data that

mildly departs from a normal distribution should be analysed with the t-test or the Mann-Whitney U test, the results were re-analysed using a t-test. Overall, Ss read significantly faster with a coloured background ($t(31) = 2.36$, $p = 0.025$).

Mann-Whitney Test and CI: White, Colour

```
         N  Median
White   31  197.00
Colour  31  178.00


Point estimate for ETA1-ETA2 is 17.00
95.1 Percent CI for ETA1-ETA2 is (-15.02,48.01)
W = 1059.5
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.2454
The test is significant at 0.2454 (adjusted for ties)
```

Nineteen (61.3%) participants read faster with their optimum screen colour. Overall, the participants read an average of 9% faster using their chosen screen colour. However, the reading speed of 12 (38.7%) participants increased by more than 10%.

4.5.3.3 Spreadsheet Analysis results

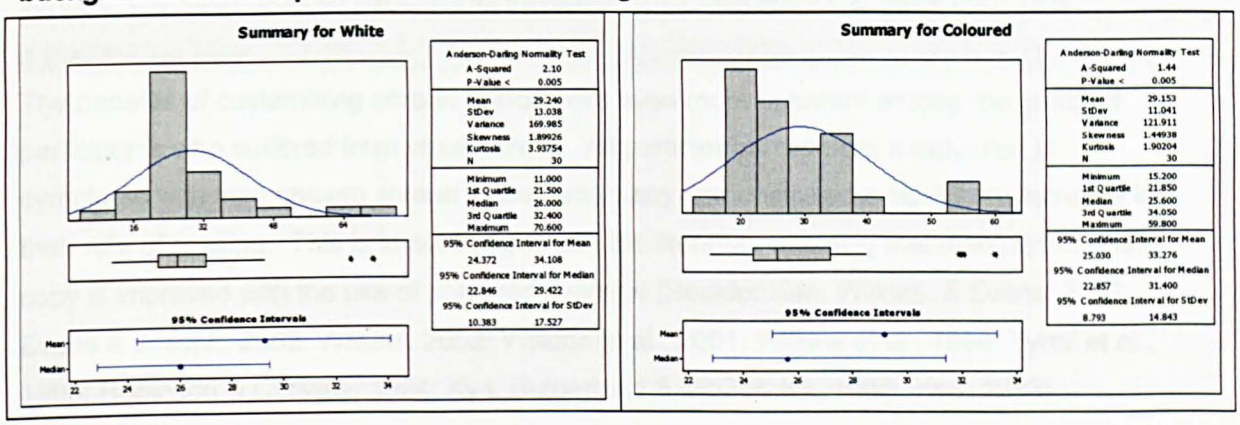
Figure 88 shows that the mean time for participants to complete the Spreadsheet test against a white background was 29.24s (s.d. = 13.03s) and against the optimum coloured background, 29.15s (s.d. = 11.04s). This was not significant using either a Mann-Whitney ($u = 0.877$; NS) or a t-test ($t(30) = 0.04$, $p = 0.965$).

Mann-Whitney Test and CI: White, Colour

```
         N  Median
White   30  26.000
Colour  30  25.600


Point estimate for ETA1-ETA2 is -0.300
95.2 Percent CI for ETA1-ETA2 is (-4.803,3.601)
W = 904.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.8766
The test is significant at 0.8766 (adjusted for ties)
```

Figure 88 – Summary of search times for the Spreadsheet Test against a white background and the preferred coloured background



4.5.3.4 Nonsense Sentences Results

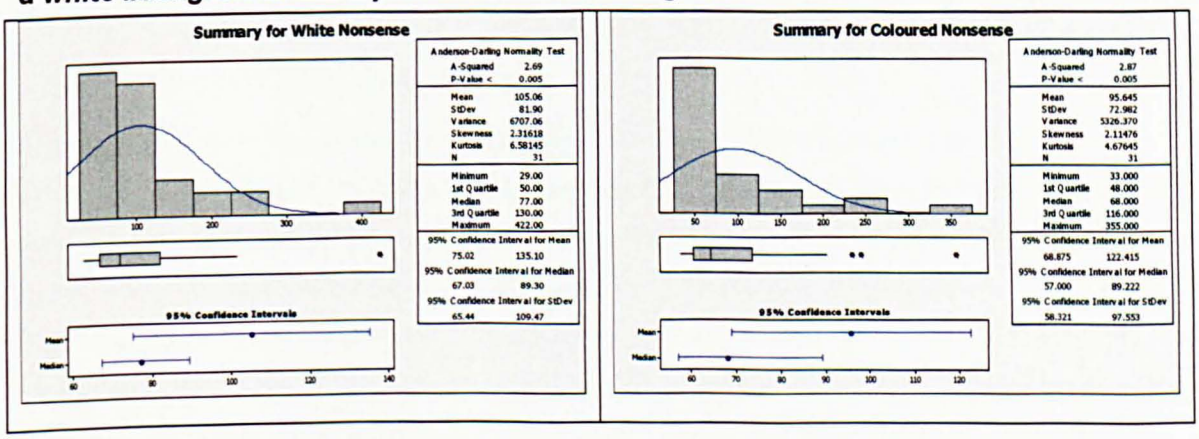
The mean time for participants to complete the Nonsense Sentences task against a white background was 105.06s (s.d. = 81.90s) and against a coloured background, 95.64s (s.d. = 72.98s) – see Figure 89. This was not significant with either a Mann-Whitney (u = 0.418; NS) or a t-test (t(31) = 1.96, p = 0.059).

Mann-Whitney Test and CI: White, Colour

```
        N  Median
White  31   77.00
Colour 31   68.00


Point estimate for ETA1-ETA2 is 6.00
95.1 Percent CI for ETA1-ETA2 is (-12.00,27.00)
W = 1034.5
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.4182
The test is significant at 0.4181 (adjusted for ties)
```

Figure 89 – Summary of time taken to complete the Nonsense Sentence task against a white background and a preferred colour background



Twenty (62.5%) of the participants increased their task speed with the use of the coloured screen. Eighteen (56.2%) participants increased their task speed by more than 10%.

4.5.4 Conclusions

The benefits of customising screen colour were even more apparent among the group of participants who suffered from visual stress. All participants reported a reduction in symptoms with their chosen screen colour and many demonstrated a significant increase in their rate of reading. This is in agreement with the literature showing that reading from hard copy is improved with the use of coloured overlays (Bouldoukian, Wilkins, & Evans, 2002; Evans & Joseph, 2002; Wilkins, 2002; Wilkins et al., 2001; Wilkins et al., 1996; Tyrell et al., 1995; Robinson & Conway, 1994; Kyd, Sutherland & McGettrick, 1992; Irlen, 1983).

However, customising screen colour did not produce a significant improvement in the Spreadsheet and Nonsense Sentence tasks. This is contrary to the findings of Tyrell et al. (1995), and Wilkins & Neary (1991) who showed an improvement in visual search performance with coloured filters. Whiting, Robinson and Parrott (1994) and Whiting & Robinson (1988) showed that comprehension improved in 70-90% of participants using coloured overlays. Other studies have reported similar findings (Robinson & Conway, 1994; Robinson & Conway, 1990; O'Connor et al., 1990; Gole et al., 1989; Hannell et al., 1989; Irlen, 1983).

4.6 Colour Memory

4.6.1 Introduction

The use of colour to improve visual "comfort" still remains controversial despite the growing body of supporting evidence. One of the persistent criticisms levelled at studies that have shown a benefit of colour is that subjects simply prefer certain colours and are able to remember their preferred colour and, therefore, replicate results from visit to visit.

As a tangential study to the main investigation, it was decided to explore the accuracy of short term and longer term memory for colours.

Memory for colours is usually considered in relation to surface colours; that is colours of meaningless patches (Perez-Carpinell et al., 2001) or real objects (Perez-Carpinell et al., 1998; Bodrogi & Tarczali, 2001). Memory is influenced by how readily a colour can be named, and how useful that name is in discriminating the colour from others in the experiment (Guest & Van Laar, 2002).

Using two experimental conditions, de Fez et al. (2001) compared differences between subjects who were required to simultaneously match and memory match a colour using Munsell Atlas reference tests. They showed that subjects tended to select brighter colours irrespective of the condition. In addition, those colours that were more successfully matched lay along the red-green axis with the worst matching lying along the blue-yellow axis. McManus, Jones, and Cottrell (1982) found that blue hues were preferable to yellow hues.

Perez-Carpinell et al. (1998) examined colour matching using simultaneous, successive and memory matching. They showed that simultaneous matching produced the most accurate results with lower mean colour differences than for either of the other two conditions. They also found that certain colours were more difficult to remember than others. These included yellow, light green, blue and pink with orange being the best remembered colour. These findings also supported those by de Fez et al. (2001) and Mcmanus et al. (1982).

Boynton and Olson (1990) found that 'basic' colours were named quicker than 'non-basic' colours. In keeping with this, Ratner and McCarthy (1990) demonstrated that 'typical' colours were recalled with greater accuracy than 'non-typical' colours.

These studies measure colour in relation to real objects. However, colour memory is rarely measured under conditions in which the eyes have a chance to adapt to the colour, as occurs when coloured light is used as a light source. Despite this, Seliger (2002) has obtained measurements of the ability of observers to remember and reproduce monochromatic light. He presented light from a monochromator for 0.2-3 secs before changing the wavelength by a minimum of 30-40nm. Subjects were then required to turn a knob to immediately reproduce the colour. Seliger measured the error in terms of the

standard deviation in nanometers. The standard deviation varied with wavelength but was generally about twice the threshold at which one wavelength can be discriminated from another. When replotted in terms of the CIE UCS space, the standard deviation of the difference in chromaticities that can reliably be discriminated averages 0.0368 (s.d.=0.0224).

The difference in chromaticity of a surface of uniform spectral reflectance under incandescent light (CIE Standard illuminant A) and under fluorescent light (CIE Type F2) is 0.0434 and between a fluorescent (F2) source and daylight (CIE Standard illuminant D65) is 0.0385. The largest such difference is between daylight and incandescent light (0.087). All these differences lie within two standard deviations of the difference in chromaticities that can reliably be discriminated.

It would make sense in evolutionary terms if memory for the colour of illumination has a precision appropriate for the variability within which changes in illuminant chromaticity are normally encountered. It seems plausible to expect the visual system to be insensitive to differences in illuminant colour that are of little survival value, including differences that are typically "discounted" in order to maintain "colour constancy". Seliger's measurements were undertaken using monochromatic light, and were, as a result, of maximum saturation and limited to spectral colours. The present study extended the measurements to non-spectral colours of low saturation in order to see whether memory for these colours was equally poor.

The study was motivated not only by a desire to determine the precision with which non-spectral colours can be remembered, but also, in part, by the effects of coloured light on reading speed in certain individuals (Wilkins et al., 2001). Reading speed has been shown to decrease with departures from optimal colour in such a way that there is little benefit of the colour once it differs from optimum by a chromaticity difference of 0.076. The question arises as to the extent to which memory for colour is playing a role in the measurement of the effects of coloured light on reading speed.

4.6.2 Methods

The study was performed at the Department of Optometry and Visual Science, City University, London. All second year undergraduate optometry students attending routine visual perception laboratories over a 16 week period between November 2003 and March 2004 were asked if they were prepared to participate in a study examining how well colour was remembered.

4.6.3 Apparatus

A liquid crystal display (Flatron 4710B flatscreen) measuring 340mm horizontally by 270mm vertically was controlled by a program on a personal computer and calibrated using a

Minolta Chroma Meter II so as to display any chromaticity on the perimeter of a circle in the CIE 1976 UCS diagram at a luminance of 120 $cd.m^{-2}$. The circle had a centre with chromaticity u'= 0.198, v'= 0.468 (that of standard illuminant D65) and a radius of 0.06. In other words, the display was of constant luminance and could vary in CIE 1976 hue angle (h_{uv}) without an associated change in the CIE 1976 saturation (s_{uv}). The computer program allowed the hue angle to be varied in a clockwise or anti-clockwise direction at the touch of one of two keys. A single depression of a key changed the hue angle by one degree.

4.6.4 Subjects

Thirty-one male and 65 female undergraduate optometry students and staff at City University aged 18-44 yrs (mean 21 yrs) took part. All participants had normal colour vision, as assessed by the Ishihara 38 plate test.

4.6.5 Procedure

Each subject was seated at a distance of 0.84m from the screen in an otherwise darkened room.

When the subject understood the instructions and was ready, the start button was pressed and the colour was presented on the screen. They were given 10 secs to observe and memorise the hue of the screen and were told they would be required to remember the colour for one week. The screen displayed one of 12 hues selected at random. The 12 hues were spaced 30 degrees apart on a hue circle in the CIE UCS diagram, as described above. The chromaticities are listed in Table 21.

Table 21 – Chromaticities of the standard (to-be-remembered) colours used in Experiment 1

Hue (deg)	u'	v'
0	0.258	0.468
30	0.250	0.498
60	0.228	0.520
90	0.198	0.528
120	0.168	0.520
150	0.146	0.498
180	0.138	0.468
210	0.146	0.438
240	0.168	0.416
270	0.198	0.408
300	0.228	0.416
330	0.250	0.438

Immediately following the 10 sec observation period, the hue angle was displaced by between 40 and 100 degrees hue angle in an anti-clockwise direction. The displacement was random, sampled with equal probability between 40 and 100 degrees. The participant was required to use two keys to vary the hue angle until confident that the screen was once again displaying the original colour, whereupon the space bar was pressed. The computer then changed the colour, again by between 40 and 100 degrees but in the opposite direction to that previously used. Four such trials were completed: for trials 1 and 3 the displacement of colour was anti-clockwise on the hue circle and for trials 2 and 4 it was clockwise. After an interval of an hour, a further four such trials were undertaken, and these were repeated again after an interval of one week. The standard (to-be-memorised) colour was presented once only at the outset of the trials.

Hues were selected at 30° intervals and were randomly assigned to subjects. Saturation and brightness were held constant. As subjects were used more than once, their hue was varied by 60° between testing.

4.6.6 Colour naming and reproduction of nameable colours

An additional six participants from City University, all female, aged 21-35 yrs (mean 27 yrs), were asked to observe the screen while they used the cursor keys to adjust the colour of the screen so that it displayed the best example of each of the following colours: red, orange, green, blue, yellow, purple, pink. The colours were requested in the above order and the participants made four adjustments for each colour in turn. Each of the 12 standard colours listed in Table 21 were then presented in clockwise order beginning with a hue angle of zero, then 330 deg etc, and the participant was required to name the colour, and to rate the acceptability of the name they had provided.

4.6.7 Results: Overall accuracy of naïve observers

The mean errors (in degrees visual angle) with respect to sign for the first four settings were respectively +16.1, +2.3, +13.9 and +0.6. The initial setting was an "undershoot", in other words observers failed fully to restore the hue to its original value. Subsequent settings erred in the same direction, despite the fact that settings 2 and 4 were from a displacement that was in the opposite direction. This suggests that the first setting biased the remaining settings. With hindsight, it may have been better to randomise the starting position. The first setting that participants made, i.e. immediately after the demonstration of the to-be-remembered hue is, therefore, likely to be the least contaminated. Consequently, the following analysis was conducted on this first setting. The data were obtained from 96 participants, a minimum of 7 subjects per hue and a maximum of 9 subjects. The mean separation of the UCS chromaticities between the standard and the adjustment was 0.0210 (s.d. 0.0178) across participants and across hues. On the basis of the data of von Kries, this corresponds to a difference of about 50 times the colour difference that can just be discerned (i.e. about 50 jnds).

4.6.8 Results: Overall accuracy of the group

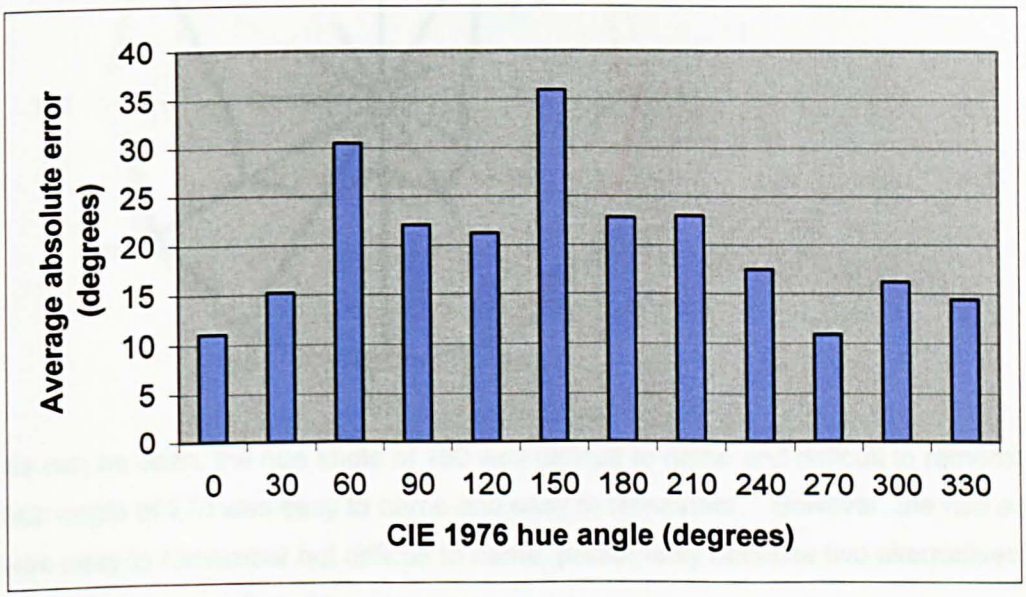
Given that some participants' settings erred in one hue direction and others in the opposite direction, the average hue difference with respect to sign between the standard and the very first setting gives an indication of how close the group as a whole came to replicating the standard immediately after it was shown. The mean was 16.1 degrees (s.d. 21.5), corresponding to a separation in UCS chromaticity of 0.0165 (0.0211) between the standard and the group average. The colour difference was in a clockwise direction from the standard, i.e. in a direction similar to that of the displacement, suggesting that observers tended to underestimate the adjustment required.

4.6.9 Results: Differences as a function of hue

Since the direction of the error may have reflected the direction of the displacement of the hue, the data set was enlarged to include all the four settings that immediately followed the

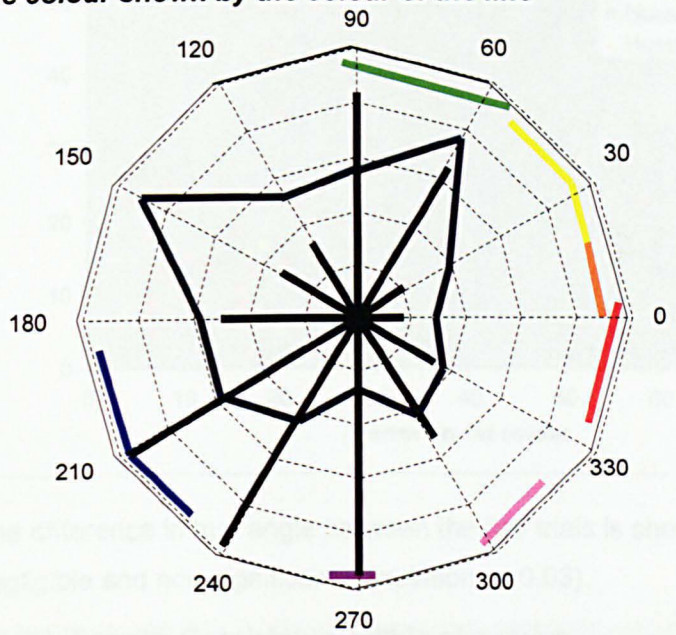
initial presentation of the sample. The absolute value of the error was calculated for each of the four settings per hue and averaged for each participant. The direction of the displacement was balanced across settings and the average across settings better reflected the effect of the sample hue as opposed to the effect of both the sample hue and the displacement. The mean errors are shown in Figure 90. One-way analysis of variance revealed a significant difference between hues ($F_{(11,84)}$=2.46, p=0.01). *Post hoc* comparisons using the method of Bonferroni revealed significant differences between 150 and 0 and 150 and 270 degrees.

Figure 90 – Average error in degrees as a function of the sample hue



A subsidiary study was undertaken in order to check whether the error scores were related to the ability to name the shade of colour shown in the to-be-remembered sample. Six observers were asked to name each of the 12 colours shown and to rate the acceptability of the name they gave. The data in Figure 85 have been replotted in polar coordinates in Figure 91 and are shown by the continuous curve. The length of the bold radial lines in Figure 91 is proportional to the number of participants (0-6) reporting their chosen name as acceptable. The longer the line, the easier the shade of colour was to capture in a colour name.

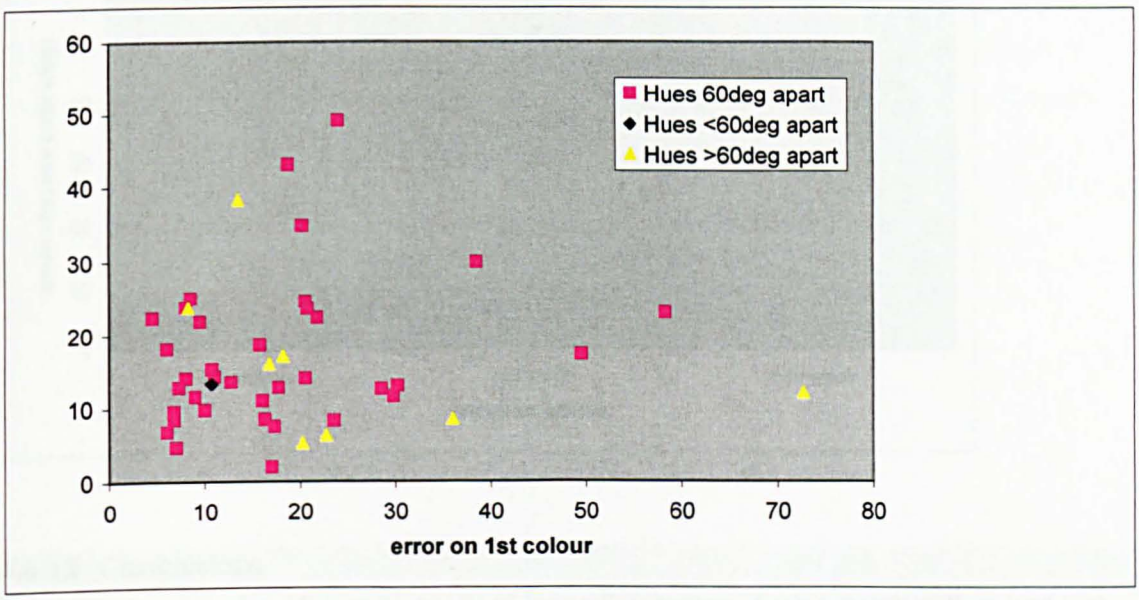
Figure 91 – Polar graph illustrating the accuracy of memory of the colour. The continuous curve shows the accuracy of reproduction of the sample from memory. The radius of the plot corresponds to 40 degrees hue angle. The length of the radial lines are proportional to the number of participants naming the colour with satisfaction. The length of the lines on the perimeter correspond to the range of settings (mean +/- 1 sd) of hue angle when participants were asked to set the hue to the colour shown by the colour of the line



As can be seen, the hue angle of 150 was difficult to name and difficult to remember. The hue angle of 270 was easy to name and easy to remember. However, the hue angle of 0 was easy to remember but difficult to name, presumably because two alternatives (red and orange) were equally valid.

The six participants were asked to adjust the hue to create the best shade of red, orange, green, blue, yellow, purple, and pink. Around the perimeter of the figure are the ranges of hue angles (mean – 1sd to mean +1sd) of the settings. The average setting for purple was 268 degrees and had the lowest standard deviation of the settings (sd = 6.7). This is consistent with the hue of 270 degrees being easy to name and remember. The setting for green was 73 degrees (sd = 21) and for blue 208 degrees (sd = 24), which might explain why, 150 degrees (blue/green) is difficult to name and remember. The border between the settings for nominal "red" and "orange" lie close to 0 degrees, which might explain why this hue is difficult to name, but there remains the question as to why it is easy to remember.

Figure 92 – Graph showing consistency within observers. The graph shows the mean absolute error in degrees hue angle on one trial plotted against the error on a second trial with different hue angle



The difference in hue angle between the two trials is shown in the legend. The data show a negligible and non-significant correlation (r=0.03).

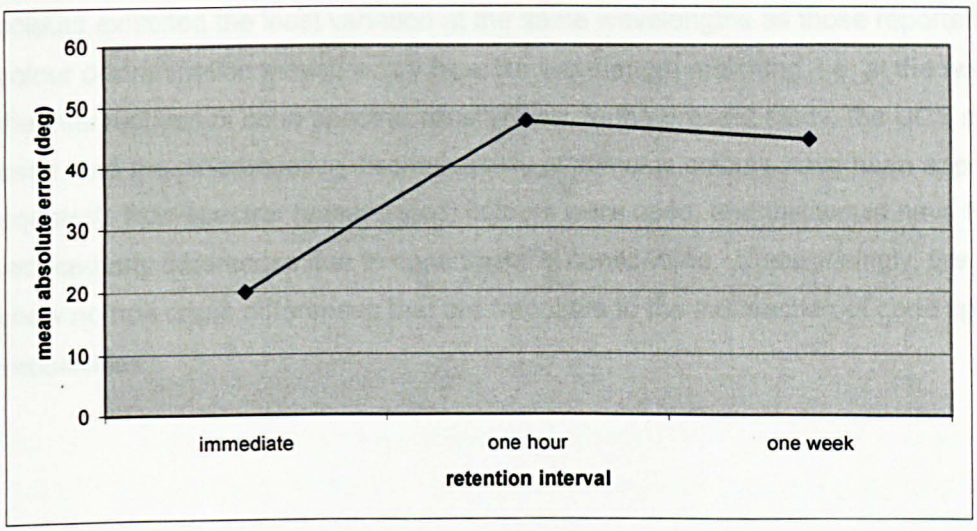
4.6.10 Results: Consistency within observers

Sixty individuals were examined twice more than one week apart, on each occasion with different hues, the hues usually spaced 60 degrees apart. Figure 92 shows the errors obtained by each individual on the two sessions. There was no significant correlation between the error on the two sessions (r=0.03), and so, nothing to suggest that some individuals were consistently more accurate than others.

4.6.11 Results: Stability over time

The sample was presented once only at the outset and the observer attempted to replicate its colour four times on three separate occasions: immediately following the presentation, again after one hour and again after a week had lapsed. The mean of the absolute values of the errors on the four settings are shown as a function of time in Figure 93. The difference between immediate memory and that at one hour was highly significant ($t_{(113)}=5.7$, $p<0.001$). The difference between one hour and one week was not ($t<1$).

Figure 93 – Graph showing the average error in degrees as a function over time



4.6.12 Conclusions

Participants were given the opportunity of immediately reproducing a colour they had just seen but their ability to do so was more than 50 times worse than their ability to match colours that are simultaneously visible according to the data of MacAdam (1942). Philips (1983) has shown that immediate memory for a spatial configuration is greatly impaired by the interpolation of a mask resembling the configuration. The presence of a sample colour, different from that observers were required to remember presumably provided interference with sensory memory similar to that provided by a mask. The method of adjustment, though rapid, carried the disadvantage that the mask was variable.

The standard deviation of the chromaticity difference was 0.0178 which was similar to the figure of 0.0368 obtained by Seliger (2002). It is of interest that in both these studies the standard deviation of the difference in colour that can be discerned from memory (given an intrusive mask) is similar to the difference in the chromaticity of a white surface under different common sources of illumination. The difference in chromaticity of a white surface under incandescent illumination (CIE Standard Illuminant A) and under (CIE Standard Illuminant D65) is 0.0807 and this is likely to be the largest difference customarily experienced. It seems plausible to argue that the visual system is insensitive to differences in illuminant colour that are of little survival value, including differences that are typically "discounted" in order to maintain "colour constancy".

In this respect, it is of interest that the memory performance is close to the limits within which colours benefit reading speed.

Seliger (2002) showed that the wavelength dependence of delayed matching of spectral colours exhibited the least variation at the same wavelengths as those reported for maximal colour discrimination measured by bipartite wavelength matching, i.e. at the wavelengths of the intersections of cone spectral sensitivities. In the present study, the UCS space was used, and the differences in discriminability of stimulus colours have been approximately equated. Non-spectral (unsaturated) colours were used, and this would have further reduced any differences due to cone spectral sensitivities. Unsurprisingly, the present data show no hue angle differences that are traceable to the intersection of cone spectral sensitivities.

4.7 Optimising the colour of displays – general conclusions

It would appear that in certain circumstances, changing the background colour on computer screens to a colour other than white may, at least subjectively, reduce symptoms of asthenopia. These data have not shown any particular trends towards certain colours and it may indeed be the case that the choice of colour is idiosyncratic.

A high proportion of an "unselected" group of computer users reported a beneficial effect of using a preferred colour as a background on their computer screen. However, this subjective improvement was not ratified by an objective improvement in visual performance using the tests developed for the study.

However, subjects with a previous diagnosis of Meares-Irlen did show a subjective benefit and an objective improvement in reading speed when the screen background colour was changed to their preferred colour.

4.7.1 Normal subjects

- Subjectively, the majority of participants (39/40) expressed a preference for a coloured background over a white background on a computer screen.
- The subjective preference shown for a coloured background was supported by a significant reduction in the prevalence and frequency of asthenopic symptoms when participants' worked at displays set up with their preferred colour for a minimum of one week.
- Almost 70% of subjects (27/39) reported that changing the background colour had "made their eyes feel more comfortable".
- Just under half of the subjects (17/39) reported that changing the background colour had made them more efficient in performing computer tasks.
- The fact that 18/39 participants were still using their preferred screen colour one month after the study is compelling support for the benefits.
- Of those subjects that reverted to white, some reported that they had done so reluctantly because the demands of the tasks that they were doing (desktop publishing, web-design).
- There were no clear trends in the choice of colour although a light green background was the most frequently selected colour.

4.7.2 Subjects with visual stress

- All participants expressed a preference for a coloured background over a white background on a computer screen.
- Just over 60% (19/31) of participants read faster with their optimum screen colour although this was not significant.
- Customising screen colour did not produce an improvement in either the Spreadsheet or Nonsense Sentences tasks.
- There were no clear trends in the choice of colour although a pale purple background was the most frequently selected colour.

4.7.3 Colour Memory

- Subjects were poor at reproducing a colour they had just seen.
- Memory performance is close to the limits within which colours benefit reading speed.

5. Optimisation of display parameters for the visually impaired

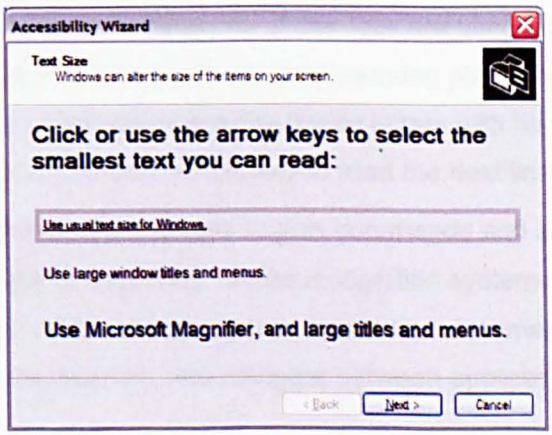
5.1 Introduction

The studies described in the previous chapters have demonstrated that, at least for users with normal vision, the modern computer interface is close to optimum in most respects. Small improvements in user efficiency and comfort may be possible by careful selection of font style and size and by customising the screen background colour but, by and large, software engineers and ergonomists have got it right.

Currently, the standard computer user interface is unsuitable for individuals with any significant degree of visual impairment. However, most operating systems provide facilities for magnifying screen fonts and changing the foreground and background colours.

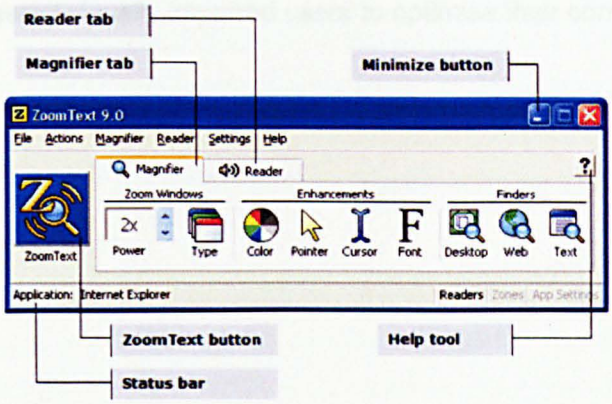
For example, Windows XP provides an Accessibility Wizard to help those with Visual Impairment to customise their screen layout (see Figure 94).

Figure 94 – Windows XP Accessibility Wizard



The functionality of the accessibility options provided by Windows is somewhat rudimentary but a wide range of products are now available to allow complete customisation of the user interface. For example, ZoomText (see Figure 95) allows the user to change font size, screen colours etc. from a simple toolbar.

Figure 95 – ZoomText



For those with severe visual impairment, screen readers which verbalize, or "speak" everything on the screen including text, graphics, control buttons, and menus are available. In essence, a screen reader transforms a graphical user interface (GUI) into an audio interface.

Another option is refreshable Braille displays. These provide tactile output of information represented on the computer screen. A Braille "cell" is composed of a series of dots. The pattern of the dots and various combinations of the cells are used in place of letters. Refreshable Braille displays mechanically lift small rounded plastic or metal pins as needed to form Braille characters. The user reads the Braille letters with his or her fingers, and then, after a line is read, can refresh the display to read the next line.

Speech recognition programs allow people to give commands and enter data using their voices rather than a mouse or keyboard. Voice recognition systems use a microphone attached to the computer, which can be used to create text documents such as letters or e-mail messages, browse the Internet, and navigate between applications and menus by voice command.

In summary, the advent of computers has provided a powerful new tool for the visually impaired. Those with severe impairment can now use screen readers, refreshable Braille displays and speech recognition to interact with computers. Those with less severe impairment can modify the user interface so that it is optimised for their particular visual deficit. However, while software is now available to change a wide range of display parameters, there is very little systematic guidance available to help the visually impaired select the optimum parameters for their visual deficit.

The aim of the pilot studies described in this final chapter was to investigate the effect of various display parameters on the visual comfort and efficiency of individuals with three common types of visual impairment: age-related macular degeneration, retinitis pigmentosa

and glaucoma. It was hoped that this information could be used to inform the development of a software tool to assist visually impaired users to optimise their computer displays.

5.2 Reading with low vision – the effects of colour and contrast

Studies described in the previous chapters have demonstrated that a high proportion of individuals with normal vision prefer using a background colour other than white. It is, therefore, not unreasonable to expect a similar result amongst the visually-impaired. Indeed, there is some reason to expect a greater benefit amongst patients with certain types of visual impairment.

For example, it might be expected that some individuals with increased light scatter in the eyes might benefit from a yellow filter which will filter out shorter wavelengths which are known to be scattered more in some cases. This could increase the contrast of the retinal image under some conditions.

It is also known that some diseases preferentially affect some cone types and/ or their associated neural pathways. For example, there is some evidence that the blue pathway is affected at an early stage in glaucoma. Any degenerative change in the retina is likely to have some effect on the way that chromatic information is processed and this is supported by evidence that colour vision is often affected at an early stage of the disease process.

If this is the case, it is not unreasonable to postulate that some improvement in visual function might be achievable by selectively reducing the input to some chromatic channels and boosting others.

Many studies have investigated the effects of various forms of visual impairment on normal reading (Rosenblum et al, 2000; Lindner et al, 1999; Szlyk et al, 1998; Lindner et al, 1996; Szlyk et al, 1990; Van den Berg, 1989; Legge et al, 1985). Szlyk et al. (1998; 1990) used a questionnaire to investigate 120 subjects with retinitis pigmentosa (RP) and Usher syndrome plus a further 72 subjects with other diseases causing visual impairment. The questions investigated their everyday lives and difficulties with specific tasks. Most subjects reported problems relating to mobility but over 40% of the RP and Usher subjects reported difficulties with reading ordinary newspaper print. Thirty percent of subjects also complained of issues with reading numbers on a television screen.

Another interesting study which unfortunately is in German so I am only able to read the abstract is that by Lindner et al. (1999) who examined 231 German subjects who had visual impairment due to glaucoma, maculopathy, choroidal or retinal dystrophy (such as RP). Subjects were shown 14 non-coloured combinations (light grey to dark grey) and 35 non-coloured/ coloured (yellow, green, red, blue, purple) combinations and 30 coloured/ colour combinations and asked to rate clarity, and hence subjective preference. Results showed that for the non-coloured group, a bright foreground was preferred; for the coloured/ non-coloured group, 90% preferred yellow on a dark background; and for the coloured/ colour

combination, 90% preferred yellow/blue or yellow/purple. This was in agreement with earlier work by Lindner et al. (1996) who demonstrated a subjective preference for positive polarity in a group of 59 ARMD subjects. Again, whites, yellows and greens were more popular than the blues, reds and purples on offer.

Rosenblum et al. (2000) examined the effect of yellow and amber filters on visual acuity and contrast sensitivity in a population of low vision subjects with a variety of ocular pathologies including cataract, macular dystrophies and albinism. The preferred filter varied depending on specific condition. Visual acuity (VA) and contrast sensitivity (CS) were recorded with and without the filter. Significant improvements in VA were demonstrated, notably in those with cataract, and in both low and high spatial frequency contrast sensitivity, notably in those with cataract and congenital macular dystrophies. Glare reduction was suggested as a significant factor in these improvements.

Corning Medical Optics, Denmark, manufacture a glass CPF 527 lens, which is an orange-yellow colour, recommended specifically for a variety of low vision conditions. It reduces the transmission of light below wavelengths of 527nm. Van den Berg (1989) tested this filter on subjects with RP and compared it with other red-coloured lenses. Three normal and 18 RP subjects were investigated both with and without the lenses. Subjects were allowed to choose their preferred red lens but, if no preference was specified, then the CPF 527 was used. The CPF 527 lens was used by all participants to investigate colour vision using the D15 chart. Results showed that all lenses assisted with dark adaptation. For visual fields (tested on a Humphrey VFA), results were variable. The colour vision results with the RP population demonstrated a slight increase in tritanopic confusion but normals were not affected. Only one RP subject demonstrated any repeatable improvements (a mean improvement of both VA and CS combined of 0.2 log units) using the Landolt C to measure VA and the Vistech to measure CS.

The research described by Legge et al. (1985) in Section 2.3 was expanded to include those with visual impairment. They examined reading speed in 16 subjects with various eye conditions utilising the same moving text task as described in Section 2.3. The differing ocular pathologies meant that subjects experienced differing limitations such as visual field problems and loss of contrast. The same transition between good and poor reading was maintained although the peak for subjects with peripheral field loss was in the region of three to six degrees, and for those with central field loss was in the region of 12 and 24 degrees. This latter figure equates to the size of A4 paper. Significant increases in reading speed were observed when contrast was reversed but only in subjects with cloudy media.

Zigman (1990) looked at the effects of using a 450nm filter on contrast sensitivity and vision in subjects with cataract, aphakia and age related macular degeneration. Results showed

improvement in high spatial frequency sensitivity for subjects with cataract, all frequencies for aphakia and both high and low frequencies for ARMD. Zigman postulates from this that vision can be improved by removing short wavelength light before it reaches the eye.

Silver, Gill and Wolffsohn (1995) demonstrated that subjectively, reverse contrast (white on black or white on dark blue) appears to be the preferred combination for reading from CRT screens. Whilst this was the preferred colour combination in the visually impaired sample comprised of subjects with macular disease, cataracts or presbyopia as well as normals, it must be pointed out that the number of normal subjects in this sample was small (N = 16). Following on from this work, Silver, Gill and Wolffsohn (1995) developed a new typeface (Tiresias Screenfont) for use as subtitles with digital television. This font was designed to have medium weight and width of characters and a simple shape and was trialled on closed circuit television with the above sample. Results from this sample of visually impaired individuals suggested that this font might indeed serve its purpose in terms of a subjective preference. However, in an unpublished MSc thesis, (Fisher, 1999) looked at the optimum typeface for elderly or mildly visually impaired VDU users. This study compared three different fonts (Times New Roman, Helvetica and Tiresias) at four different sizes. Fifteen elderly subjects were required to read aloud a passage of text on a VDU screen which was timed. Results indicated that Helvetica point 22 was the optimum font for this population of VDU users although the sample size was small.

Rubin et al. (2006) examined the effects of line width and font on reading speed for a low vision population. The participants in this study all had acuities between 6/9 and 6/36 in their better eye. Rubin et al showed that line width (for characters widths between 35 and 90), had no significant effect using the MNRead charts. The reading speed with four different fonts (Foundry Form Sans, Helvetica, Tiresias PCfont (TIR), and Times New Roman (TNR)) was also compared in this study. TIR was read at an average of 8 wpm faster than the others but this was attributed to the larger size of the letters. Rubin et al then adjusted all the fonts to be the same size, i.e. the same degree of horizontal and vertical space, and subsequently found no differences in reading speed. They concluded that point size of text is the only factor, which significantly contributes to reading speed.

5.3 Definitions of visual impairment

Internationally, there are a number of different definitions for visual impairment or low vision. The World Health Organisation (World Health Organisation, 1992) has recommended an international standardised classification but, in general, though recognised, is not usually accepted as registration criteria.

In the UK, the National Assistance Act 1948 states that a person can be certified as severely sight impaired if they are *"so blind as to be as to be unable to perform any work for which eyesight is essential"*.

There is no legal definition of sight impairment. The guidelines are that a person can be certified as sight impaired if they are "*substantially and permanently handicapped by defective vision caused by congenital defect or illness or injury*".

In the UK, only a consultant ophthalmologist can register a person as sight impaired or severely sight impaired. Only the condition of the person's *eyesight* can be taken into account; other physical or mental conditions must be ignored. The main consideration for sight impairment is visual acuity measured in Snellen notation.

Severely sight impaired persons can be classified into three groups:

- **Group 1**: People who are below 3/60 Snellen, except people who have visual acuity of 1/18 Snellen, unless they also have considerable restriction of visual field.
- **Group 2**: People who have visual acuities between 6/60 and 3/60 Snellen and who have a very contracted field of vision. This usually does not include people who have had a visual defect for a long time.
- **Group 3**: People who are 6/60 Snellen or better, and who have a contracted field of vision especially if the contraction is in the lower part of the field. People who are suffering from homonymous or bitemporal hemianopia who still have central visual acuity of 6/18 Snellen or better should not be registered.

For sight impairment, people can be classified into three groups:

- **Group 1**: People who are between 3/60 to 6/60 Snellen with full visual fields.
- **Group 2**: People who are up to 6/24 Snellen with moderate contraction of the field, opacities in the media, or aphakia.
- **Group 3**: people who are 6/18 Snellen or better with a gross field defect e.g. hemianopia or a marked contraction of the visual field.

A consultant ophthalmologist should also consider a person's age and the duration of their underlying condition when deciding upon suitability for certification.

5.4 Prevalence and causes of visual impairment

The World Health Organisation (WHO) estimates there are over 150 million people in the world with visual impairment. Internationally, the major causes of blindness differ according to country. As of March 2006, there are currently 152,000 people registered as severely sight-impaired, and 155,000 people registered as sight impaired in the UK (Adult Social Services Statistics, 2006).

The causes of visual impairment differ between age groups. The most common causes in children are optic atrophy, congenital cataract, and nystagmus. In the working age and early adult population, the most common causes are retinitis pigmentosa, diabetic retinopathy, and corneal dystrophies. Age-related macular degeneration and glaucoma are the most common causes in the elderly population. The extent of loss of vision and visual function differs with disease, duration and individual.

The studies described in this chapter were limited to patients with the most common causes of visual impairment:

- Age related macular degeneration
- Primary open angle glaucoma
- Retinitis Pigmentosa

5.4.1 Age-related macular degeneration (ARMD)

Age related macular degeneration (ARMD) is usually classified into two distinct forms: "wet" and "dry". Both types cause varying degrees of degradation to central vision. Dry ARMD, also termed non-exudative or atrophic, is the more common.

5.4.1.1 Prevalence of Age-Related Macular Degeneration

ARMD accounts for 30-49% of new blind registrations in the UK (Jackson and Wolffsohn, 2006). It is the most common cause of irreversible visual loss in people over 65 years of age. Heredity, age, race, smoking and hypertension are the most common risk factors (Bourla and Young, 2006). The prevalence of ARMD increases with advancing age. The dry form is by far the most common accounting for approximately 90% of cases of ARMD.

Khan et al. (2006) reports that ARMD is most prevalent in Caucasian races, though there are genetic and environmental risk factors such as smoking.

ARMD classically occurs after 50 years of age, though there are similar conditions that can occur at a younger age.

5.4.1.2 Ocular manifestations of Age-Related Macular Degeneration

Dry ARMD is usually characterised by the presence of drusen which appear as yellow sub-retinal deposits. Drusen may be further described as hard, soft, mixed, confluent, nodular or

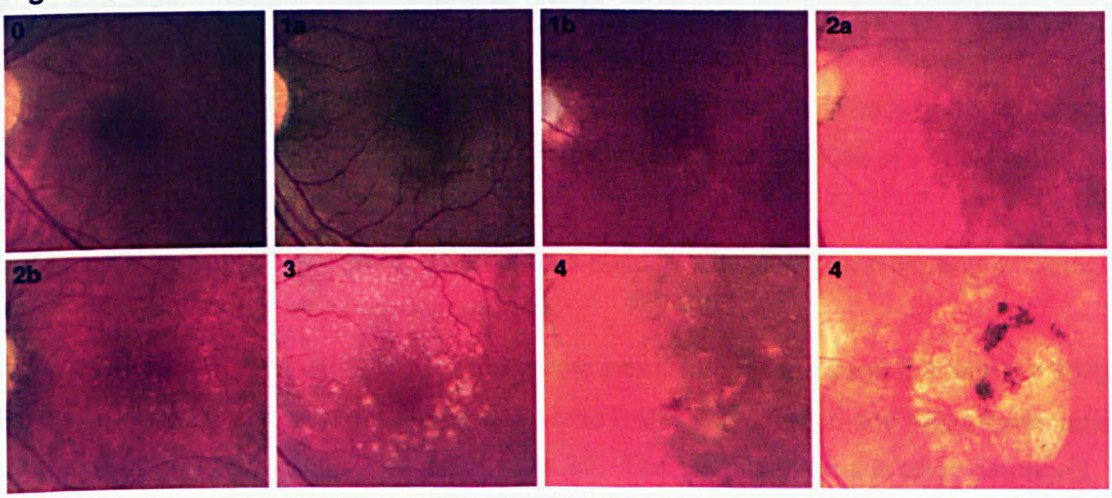
calcified (Kanski, 2003). Confluent drusen may lead to retinal pigment epithelial detachments. Widespread atrophy occurs as the disease progresses.

The other, less common, form of ARMD is usually referred to as "wet", but the terms exudative and neovascular are also used synonymously. With the wet form, the visual loss is usually sudden and severe. The dry form can often progress to the more severe wet form.

Wet ARMD is characterised by choroidal neovascularisation and/ or formation of a neovascular membrane. This results in fluid leakage into the sub-retinal space. Exudative serous RPE detachments may then advance to the neovascular stage.

Seddon & Chen (2004) and Beatty et al. (1999) note a recommendation for an international classification and grading system for ARM. Figure 96 and Table 22 show the modified international grading system for ARM.

Figure 96 – The modified international grading system for ARM



After: Hamada et al. (2006)

Table 22 – The modified international grading system for ARM

Stage	Description
0a	No signs of ARM at all
0b	Hard drusen (<63 μm) only
1a	Soft distinct drusen (≥63 μm) only
1b	Pigmentary abnormalities only, no soft drusen (≥63 μm)
2a	Soft indistinct drusen (≥125 μm) or reticular drusen only
2b	Soft distinct drusen (≥63 μm) with pigmentary abnormalities
3	Soft indistinct (≥125 μm) or reticular drusen with pigmentary abnormalities
4	Atrophic or neovascular AMD

After: Hamada et al. (2006)

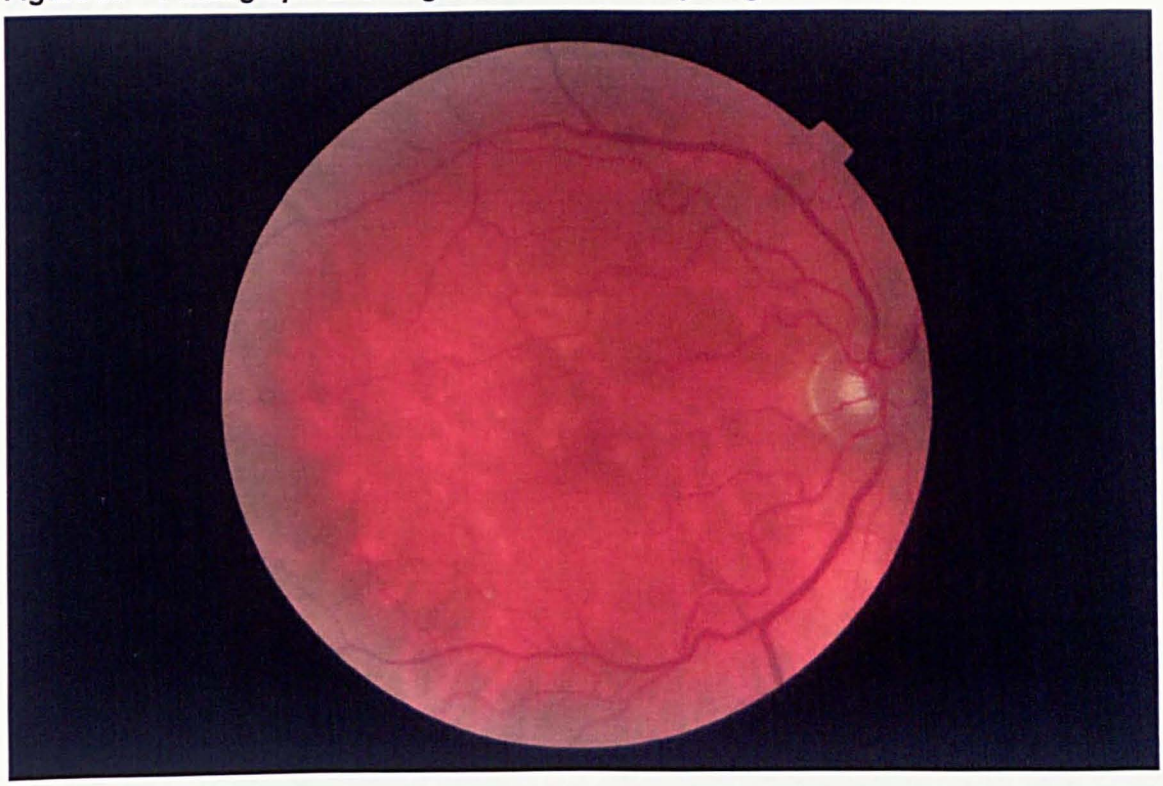
5.4.1.3 Symptoms and signs of Age-Related Macular Degeneration

Dry ARMD is usually slow progressing and in the very early stages, may be asymptomatic. The first symptom may simply be a reduction in acuity. The acuity gradually deteriorates with time, with patients subsequently becoming aware of a central loss of visual field. One or both eyes may be affected.

Exudative (or wet) ARMD usually presents as a sudden loss or extreme blurring of central vision often associated with metamorphopsia.

In the early stages of dry ARMD, discrete yellow excrescences are seen beneath the RPE in the macular region (i.e. drusen), along with some hyperpigmentation and hypopigmentation of the retinal pigment epithelium – see Figure 97. The choriocapillaris is often damaged.

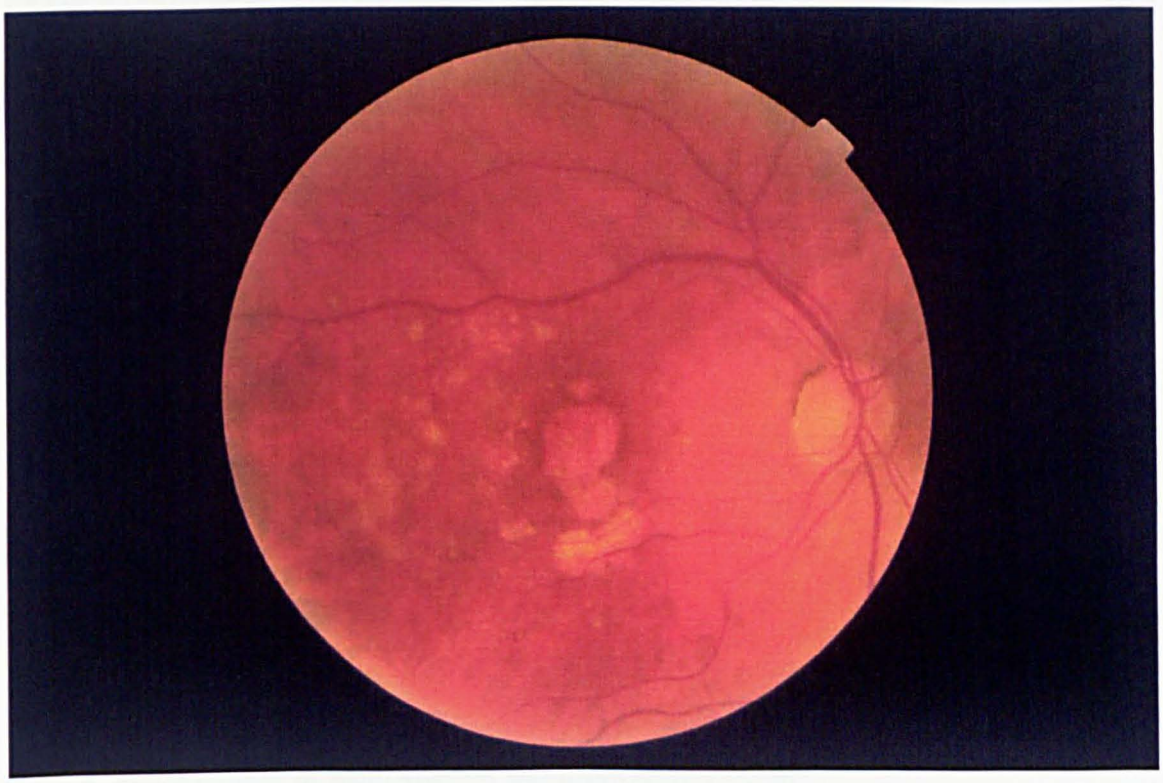
Figure 97 – Photograph showing drusen in the early stages of ARMD



Small distinct drusen are normally referred to as 'hard drusen' and may have no or minimal effect on vision. 'Soft drusen' are usually larger and less distinct and often continue to enlarge with time and may even unite to form bigger areas. Soft drusen are often pre-cursors to exudative ARMD.

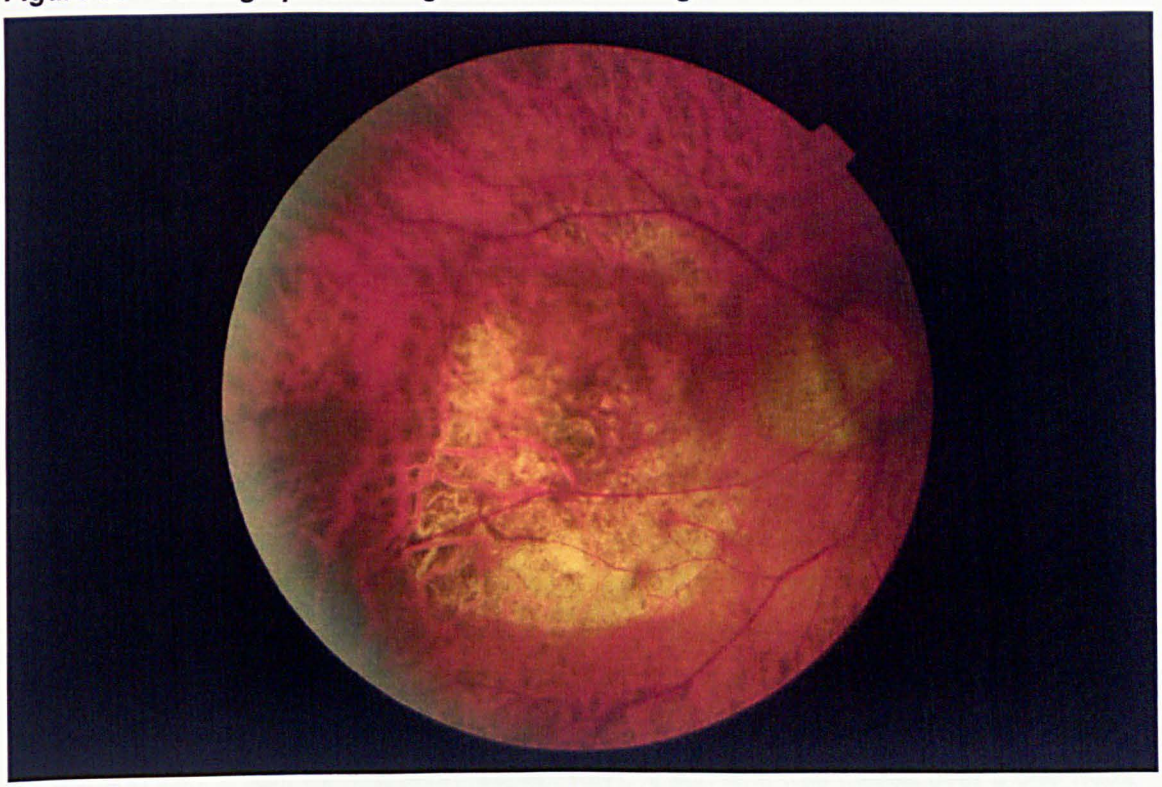
The later stages lead to geographic atrophy of the RPE, pigment epithelium detachment, sub-retinal neovascularisation, haemorrhaging and exudates. Scar tissue may also form – see Figure 98.

Figure 98 – Photograph showing geographic atrophy of the RPE



Exudative ARMD is caused by choroidal neovascularisation from the choriocapillaris. This choroidal neovascularisation may extend into the sub-retinal space. Latter stages may include retinal haemorrhaging, pigment epithelium detachment, vitreous haemorrhaging and disciform scarring – see Figure 99.

Figure 99 – Photograph showing disciform scarring



5.4.1.4 Management of Age-Related Macular Degeneration

There is currently no cure or treatment for dry ARMD. Argon Laser is sometimes applied prophylactically. Patients are sometimes advised to take antioxidant supplements though this is controversial, as there is limited evidence to support the efficacy of this treatment. The Age-Related Eye Disease Study (AREDS) demonstrated some evidence that supplements may slow the progression of dry ARMD (AREDS, 2001).

Fluorescein angiography is often used to aid the diagnosis of wet ARMD and inform decisions relating to its management. Traditionally, exudative ARMD was treated by argon laser photocoagulation, but more recently photodynamic therapy (PDT) has become the treatment of choice. PDT utilises verteporfin; a light sensitive drug which is injected intravenously usually into a patient's arm. When the verteporfin passes through the abnormal vessels of the eye, it is activated by a laser thus sealing the damaged vessels. In 2003, the National Institute for Health and Clinical Excellence (NICE) recommended that PDT be the treatment for people "with confirmed diagnosis of classic subfoveal choroidal neovascularisation (CNV), with no sign of occult CNV".

In rare cases, sub-macular and macular translocation therapies have been used. Laser photocoagulation is effective for extra foveal lesions, and hence is only useful for a small number of patients (Royal College of Ophthalmologists, 2007).

Recent developments have shown that new treatments involving the application of anti-vascular endothelial growth factors (anti VEGF) via intravitreal injection may be beneficial. The use of anti-VEGFs are topical and controversial. It is known that vascular endothelial growth factors play a significant role in the development of choroidal neo-vascularisation (CNV). Three anti-VEGF agents have been investigated for treatment of wet ARMD: Pegaptanib (Macugen) , Ranibizumab (Lucentis) and Bevacizumab (Avastin). In the UK, NICE are in the process (as of the beginning of 2008) of making Lucentis available on the NHS.

As both atrophic and exudative macular degeneration result in permanent vision loss, patients are often referred for low vision assessments. The result of these assessments may mean that patients are provided with low vision aids such as magnifiers or CCTV.

1.4.1.5 Reading and Age-Related Macular Degeneration

There have been several studies examining how coloured lenses may benefit patients with ARMD (Eperjesi et al, 2004; Wolffsohn et al, 2002; Eperjesi et al, 2002; Jacobs, 1990). Wolffsohn, Dinardo and Vingrys (2002) asked ten elderly subjects with dry ARMD and five elderly controls to trial four different lenses (grey, red, orange and yellow; 10.3%, 16.8%, 22.9% and 29.7% light transmission respectively). Each lens was trialled over a one week period. Subjects were required to keep a diary on how many hours per day they wore each lens as well as giving each lens a rating for 'brightness', 'distinctiveness', 'colours' and 'overall performance'. At the end of each week, subjects were tested on objective measures ('distance visual acuity', 'contrast sensitivity', 'glare sensitivity', 'extra-foveal sensitivity' and 'colour vision' using the Farnsworth-Munsell 100 hues test). Results showed that the lenses with lower light transmission (i.e. red and grey) not surprisingly reduced contrast sensitivity (CS), whilst those with the higher light transmissions (i.e. yellow and orange) tended to increase CS. It is worth pointing out that these results were not significant though. As could be predicted, the low transmission lenses fared less well on all objective tests and this is presumably because they let less light through.

A subsequent study looked at 32 participants with atrophic ARMD, examining CS with and without filter lenses. They found no statistically significant improvement with high contrast charts, but with the low (10%) contrast they found an improvement with the LVI 527 filter. In a review of the literature, Eperjesi, Fowler and Evans (2002) identified a number of studies that had investigated the potential benefits of tinted lenses and filters for the visually-impaired but concluded that the results were ambiguous and "failed to prove any consistent objective benefit of tinted lenses or filters". They were not able to find any evidence that filters had any positive effect on visual function or that indeed specialist filters were any better than conventional sunglasses.

Eperjesi, Fowler and Evans (2004) examined 12 ARMD sufferers using coloured overlays, and measured their reading rate. They failed to elicit a clinically significant improvement.

Jacobs (1990) examined reading speed for 16 subjects with various eye pathologies including five with ARMD. Jacobs found that changing the screen colour between white, green and amber had no significant effect on reading speed.

5.4.2 Glaucoma

Glaucoma is a group of diseases characterised by an irreversible and usually progressive optic neuropathy. There are many types of glaucoma but they can be broadly divided into open-angle or closed-angle (angle-closure) glaucoma. In the UK, the most common form is primary open angle glaucoma (POAG), affecting approximately 1 in 200 people over the age of 40 (Kanski, 2003).

Glaucoma is a leading cause of irreversible blindness in the world. The World Health Organisation (1995) reported that glaucoma accounts for blindness in 5.2 million people or 15% of global blindness. Quigley and Broman (2006) found that more women and Asians are affected.

A Royal College of Ophthalmologists (RCO) study (2002) estimated that 5% of new blind and partial sight certification for the UK population aged 16-64 was due to glaucoma. The RCO also estimates that glaucoma accounted for 13% of all new blindness certifications in one year (for those aged 65 years and over).

Reidy et al. (1998) examined visual impairment in an elderly population. They established that 3% had chronic open angle glaucoma whilst 7% had suspected glaucoma. The RCO estimate that between a quarter and a third of all patients attending ophthalmology clinics have glaucoma with 15,000 new cases presenting each year.

People with a family history of glaucoma are approximately ten times more likely to develop glaucoma if they have a first degree relative with the disease (Wolfs et al., 1998). Diabetics and African-American people are three times more likely to develop primary open angle glaucoma. A number of studies also suggest that there is a correlation, not necessarily causal, between glaucoma and systemic hypertension. (Mitchell et al, 2004; Bonomi et al, 2000).

5.4.2.1 Symptoms and Signs of Primary Open Angle Glaucoma

In the early stages of POAG, patients are usually asymptomatic and may only become symptomatic in the very advanced stages when severe visual field loss has occurred.

The typical optic neuropathy associated with glaucoma is usually coupled with characteristic field loss. Foster et al. (2002) state that it is the characteristic pattern of damage to the optic nerve head "that differentiates glaucoma from other causes of visual morbidity". It is usually

accepted that the damage is noted at the inferior and superior aspects of the disc, and many practitioners will record vertical cup disc changes. Other signs include a large cup to disc ratio >0.3, a vertically oval cup, asymmetrical CD (>0.2) between the two eyes, disc pallor, nasal displacement of blood vessels, notching at the neuroretinal rim and splinter haemorrhages. There are two other less significant retinal signs with POAG; the first with the retinal nerve fibre layer and the second, in the parapapillary area.

Elevated intraocular pressure is an extremely common causative risk factor for POAG. However, elevated IOP is rarely used as a single diagnostic factor. There are two theories regarding the mechanism of glaucomatous damage due to elevated intraocular pressure (Kanski, 2003). Kanski describes the first as the "indirect ischaemic theory" which is where raised intraocular pressure causes nerve fibre death by "interfering with the microcirculation of the optic nerve head". The second theory is the direct mechanical theory where the raised pressure directly damages nerve fibres. It should be noted however, that not all glaucomas are associated with raised intraocular pressure.

Intra-ocular pressures over 21mmHg are usually suspicious as is a >4mmHg difference between the eyes. A diurnal variation >5mmHg is also cause for concern.

The functional damage from glaucoma is fundamentally loss or damage to the visual field. Foster et al. (2002) described the generally accepted characteristic glaucomatous field loss as:

- Asymmetrical across the horizontal midline (in early/moderate cases)
- Located in the mid-periphery (in early/moderate cases)
- Clustered in neighbouring test points
- Reproducible on at least two occasions
- Not explained by any other disease
- Considered a valid representation of the subjects functional status

  (based on performance indices such as false positive rate)

The diagnosis of glaucoma is usually confirmed if the eye in question has a combination of factors. Foster et al suggested that glaucoma should be "classified according to three levels of evidence". Their suggestions are shown in Table 23.

Table 23 - The diagnosis of glaucoma in cross sectional prevalence surveys

Category 1 diagnosis (structural and functional evidence)
Eyes with a CDR or CDR asymmetry >97.5th percentile for the normal population, or a neuroretinal rim width reduced to <0.1 CDR (between 11 to 1 o'clock or 5 to 7 o'clock) that also showed a definite visual field defect consistent with glaucoma.

Category 2 diagnosis (advanced structural damage with unproved field loss) If the subject could not satisfactorily complete visual field testing but had a CDR or CDR asymmetry > 99.5th percentile for the normal population, glaucoma was diagnosed solely on the structural evidence.
Category 3 diagnosis (Optic disc not seen. Field test impossible) If it is not possible to examine the optic disc, glaucoma is diagnosed if: (A) The visual acuity <3/60 and the IOP >99.5th percentile, or (B) The visual acuity <3/60 and the eye shows evidence of glaucoma filtering surgery, or medical records were available confirming glaucomatous visual morbidity.

After: Foster et al. (2002)

5.4.2.2 Management of Primary Open Angle Glaucoma

Management of POAG is usually pharmacological. There are a number of different topical medications used, the most commonly prescribed being:

- Prostoglandin Analogues which increase uveoscleral outflow of aqueous humour.
- Carbonic Anhydrase Inhibitors which lower secretion of aqueous humour by inhibiting carbonic anhydrase in the ciliary body.
- Beta Blockers which decrease aqueous humour production.
- Sympathomimetics which increase outflow of aqueous humour through both the trabecular meshwork and uveoscleral pathway.
- Miotics which work by contraction of the ciliary muscle and, therefore, pulling on the trabecular meshwork causing increased outflow of the aqueous humour.
- Alpha-Agonists which decrease aqueous production as well as increase outflow via the uvsoscleral route.

5.4.3 Retinitis Pigmentosa (RP)

First discovered by Donders in 1857, Retinitis Pigmentosa (RP) (also termed Pigmentary Retinal Dystrophy or Degeneration) is a group of diseases affecting the retina (Kanski, 2003; Kanski & Thomas, 1990). It is a genetic, hereditary disease primarily affecting the rods, though cones are affected to a lesser extent (Miller, 1990). From a visual function perspective, RP causes progressive field loss (Grover et al., 1996).

Typically, RP is classified according to its mode of inheritance with one or more defective genes: autosomal dominant, autosomal recessive, x-linked and mitochrondrial (maternally inherited) (Rivolta et al., 2002) although atypical variations exist associated with systemic disease. The most common systemic association is Usher Syndrome which is RP coupled with hearing difficulties (Weleber, 1989).

5.4.3.1 Prevalence of Retinitis Pigmentosa

RP is an inherited, degenerative rod-cone dystrophy affecting approximately 0.02% of the population globally (Rivolta et al., 2002). Mohidin and Yusoff (1998) showed that RP was the most common cause of visual impairment recorded in people attending a low vision clinic in Malaysia, accounting for 13.3% of the total sample population. In the age group 30-59 yrs, RP was the commonest cause of visual impairment (21.5%) whereas it had accounted for only 12.8% of the group less than 30 yrs of age. However, the Malaysian population is much younger than a UK population with less than 4% of people being older than 65 yrs.

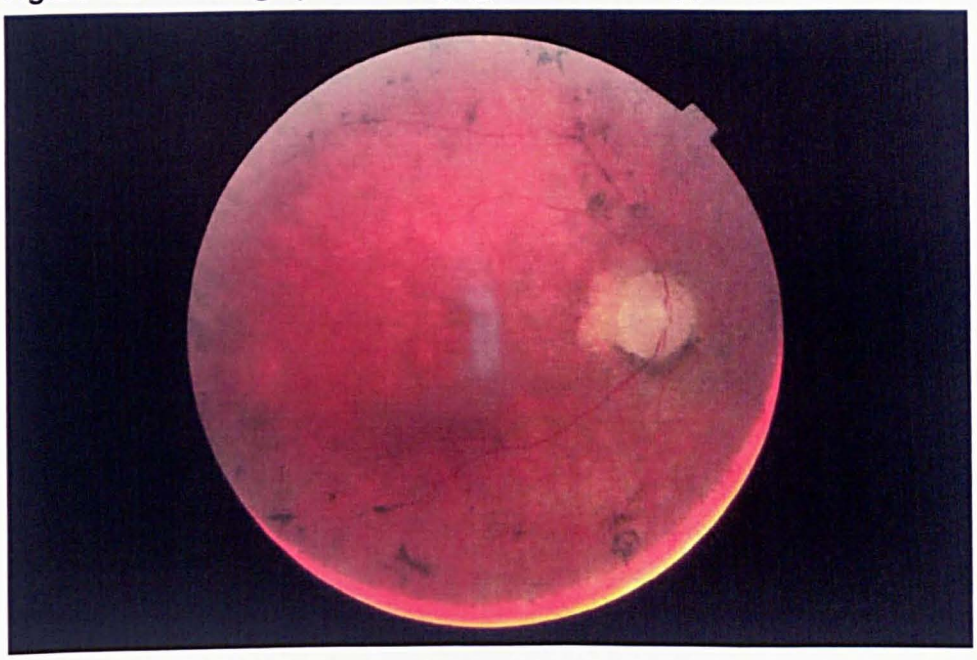
5.4.3.2 Symptoms and Signs of Retinitis Pigmentosa

RP patients frequently exhibit cataracts; the most common type being posterior subcapsular. Patients are usually myopic (Kanski, 2003; Pruett, 1983). Pruett (1983) also describes vitreous changes including vitreous detachment. Kanski (2003) states that optic nerve head drusen (ONH) are seen more often in patients with RP than in those without. Kanski also mentions that primary open angle glaucoma (POAG) is seen in 3% of cases.

In the initial stages of RP, typically patients present complaining of night blindness (*nyctalopia*). Due to the progressive nature of the disease, patients are not usually aware of any visual field loss until the latter stages (Weleber, 1989).

The classic sign seen in RP is "bone spicule" pigmentary degeneration (Kanski, 2003). This resembles pigment clumps which initially appear in the mid-peripheral retina – see Figure 100. Initially, rods are affected (hence the term 'rod-cone dystrophy' is sometimes used) with outer segment degeneration before inner segment degeneration leading to a gradual hyper/ hypopigmentation of the retinal pigment epithelial cells.

Figure 100 – Photograph showing typical fundus appearance with RP

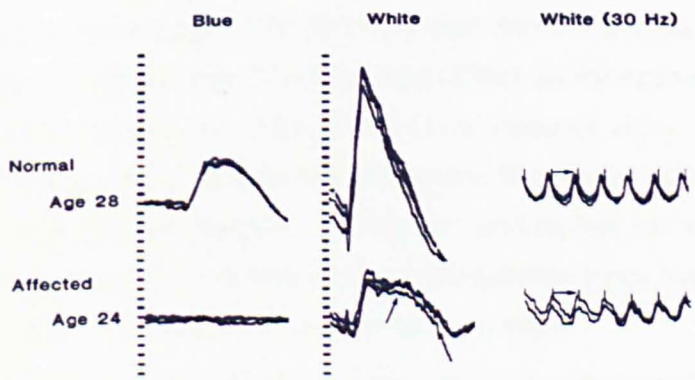


The pigmentation is not always seen in the very early stages of the disease and, consequently, is termed as retinitis pigmentosa sine pigmento. Pruett (1983) also describes narrowing of retinal blood vessels. Maculopathy may also be observed.

Visual field loss characteristically occurs in the mid-peripheral field, typically 30-50 degrees from fixation (Weleber, 1989).

RP is frequently investigated using the electroretinogram (see Figure 101). The electroretinogram measures retinal response to stimulation of light. The rods show reduced response in the early stages, then combined rod and cone, with the isolated cone system showing reduced response in the latter stages (Kanski, 2003).

Figure 101 – ERG response for a normal and an RP subject (After Berson, 1990)



5.4.3.3 Aetiology of Retinitis Pigmentosa

There are four types of RP (Kanski, 2003):

- X-linked
- Autosomal recessive
- Autosomal dominant
- Idiopathic

The X-linked form is the rarest form (Pruett, 1983) but is also the most aggressive (Kanski, 2003). Miller (1990) states that with the X-linked form, the symptoms of nyctalopia and visual field loss occur earlier than with the other forms.

The most common form of RP is the autosomal recessive form usually occurring in the third decade of life. The next most common is the autosomal dominant form, and is usually less aggressive than the autosomal recessive, and tends to develop later in life (Kanski 2003).

5.4.3.4 Management of Retinitis Pigmentosa

There is currently no cure for RP and management primarily involves the provision of suitable low vision aids such as magnifiers, CCTV systems and field expanders.

In the late 1960s / early 1970s, Berson hypothesised that light entering the eye could be leading to a destruction of rod photoreceptors. His suggestions of long term occlusion to protect the eye from light were neither practical nor proven (Berson, 1971). However, it was thought that a more suitable solution may be tinted lenses which could reduce the amount of light entering the eye thus giving it some protection. It is usually thought that brown, yellow or red - avoiding blue tints which let through harmful rays from the sun - are the most helpful for sufferers with RP (www.bprs.org.uk, 2008).

5.4.3.5 Treatment of Retinitis Pigmentosa

There is currently no treatment for RP. There have been studies to investigate whether vitamins or pharmacological therapy may have some effect (Bahrami et al, 2006; Greenstein et al, 1993). Bahrami, Melia and Dagnelie (2006) demonstrated that lutein supplementation preserved the central visual field of those in a crossover study. However, VA and CS showed no significant improvement with lutein. The effects of lutein were seen to continue after the controlled study period had finished, so that they ran into the placebo stage. Similarly, for the group who went through the placebo stage first, the full effects of the lutein were not seen until after the study period had ended.

Greenstein et al. (1993) investigated the effects of acetozolamide, and found no significant improvements.

5.4.3.6 Reading speed and Retinitis Pigmentosa

Alexander, Derlacki and Fishman (1995) studied the reading speed of patients with RP. They investigated the relationship between VA and CS and reading speed using the Lighthouse Distance Visual Acuity Test and Pelli-Robson Contrast Sensitivity Chart. They demonstrated that both VA and CS have similar reductions with RP but there is greater inter-subject variability with CS. The conclusion was that VA was a more sensitive test for predicting low maximum reading speed.

Virgili et al. (2004a) and Virgili et al. (2004b) examined 76 patients with RP and found that time since diagnosis was the best predictor of reading speed which reflects the progressive nature of the disease (Grover et al., 1998). The same study showed that VA, CS and extent of visual fields were significant factors affecting reading speed. CS best explained the inter-subject variation in maximum reading speed.

Sandberg and Gaudio (2006) tested 33 subjects with either RP or with a disease affecting the retinal choroidal layer, comparing reading speeds with TNR and Courier, differing font sizes, and reverse contrast text, using sentences on a CRT computer screen. MNRead sentences were presented for a fixed duration with subjects required to read the words silently and then aloud to the examiner. CS was demonstrated to be the single most successful predictor of maximum reading speed. Again VA had an effect, but visual fields did not. Participants read TNR significantly faster than Courier, but Sandberg and Gaudio suggest this is because TNR is less widely spaced than Courier so those with reduced central field will read more TNR letters at any given time. The study also established that reversed contrast was more effective in patients with reduced CS.

Due to variability in results, it is difficult to have confidence in the reliability of VA and CS measurements with a low vision population. Kiser et al. (2005) established that variation with VA and CS was two or even three times greater with advanced eye disease than variations recorded with a normal population. This increased variation explains why studies often elicit inconsistent conclusions.

5.5 The effects of display parameters on the performance of the visually impaired

5.5.1 Introduction

The aim of the experiments described in this chapter was to investigate the effects of various display parameters on the performance of a small group of individuals with age-related macular degeneration, glaucoma and retinitis pigmentosa.

The heterogeneous nature of these conditions and the hugely variable visual deficits associated with them makes this form of study extremely difficult. With the relatively small number of subjects used in these experiments, the current study can only be considered as a pilot-study. However, it is hoped that the results and some of the procedures devised to capture the results will provide a basis for future studies with much larger sample sizes.

On the basis of the results described in previous chapters and a review of the literature, the effect of the following display parameters on reading performance was examined.

- **Contrast polarity**: black on white and white on black
- **Colour (positive polarity)**: black text against coloured backgrounds
- **Colour (negative polarity)**: coloured text against a black background
- **Colour (mixed colours)**: combinations of coloured text and coloured background
- **Fonts**: three different fonts were tested with black on white: Arial (sans serif), Times New Roman (serif) and Tiresias PC font. (In retrospect, given the results of the experiment described in Chapter 3, it would of beeen of interest to include Trebuchet and Verdana fonts. However, this data was not available when this study was commenced.).

The following data were collected for analysis.

- **Demographic details** – age and sex.
- **Clinical details** – diagnosis and year of diagnosis.
- **Visual acuity** at distance using Test Chart 2000 (logMAR) and near (N-point).
- **Contrast sensitivity** using a Pelli-Robson chart at 1m illuminated to give a background luminance of 150 cdm^{-2}.

5.5.2 Subjects

Ethical approval was obtained from the City University Research and Ethical Committee in compliance with the Declaration of Helsinki (2000). All subjects were sent a patient information leaflet prior to commencing the study (see Appendix 1) as represents good

routine practice and all subjects signed a consent form prior to the start of the study (see Appendix 2).

The study recruited:

- Ten participants with a diagnosis of retinitis pigmentosa. These were recruited by placing an advertisement in the Retinitis Pigmentosa 'Fighting Blindness' in-house magazine as well as through the RNIB, and the university refraction and low vision clinics.
- Ten participants with a diagnosis of primary open angle glaucoma. These were recruited through the university refraction and low vision clinics.
- Ten participants with a diagnosis of age-related macular degeneration. These were recruited by placing an advertisement in the Macular Disease 'Side View' in-house magazine as well as through the university refraction and low vision clinics.

All participants had near visual acuities of N24 or better.

The characteristics and clinical details of the participants is shown in Tables 24 and 25 respectively.

Table 24 – Characteristics of patients recruited

Characteristic	ARMD	Glaucoma	Retinitis Pigmentosa
N	10	10	10
Sex (F/M)	4/6	5/5	3/7
Age	Mean = 77.6 yrs Range = 60 – 87 yrs s.d. = 8.07	Age = 71.3 yrs Range = 61 - 80 yrs s.d. = 7.2 yrs	Mean = 43.1 yrs Range = 26 - 68 yrs s.d. = 13.5
Years since diagnosis	Mean = 8.05 yrs Range = 2.5 – 20 yrs s.d. = 5.80	Mean = 10.5 yrs Range = 3 – 25 yrs s.d. = 6.6	Mean = 15.8 yrs Range = 2 – 35 yrs s.d. = 9.5
Vision/visual acuities	Mean = 0.35 logMAR (BEO) Range = -0.3 – 0.9 logMAR s.d. = 0.38	Mean = 0.08 logMAR (BEO) Range = 0 – 0.2 logMAR s.d. = 0.08	Mean = 0.32 logMAR (BEO) Range = 0.1 – 0.7 logMAR s.d. = 0.20
Near vision	Mean = N10.8 Range = N5 – N24	Mean = N5.9 Range = N5 – N14	Mean = N5.4 Range = N5 – N8
Pelli-Robson	Mean = 1.22 Range = 0.45 – 1.65 s.d. = 0.41	Mean = 1.64 Range = 1.5 – 1.65 s.d. = 0.05	Mean = 1.2 Range = 0.45 – 1.65 s.d. = 0.44

Table 25 – Clinical details of patients recruited

Age-related Macular Degeneration Subjects									
Subject	**Sex**	**Age**	**Dx**	**Yrs since dx**	**Peli-Robson**	**Dist VA (RE)**	**Dist VA (LE)**	**Nr VA (RE)**	**Nr VA (LE)**
ARMD01	M	77	Dry BEs	14	0.9	0.58	0.8	N8	N14
ARMD02	F	83	Wet BEs	13	1.35	0.72	1.24	N18	<N48
ARMD03	F	86	Dry BEs	6	0.45	1.48	0.64	N48	N14
ARMD04	F	77	R Dry L Wet	3	1.35	0.34	2.06	N5	<N48
ARMD05	M	60	Dry BEs	20	1.05	0.9	0.9	N24	N24
ARMD06	M	76	Dry BEs	8	1.65	-0.1	-0.1	N5	N5
ARMD07	M	74	Dry BEs	6	1.65	-0.1	0	N5	N5
ARMD08	M	84	Dry BEs	5	0.75	0.6	0.5	N48	N18
ARMD09	M	87	L Dry	2	1.5	0.1	0.18	N6	N6
ARMD10	F	72	R Dry	2.5	1.5	1.38	0.02	N36	N5
Primary Open Angle Glaucoma Subjects									
Subject	**Sex**	**Age**	**Dx**	**Yrs since dx**	**Peli-Robson**	**Dist VA (RE)**	**Dist VA (LE)**	**Nr VA (RE)**	**Nr VA (LE)**
POAG01	M	68	POAG	3	1.65	0.28	0.1	N5	N5
POAG02	M	79	POAG	12	1.65	0	0.3	N14	N18
POAG03	M	67	POAG	25	1.65	0.16	0.12	N8	N5
POAG04	F	75	POAG	11	1.65	0	0.08	N5	N5
POAG05	F	61	POAG	15	1.65	0.02	0.02	N5	N5
POAG06	F	75	POAG	8	1.65	-0.04	-0.02	N5	N5
POAG07	F	62	POAG	5	1.65	0	0	N5	N5
POAG08	M	80	POAG	6	1.5	0.08	0.12	N5	N5
POAG09	M	79	POAG	5	1.65	0.12	0.12	N5	N5
POAG10	F	67	POAG	15	1.65	0.2	0.2	N5	N5

Retinitis Pigmentosa subjects									
Subject	**Sex**	**Age**	**Dx**	**Yrs since dx**	**Peli-Robson**	**Dist VA (RE)**	**Dist VA (LE)**	**Nr VA (RE)**	**Nr VA (LE)**
RP01	M	26	Not known	13	1.5	0.44	0.26	N6	N5
RP02	M	29	x-linked	17	Not done	0.60	0.52	N5	N18
RP03	F	48	x-linked	2	1.6	0.2	PL	N5	PL
RP04	M	46	Dominant	12	1.65	0.1	0.1	N5	N5
RP05	F	33	?Recessive	23	1.05	0.32	0.22	N10	N5
RP06	M	42	?Dominant	11	1.5	0.2	0.24	N5	N6
RP07	M	68	?Recessive	35	0.45	0.90	0.58	N8	N14
RP08	M	61	Recessive	10	0.9	0.62	0.24	N6	N18
RP09	F	43	Not known	10	1.65	0.22	0.3	N5	N8
RP10	M	35	Not known	25	0.75	0.5	0.7	N5	N18

NB. Due to practical constraints, visual fields were not measured as part of this pilot study. It would be of interest to include such measurements and perhaps some form of quantification of retinal and lens changes as part of any future studies in this area.

5.5.3 General methods

For all experiments described in this chapter, participants viewed an LCD display (LG Multisync LCD 1860NX flatscreen) from a distance of 40 cm. All patients wore their optimum refractive correction for this viewing distance. The screen measured 360mm horizontally by 290mm vertically. A chin rest was used so that the viewing angle and the distance from the computer screen remained constant throughout. The screen luminance was adjusted to 212 cdm^{-2} and the maximum screen contrast was approximately 400:1. This is the ratio of light to dark (i.e. the ratio of the luminance of the white background to the luminance of the dark text or vice versa). The test was performed in a room with subdued lighting and free from distractions.

The display was linked to a Shuttle computer and software was written in Visual Basic specifically for each experiment.

Reading performance was measured using a modified version of the MNRead test. Two sentences from the modified MNRead were randomly presented at ten font sizes corresponding to logMAR values of 0.1 to 1.5. A full stop was used to separate the sentences so that meaning was maintained. The mean number of words for each sentence was ten. Font sizes were presented in descending order only as all subjects had some form of visual impairment.

Following an audible cue, the sentences were displayed and the observer was instructed to read the sentence aloud as quickly as possible. On completing both sentences, the examiner (PJD) pressed a stop key. Subjects were only required to read the sentences once due to it being a visually demanding task.

5.6 The relationship between reading speed and visual acuity, contrast sensitivity and years since diagnosis

5.6.1 Methods

Reading speed was measured using the procedure outlined above with black text (Arial font) against a white background. The mean reading time was calculated as the average reading speed for the range of letters which can be read at maximum reading speed (see Section 2.3.2). The relationship between mean reading time and visual acuity, contrast sensitivity and "years since diagnosis" is described for patients in each disease group in the sections below.

All measurements of reading speed and visual acuity and contrast sensitivity were taken binocularly as we wished to simulate normal viewing conditions as closely as possible.

5.6.2 Summary Results (ARMD)

Figure 102 shows the mean reading speed as a function of contrast sensitivity for the ten subjects with ARMD. The results show a wide variation in contrast sensitivity among the sample group but, in general, participants with poorer contrast sensitivity read more slowly (correlation: $R^2 = 0.47$).

Figure 102 – Graph showing mean reading speed vs' contrast sensitivity as measured using the Pelli-Robson for subjects in the ARMD group

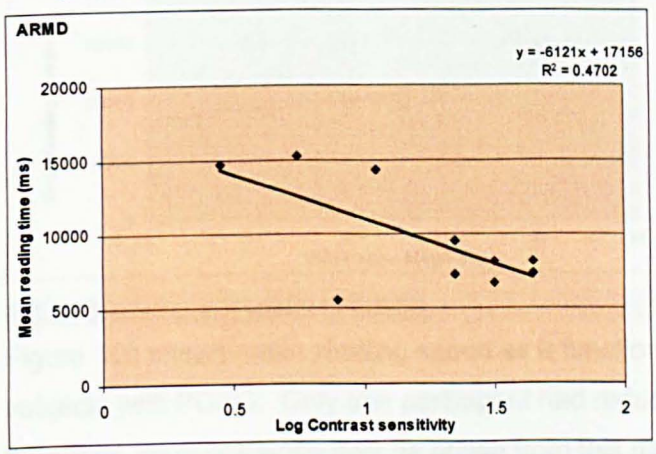


Figure 103 shows mean reading speed plotted as a function of binocular visual acuity for the ten subjects with ARMD. The graph shows the wide variation in visual acuity within the group and, not surprisingly, shows that those with poorer visual acuity tend to read more slowly ($R^2 = 0.31$).

Figure 103 – Graph showing the correlation between visual acuity and reading speed using normal contrast i.e. black on white for subjects in the ARMD group

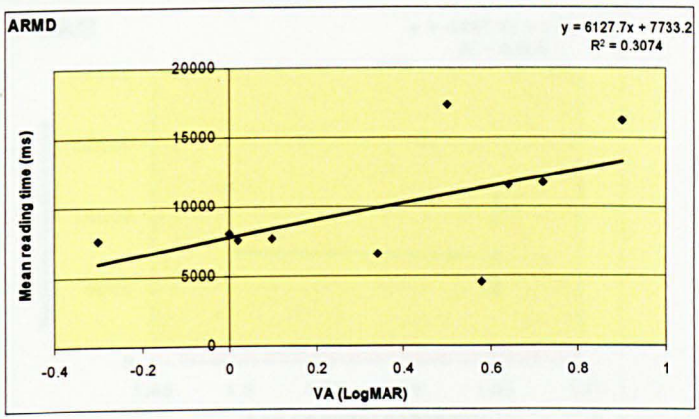
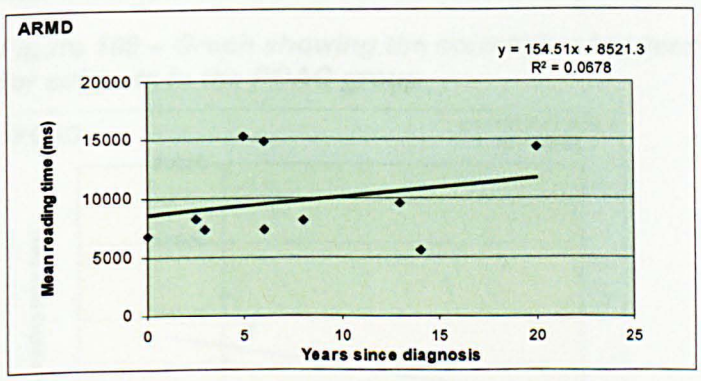


Figure 104 shows mean reading speed as a function of "years since diagnosis". As a progressive disease, it might be expected that visual performance and hence reading speed would be negatively correlated with "years since diagnosis" (correlation: $R^2 = 0.07$).

Figure 104 – Graph showing the correlation between years since diagnosis and reading speed using normal contrast i.e. black on white for subjects in the ARMD group



5.6.3 Summary Results (POAG)

Figure 105 shows mean reading speed as a function of contrast sensitivity for the ten subjects with POAG. Only one participant had reduced contrast sensitivity in this group and, therefore, no conclusions may be drawn from this data.

Figure 105 – Graph showing mean reading speed vs' contrast sensitivity as measured using the Pelli-Robson for subjects in the POAG group

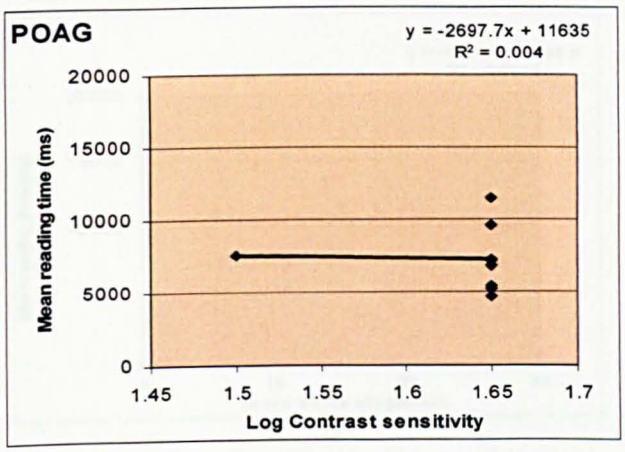


Figure 106 shows mean reading speed as a function of visual acuity for the ten subjects with POAG. As POAG does not affect central vision until the late stages of the disease process, it is not surprising to find that the visual acuity of most subjects was relatively good. Indeed, the variation in visual acuity between subjects is likely to have been attributable to factors other than the glaucoma. However, the data does show that in general, subjects with better visual acuity had faster reading speeds ($R^2 = 0.40$).

Figure 106 – Graph showing the correlation between reading speed and visual acuity for subjects in the POAG group

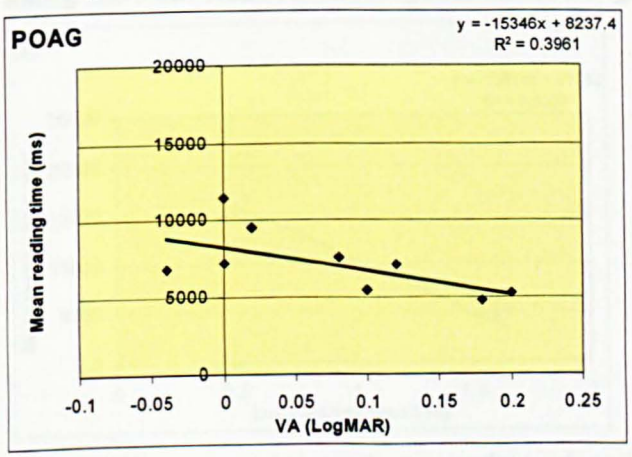
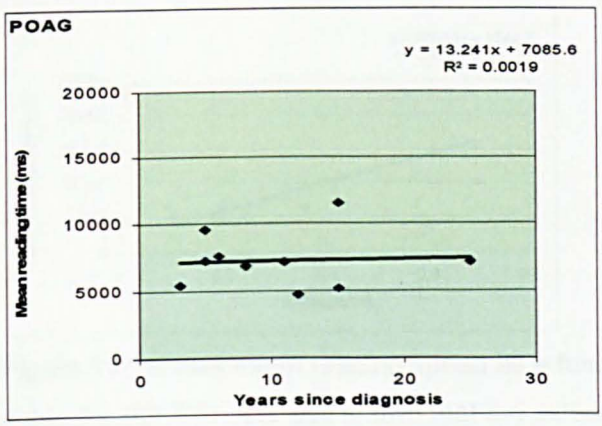


Figure 107 shows mean reading speed as a function of "years since diagnosis" for the ten subjects with POAG. As field size tends to diminish over time, some correlation between reading speed and "years since diagnosis" might have been expected. However, all subjects in this group were receiving treatment and were relatively stable and the relationship between reading speed and "years since diagnosis" was very weak ($R^2 = 0.002$).

Figure 107 – Graph showing the correlation between reading speed and years since diagnosis for subjects in the POAG group



5.6.4 Summary Results (RP)

Figure 108 shows reading speed as a function of contrast sensitivity for nine subjects with RP. This group of patients showed a large spread of results for contrast sensitivity which was somewhat surprising given that it is commonly held that RP tends to spare central visual function until the relatively late stages of the disease process. In general, subjects with lower contrast sensitivity tended to read more slowly ($R^2 = 0.65$).

Figure 108 – Graph showing mean reading speed vs' contrast sensitivity as measured using the Pelli-Robson for subjects in the RP group

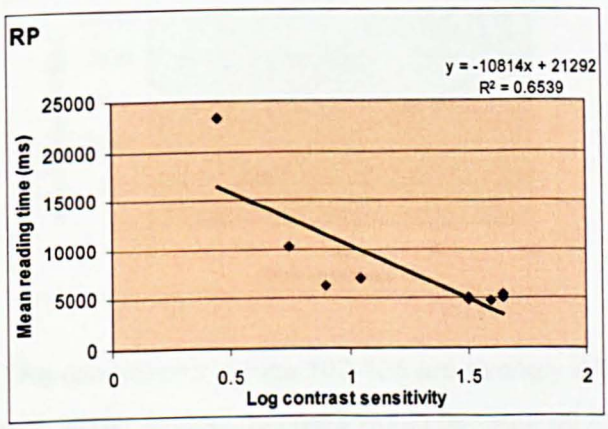


Figure 109 shows mean reading speed as a function of binocular visual acuity for nine subjects with RP. Six of the subjects had good binocular visual acuity, one slightly reduced and two markedly reduced.

Figure 109 – Graph showing the correlation between reading speed and visual acuity for subjects in the RP group

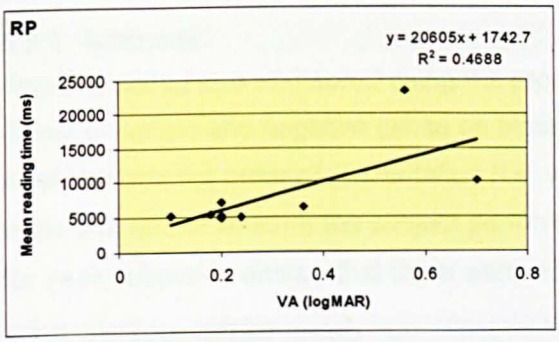
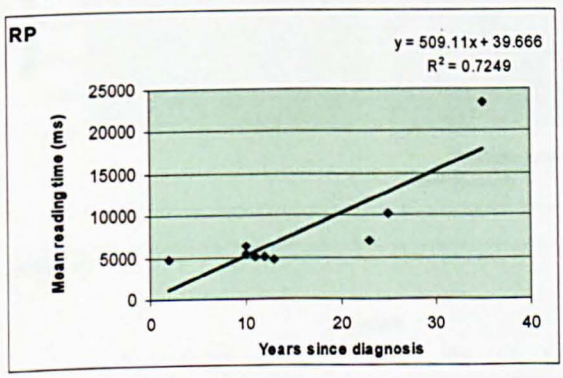


Figure 110 shows mean reading speed as a function of "years since diagnosis" for nine subjects with RP. It is well known that the extent of the central field in RP decreases as the disease progresses and so it was reasonable to expect some correlation between "years since diagnosis" and reading speed. However, the rate of progression depends on the type of RP and possibly other factors and this would tend to weaken the correlation in a mixed group such as this. However, the correlation between years since diagnosis and mean reading speed is strong ($R^2 = 0.72$).

Figure 110 – Graph showing the correlation between reading speed and years since diagnosis for subjects in the RP group



The correlations in Figs 103-105 are strongly influenced by an outlier and further research with larger subject numbers would be required to determine whether the associated R-squared values are valid.

5.7 The relationship between reading speed and visual acuity, contrast sensitivity and years since diagnosis

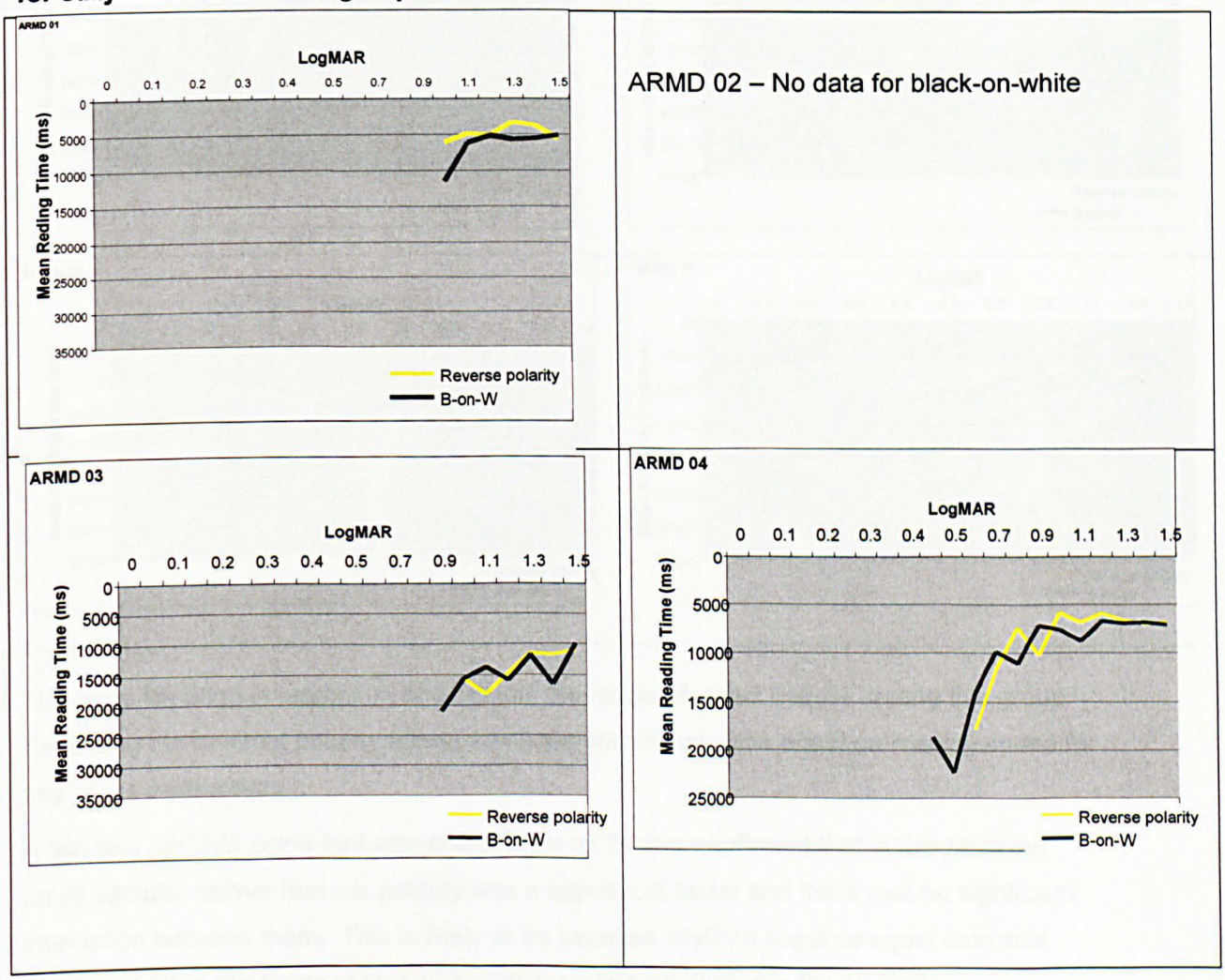
5.7.1 Methods

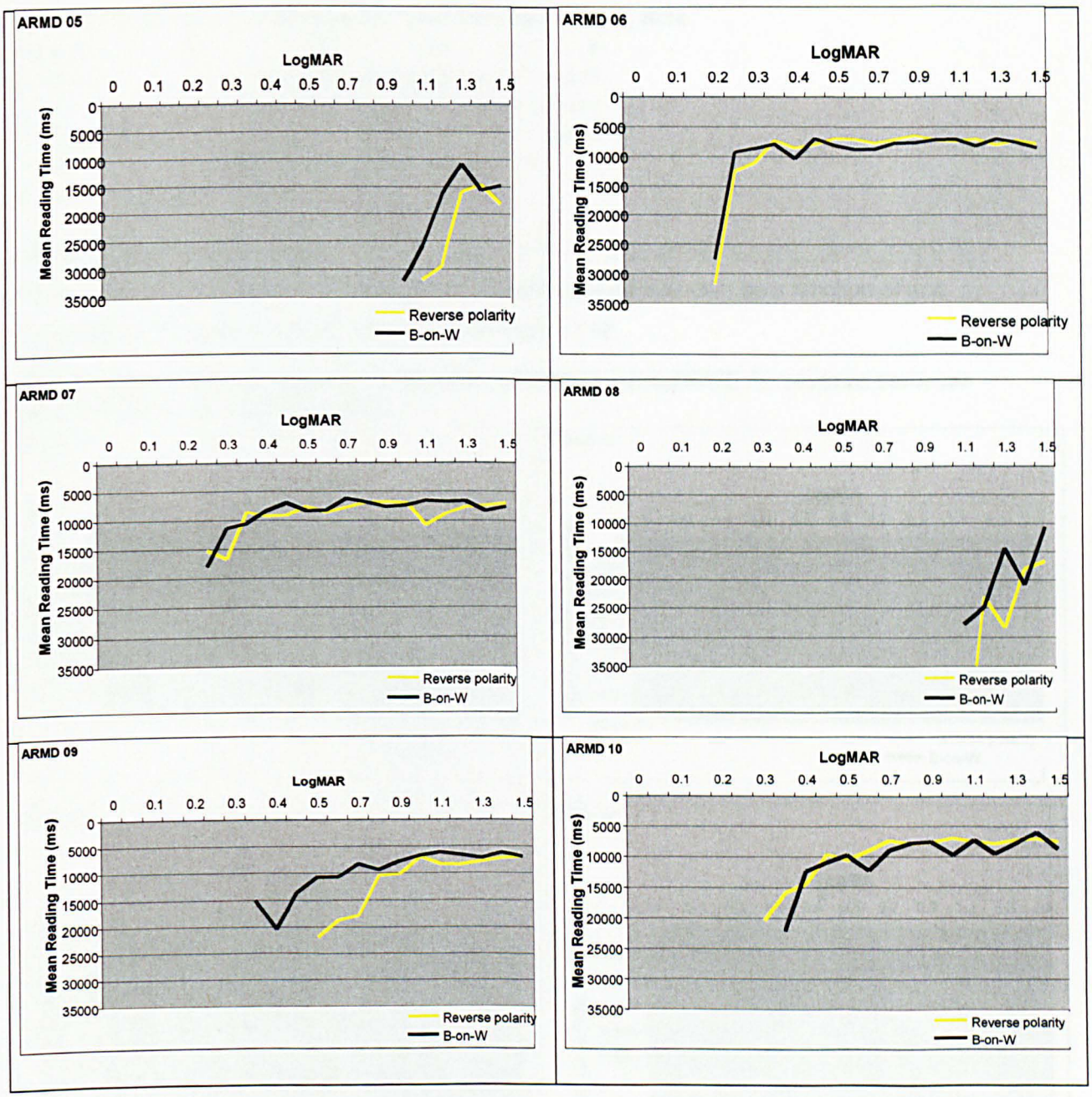
Reading speed was measured using the procedure outlined above for displays with positive (black on white) and negative (white on black) contrast polarity. The text was displayed in Arial font and the order of presentation (i.e. whether the subject performed the black on white trial first or whether the subject performed the white on black trial first), was balanced for each subject to ensure that there were no order effects.

5.7.2 Results: ARMD group

The entire data set is given in Appendix 3. Figure 111 shows reading speed as a function of text size (logMAR) for each subject in the ARMD group.

Figure 111 – Reading speed as a function of font size (LogMAR) for reverse contrast for subjects in the ARMD group





The large variation in reading speed reflects the range of visual deficits among this group. Reversing the contrast polarity appears to have surprisingly little effect on reading speed for any of the participants.

A two way ANOVA using font size and polarity as factors confirmed that in this relatively small sample, neither font nor polarity was a significant factor and there was no significant interaction between them. This is likely to be because ANOVA requires equal data sets which restricted the range of font sizes which could be included in the analysis.

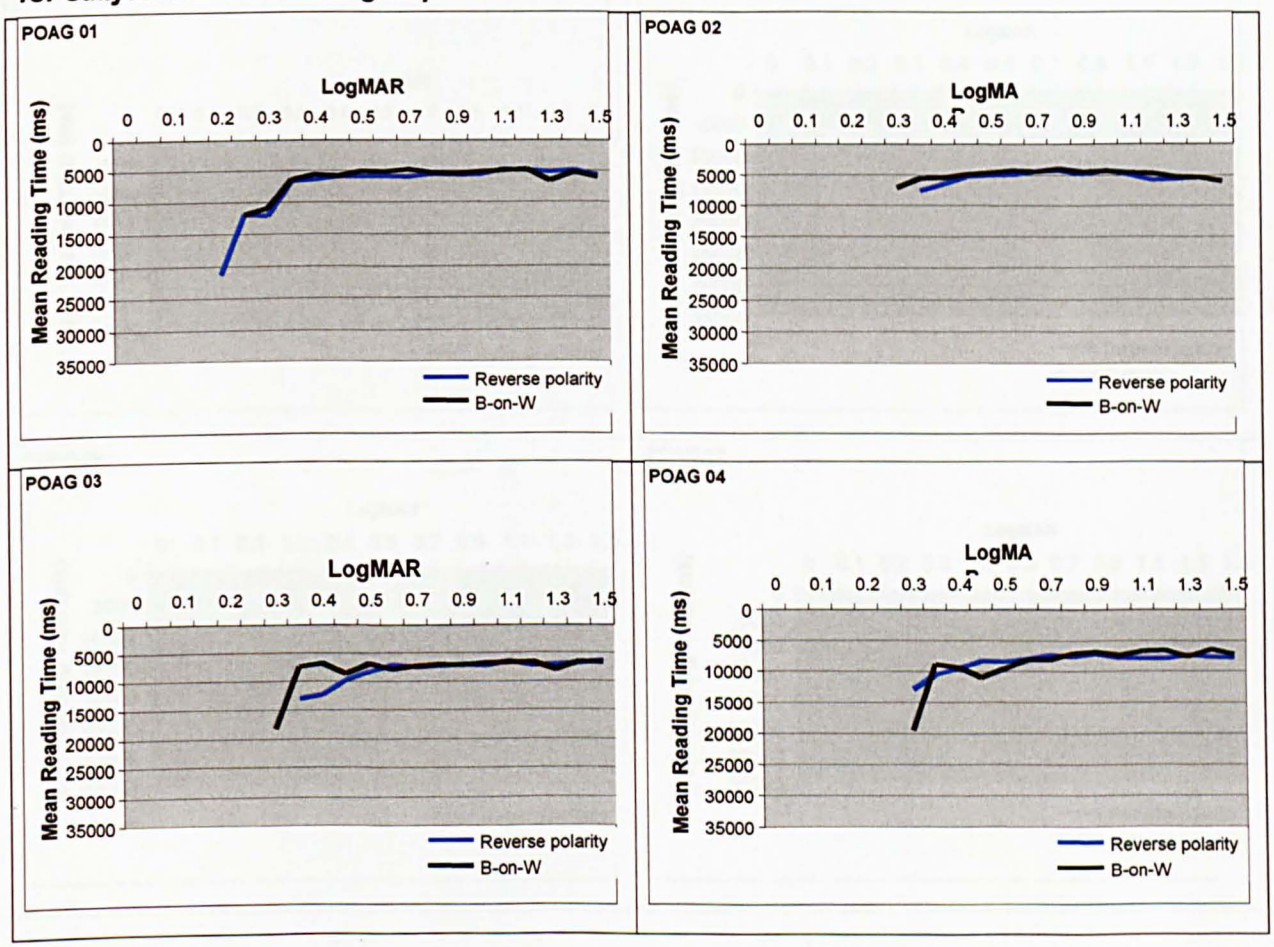
Two-way ANOVA: Reading speed (ms) versus Polarity, Size

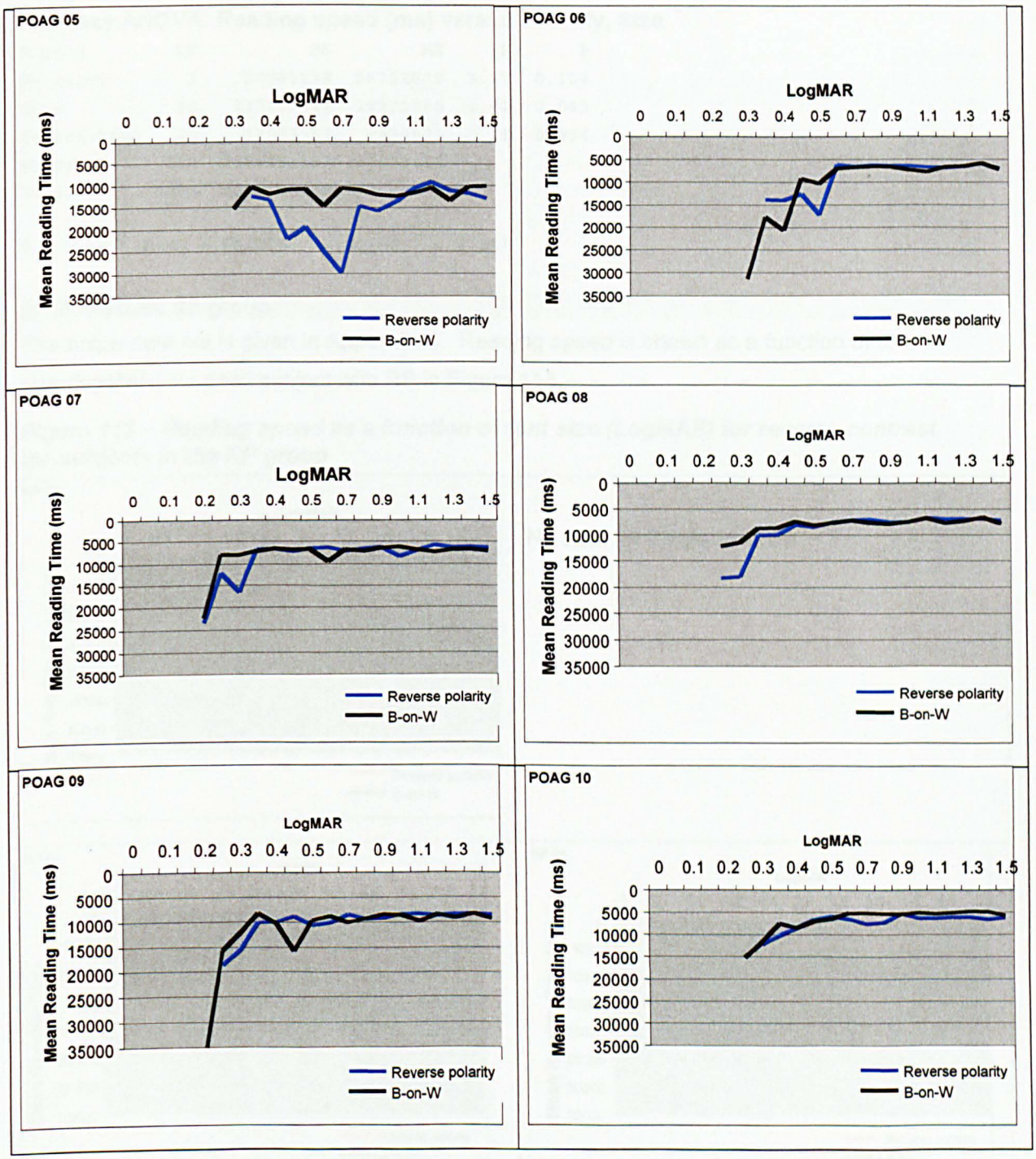
Source	DF	SS	MS	F	P
Polarity	1	61763881	61763881	1.19	0.279
Size	4	372831936	93207984	1.79	0.138
Interaction	4	61281688	15320422	0.29	0.881
Error	90	4688529464	52094772		
Total	99	5184406969			

5.7.3 Results: POAG group

The entire data set is given in Appendix 3. Reading speed is shown as a function of text size (logMAR) for each subject with POAG in Figure 112.

Figure 112 – Reading speed as a function of font size (LogMAR) for reverse contrast for subjects in the POAG group





The results for this group were very similar to those obtained for subjects with normal vision. Apart from one "idiosyncratic" result, contrast polarity was found to have surprisingly little effect on reading speed.

A two way ANOVA using font size and polarity as factors confirmed that font size was a significant factor but contrast polarity was not. There was no significant interaction between font size and contrast polarity.

Two-way ANOVA: Reading speed (ms) versus Polarity, Size

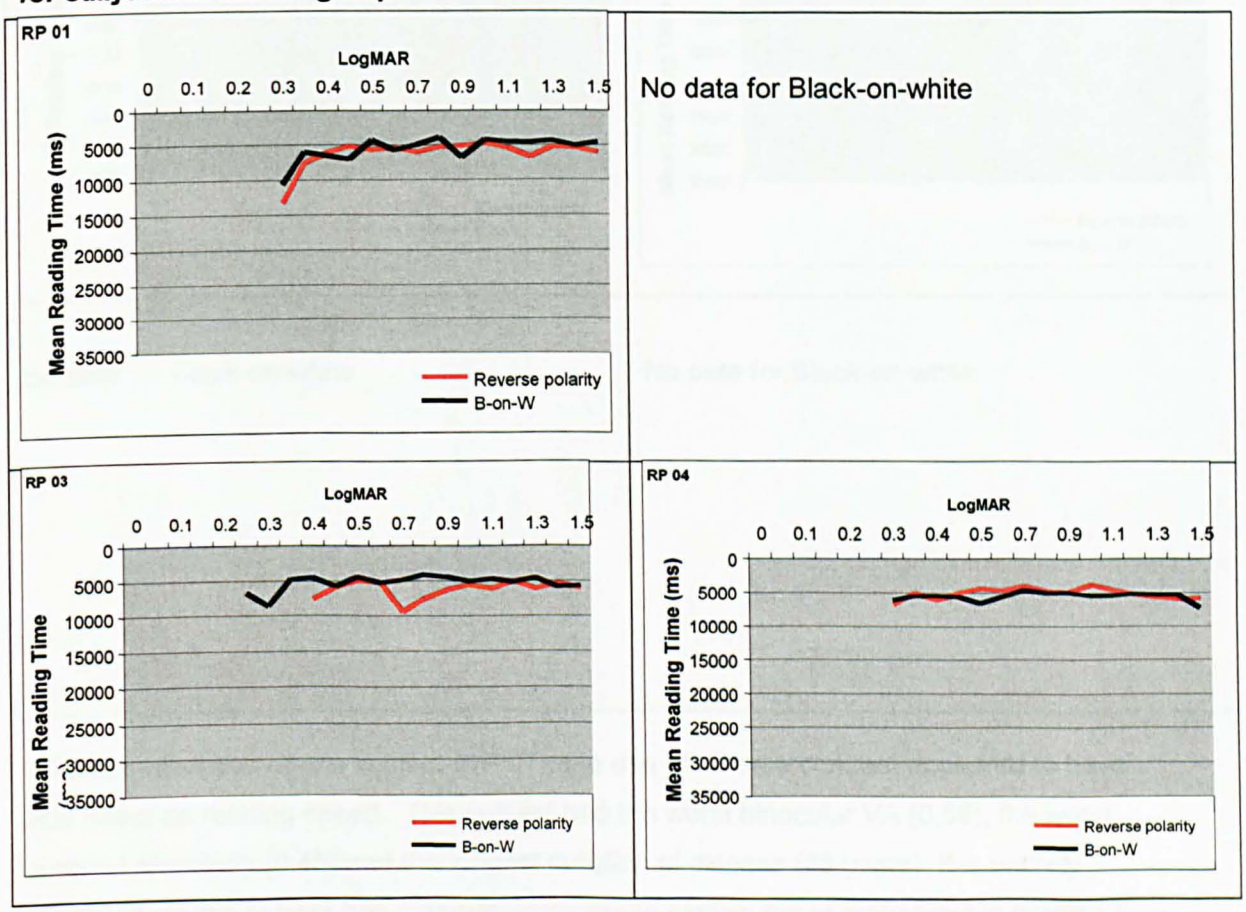
Source	DF	SS	MS	F	P
Polarity	1	26761879	26761879	2.67	0.104
Size	13	237005446	18231188	1.82	0.041
Interaction	13	32953352	2534873	0.25	0.996
Error	252	2528451163	10033536		
Total	279	2825171839			

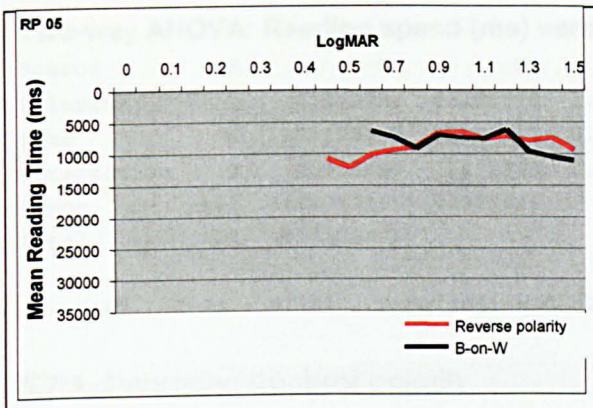
S = 3168 R-Sq = 10.50% R-Sq(adj) = 0.91%

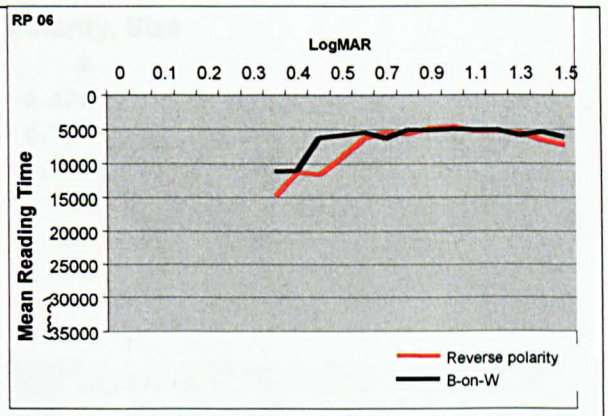
5.7.4 Results: RP group

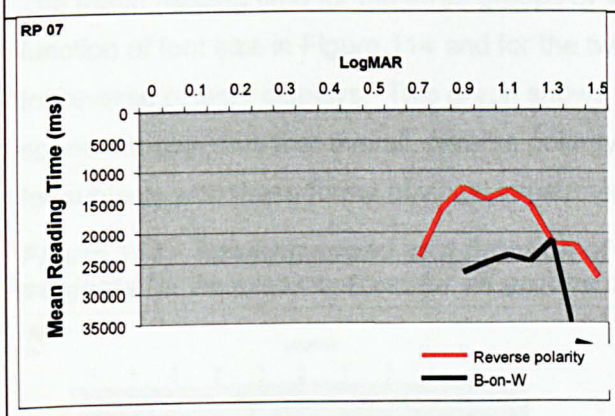
The entire data set is given in Appendix 3. Reading speed is shown as a function of text size (logMAR) for each subject with RP in Figure 113.

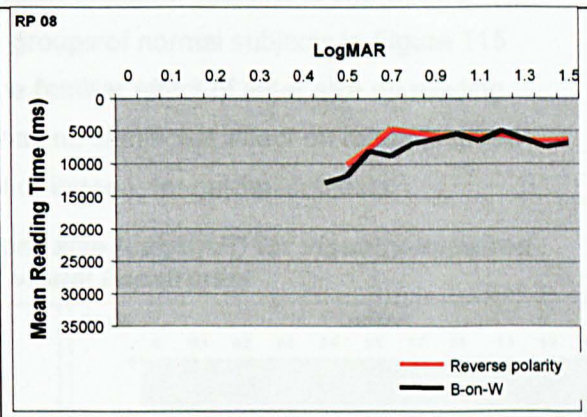
Figure 113 – Reading speed as a function of font size (LogMAR) for reverse contrast for subjects in the RP group











No data for Black-on-white

No data for Black-on-white

With the exception of one subject (RP 07), the use of reverse contrast appeared to have little effect on reading speed. This subject had the worst binocular VA (0.58), the worst contrast sensitivity (0.45) and the longest duration of disease (35 years). It is entirely possible that this subject had cataract which would explain the improvement in reading time using reverse contrast but this is speculation only as unfortunately, clinical data was not recorded.

A two way ANOVA using font size and polarity as factors confirmed that neither of these factors was significant and that there was no significant interaction between them.

Two-way ANOVA: Reading speed (ms) versus Polarity, Size

Source	DF	SS	MS	F	P
Polarity	1	61168728	61168728	1.46	0.229
Size	6	151173975	25195663	0.60	0.728
Interaction	6	20836608	3472768	0.08	0.998
Error	112	4684741165	41828046		
Total	125	4917920476			

S = 6467 R-Sq = 4.74% R-Sq(adj) = 0.00%

5.7.5 Summary: Contrast polarity

The mean reading time for the three groups of visually impaired subjects is shown as a function of font size in Figure 114 and for the two groups of normal subjects in Figure 115 for reverse polarity displays. This graph shows the familiar effect of letter size on reading speed but suggests that overall, reverse polarity has no significant effect on reading speed for subjects with these forms of visual impairment or indeed, for normal subjects.

Figure 114 – Reading speed as a function of font size (LogMAR) for visually-impaired subjects for reverse contrast for all groups of visual impairment

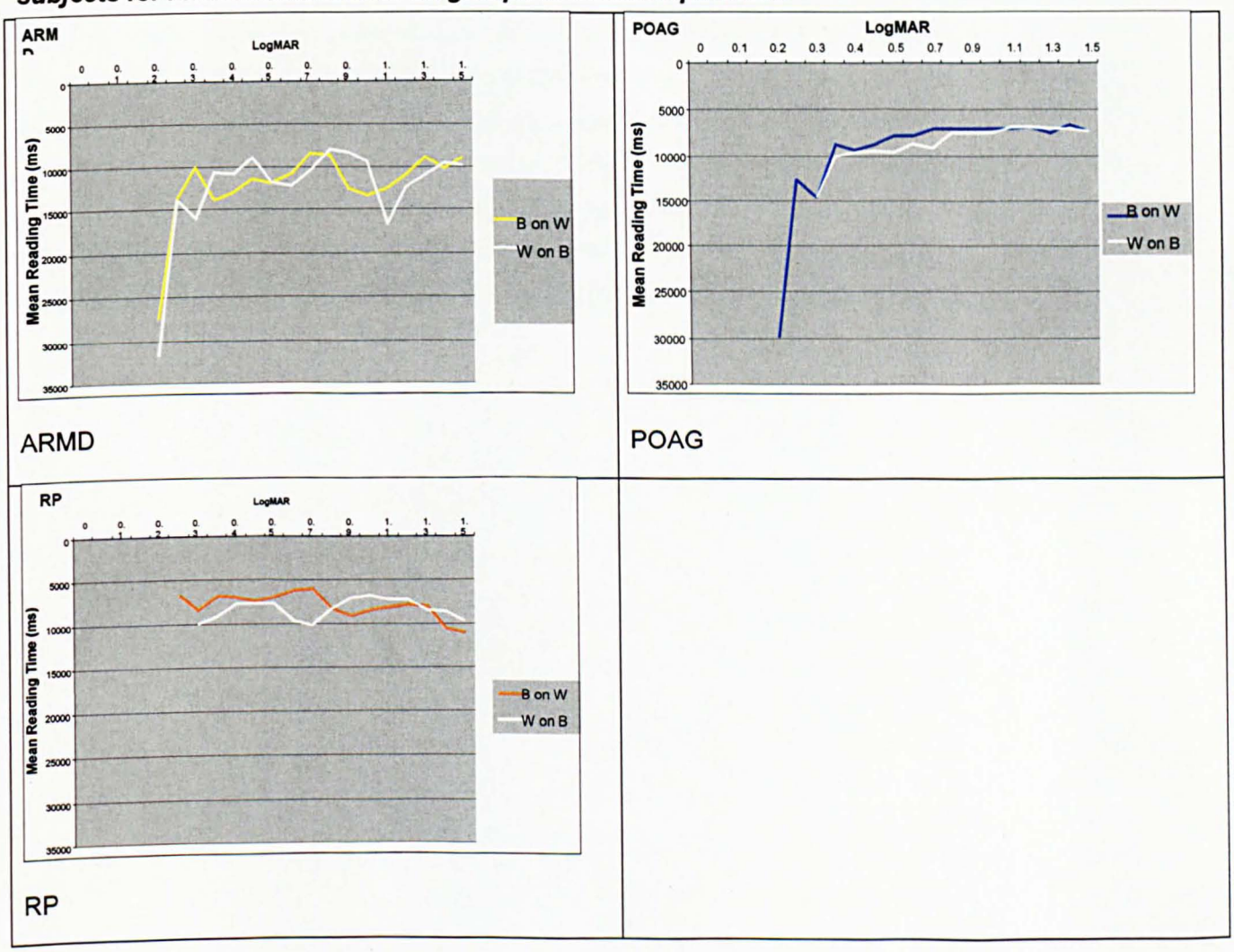
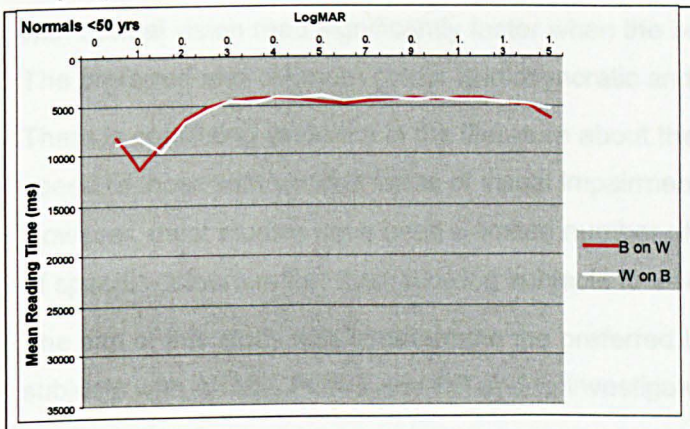
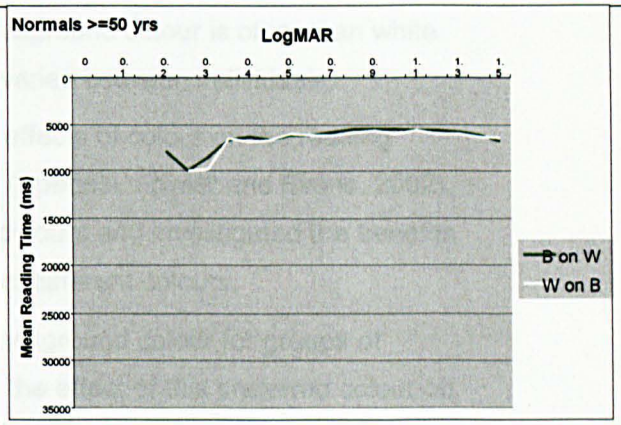


Figure 115 – Reading speed as a function of font size (LogMAR) for reverse contrast displays for normal subjects



Normals <50 yrs



Normals >=50 yrs

5.8 The effect of background colour on reading speed

The experiments described in previous chapters have shown that a proportion of individuals with normal vision read significantly faster when the background colour is other than white. The preferred and optimum colour is idiosyncratic and varies between individuals.

There is conflicting evidence in the literature about the effects of colour on the reading speed of those with various forms of visual impairment (Eperjesi, Fowler and Evans, 2002). However, most studies have used a limited number of colours and investigated the benefits of specific colours rather than allowing subjects to select different colours.

The aim of this study was to determine the preferred background colour for groups of subjects with ARMD, POAG and RP and to investigate the effect of this preferred colour on reading speed.

5.8.1 Methods

The apparatus and test conditions are described above. The LCD screen was carefully calibrated using a Minolta Chroma Meter II. Using this information, sixteen chromaticities were selected from a circle drawn in CIE 1976 UCS space centred at u' = 0.1978, v' = 0.4683 (D65) and a radius of 0.0369. The sixteen chromaticities were equally spaced at 22.5 degree intervals and the luminance of each colour was kept as close to 120 cdm^{-2} as possible (range 115 – 125 cdm^{-2} ; mean = 120.1 cdm^{-2}) thus maintaining approximately constant saturation, brightness and contrast. In other words, the background was varied in CIE 1976 hue angle (h_{uv}) without an associated change in the CIE 1976 saturation (s_{uv}) and luminance. The u',v' and associated computer R,G,B values are shown in Table 26.

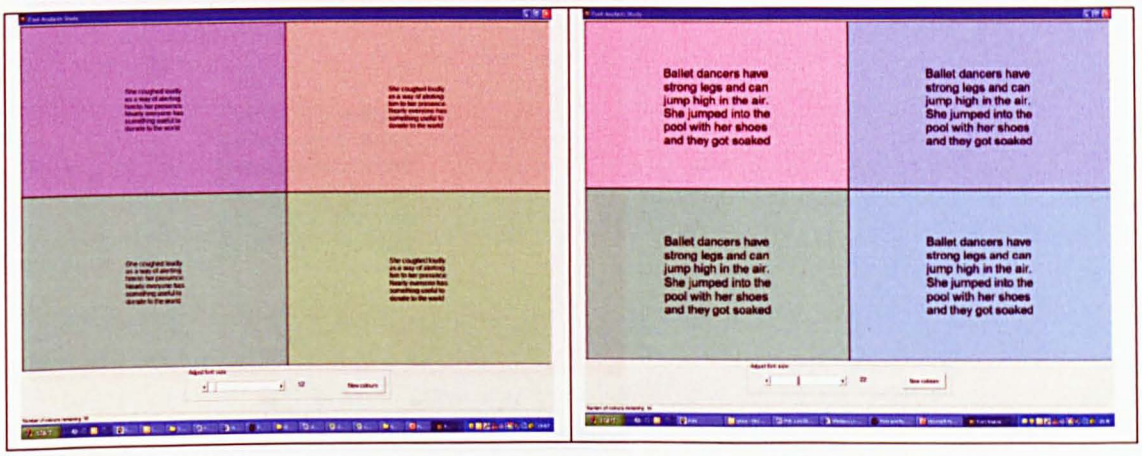
Table 26 – u'v' values and corresponding RGB values required to achieve these on the* Multisync LCD 1860NX *screen

Colour	A (degs)	u'	v'		Illuminance	R	G	B
1	0	0.235	0.468		120	235	169	199
2	22.5	0.232	0.482		119	229	174	177
3	45	0.224	0.494		119	219	182	161
4	67.5	0.212	0.502		120	206	192	150
5	90	0.198	0.505		121	189	200	148
6	112.5	0.184	0.502		121	169	205	154
7	135	0.172	0.494		121	151	208	167
8	157.5	0.164	0.482		120	137	209	186
9	180	0.161	0.468		120	132	207	207
10	202.5	0.164	0.454		121	138	203	226
11	225	0.172	0.442		125	158	199	252
12	247.5	0.184	0.434		117	172	182	247
13	270	0.198	0.431		115	192	172	255
14	292.5	0.212	0.434		121	215	169	250
15	315	0.224	0.442		121	229	166	235
16	337.5	0.232	0.454		120	234	165	217
				Mean	120.1			
				Min	115			
				Max	125			

The following algorithm was used to determine the preferred background colour for each subject.

Phase 1: The screen was divided into four quadrants with a passage of text displayed in the centre of each quadrant (see Figure 116). Each quadrant had a different background colour selected from the sixteen colours described above. Subjects were invited to change the font size using a scroll bar until it could be read comfortably. Subjects were then asked to study the passage of text in each quadrant and click on the colour that was the **least** comfortable to read.

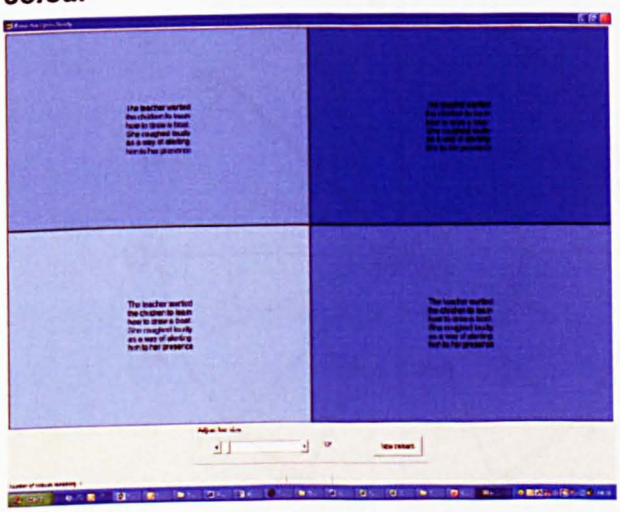
Figure 116 – Phase 1 of the algorithm – subjects were invited to change the font size according to their VA. Four background colours were selected from the sixteen calibrated colours



The colour selected was eliminated and four more colours were selected at random. This process was repeated until a single colour remained.

Phase 2: The preferred colour was then presented at four saturations and subjects were instructed to eliminate the least preferred saturation until a single saturation remained (see Figure 117).

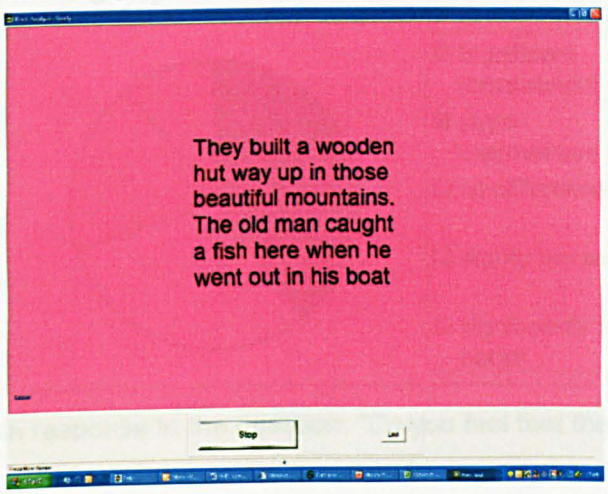
Figure 117 – Phase 2 of the algorithm showing different saturations of the remaining colour



Having determined the preferred colour and saturation, the background of the entire screen was set to this colour (see Figure 118) and reading speed was measured as a function of font size in the manner described above.

At the end of the trial, subjects were asked to rate whether changing the background colour had changed the "comfort" and "legibility" of the display using the scale: significant improvement, slight improvement, no difference, slightly worse, significantly worse.

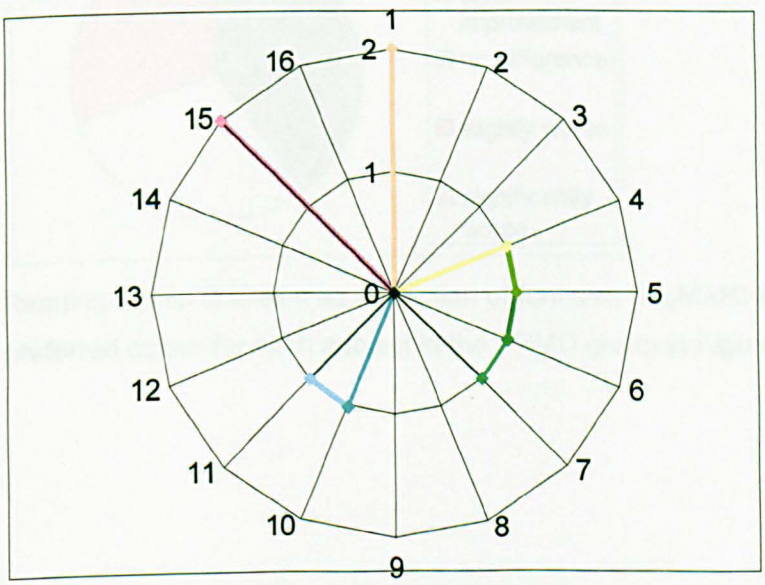
Figure 118 – Phase 3 of the algorithm showing preferred colour and saturation of the remaining colour



5.8.2 Results: ARMD group

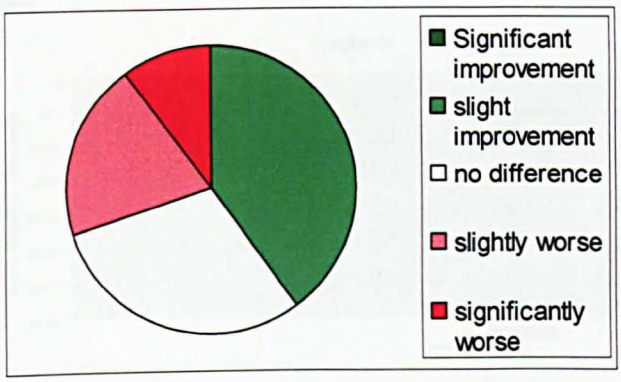
The colours chosen by the ten subjects in the ARMD group are shown in Figure 119. The graph shows that subjects each chose different colours except for two who selected pink and purple.

Figure 119 – Polar graph showing preferred choice of background colour for subjects in the ARMD group



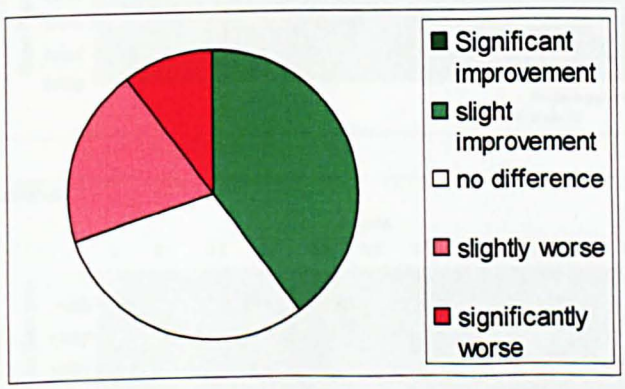
In response to the question: "Do you feel that the screen colour has made your eyes feel any more comfortable?", four reported a 'slight improvement', three felt it made no difference, two felt it had made it 'slightly worse' and one subject reported that it was 'significantly worse' – see Figure 120.

Figure 120 – Pie chart showing 'comfort' with background colour for subjects in the ARMD group



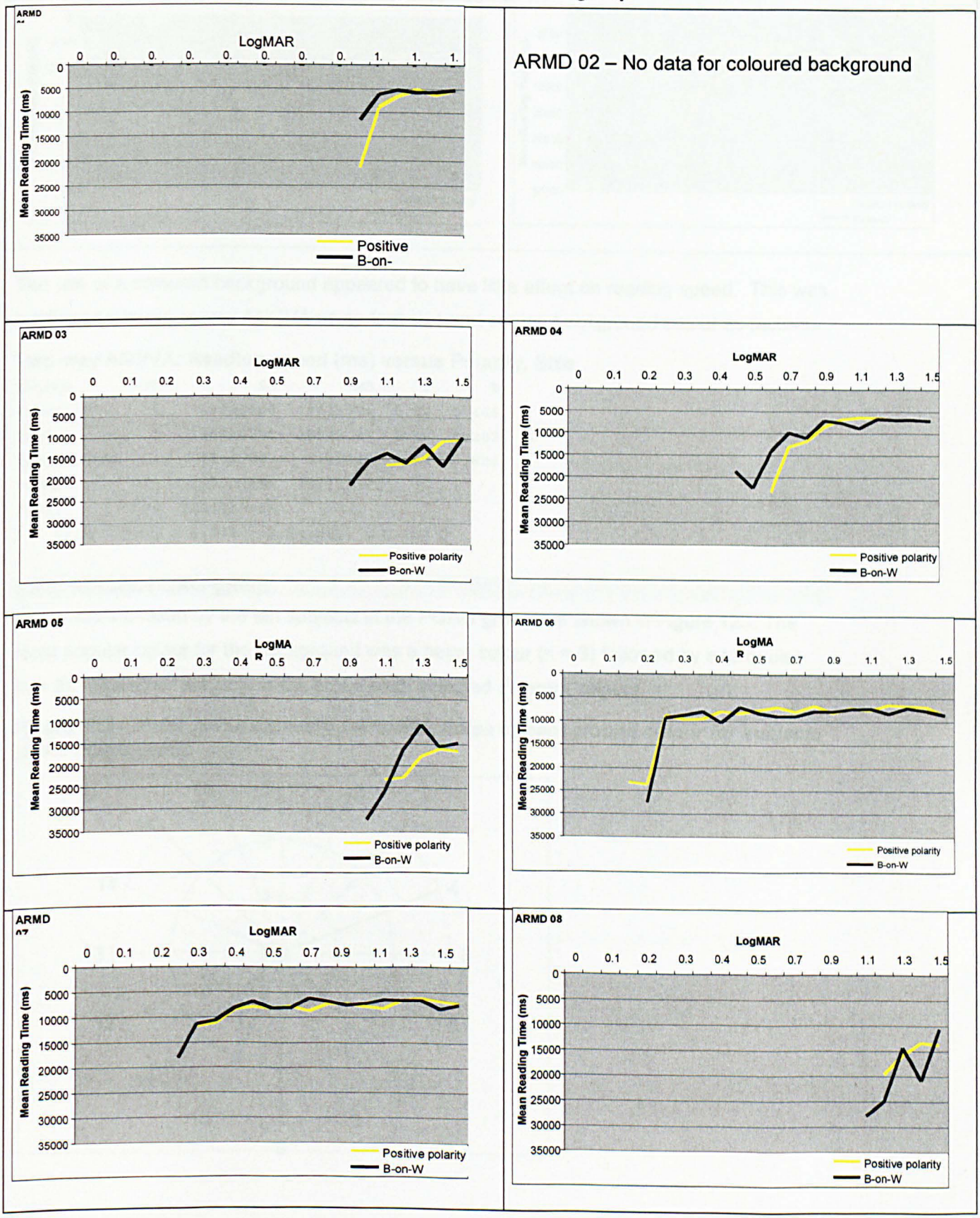
In response to the question: "Do you feel that the screen colour has made it any easier for you to read text on the computer?", four reported a 'slight improvement', three felt it made no difference, two felt it had made it 'slightly worse' and one subject reported that it had made reading 'significantly worse' – see Figure 121.

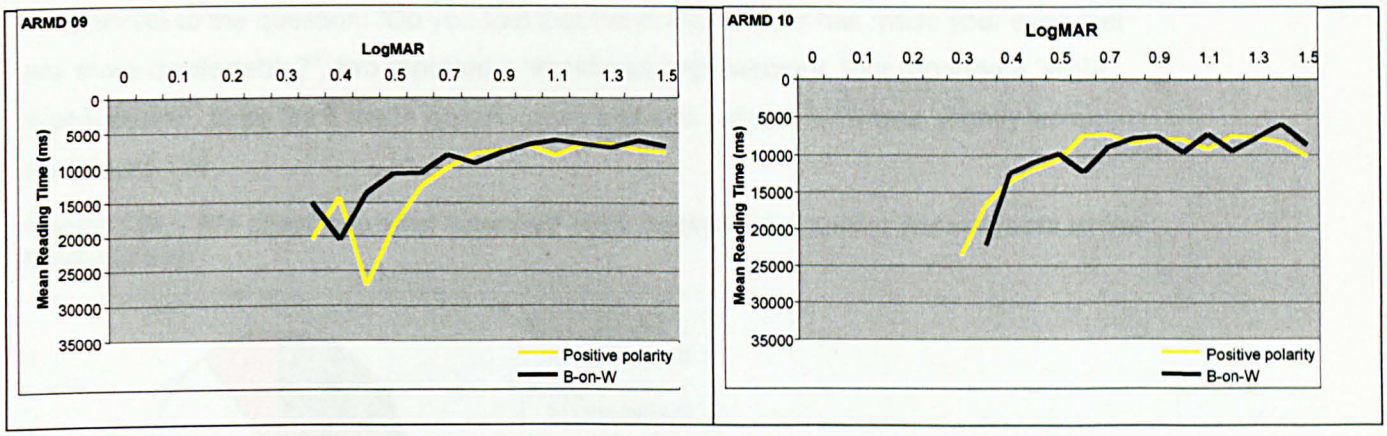
Figure 121 – Pie chart showing 'ease of reading' with background colour for subjects in the ARMD group



Reading speed is shown as a function of font size (logMAR) for black on white and black on preferred colour for each subject in the ARMD group in Figure 122.

Figure 122 – Reading speed as a function of font size (LogMAR) for white background and preferred colour background for subjects in the ARMD group





The use of a coloured background appeared to have little effect on reading speed. This was confirmed with a two way ANOVA using font size and screen background colour as factors.

Two-way ANOVA: Reading speed (ms) versus Polarity, Size

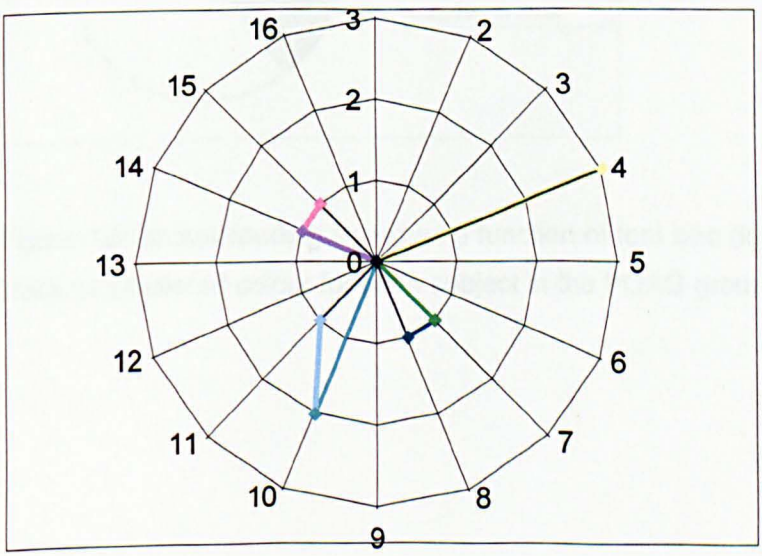
Source	DF	SS	MS	F	P
Polarity	1	14643594	14643594	0.54	0.466
Size	3	106030758	35343586	1.30	0.282
Interaction	3	24427042	8142347	0.30	0.826
Error	72	1960009495	27222354		
Total	79	2105110889			

S = 5218 R-Sq = 6.89% R-Sq(adj) = 0.00%

5.8.3 Results: POAG group

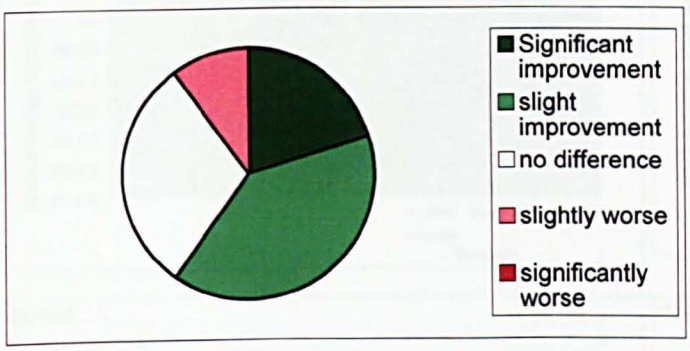
The colours chosen by the ten subjects in the POAG group are shown in Figure 123. The most popular colour for the background was a beige colour (n = 3) followed by a turquoise (n = 2). The other subjects in the group each selected different colours.

Figure 123 – Polar graph showing preferred choice of background colour for subjects in the POAG group



In response to the question: "Do you feel that the screen colour has made your eyes feel any more comfortable?", two reported a 'significant improvement, four reported a 'slight improvement', three felt it made no difference and one subject felt it was 'slightly worse' – see Figure 124.

Figure 124 – Pie chart showing 'comfort' with background colour for subjects in the POAG group



In response to the question: "Do you feel that the screen colour has made it any easier for you to read text on the computer?", two reported a 'significant improvement', two a 'slight improvement', four felt it made no difference and two felt it had made reading 'slightly worse' – see Figure 125.

Figure 125 – Pie chart showing 'easiness to read' with background colour for subjects in the POAG group

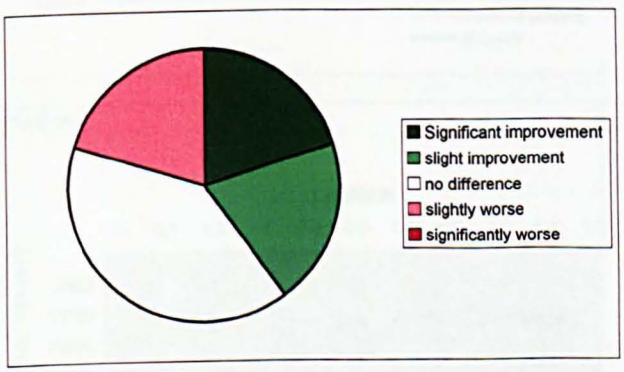
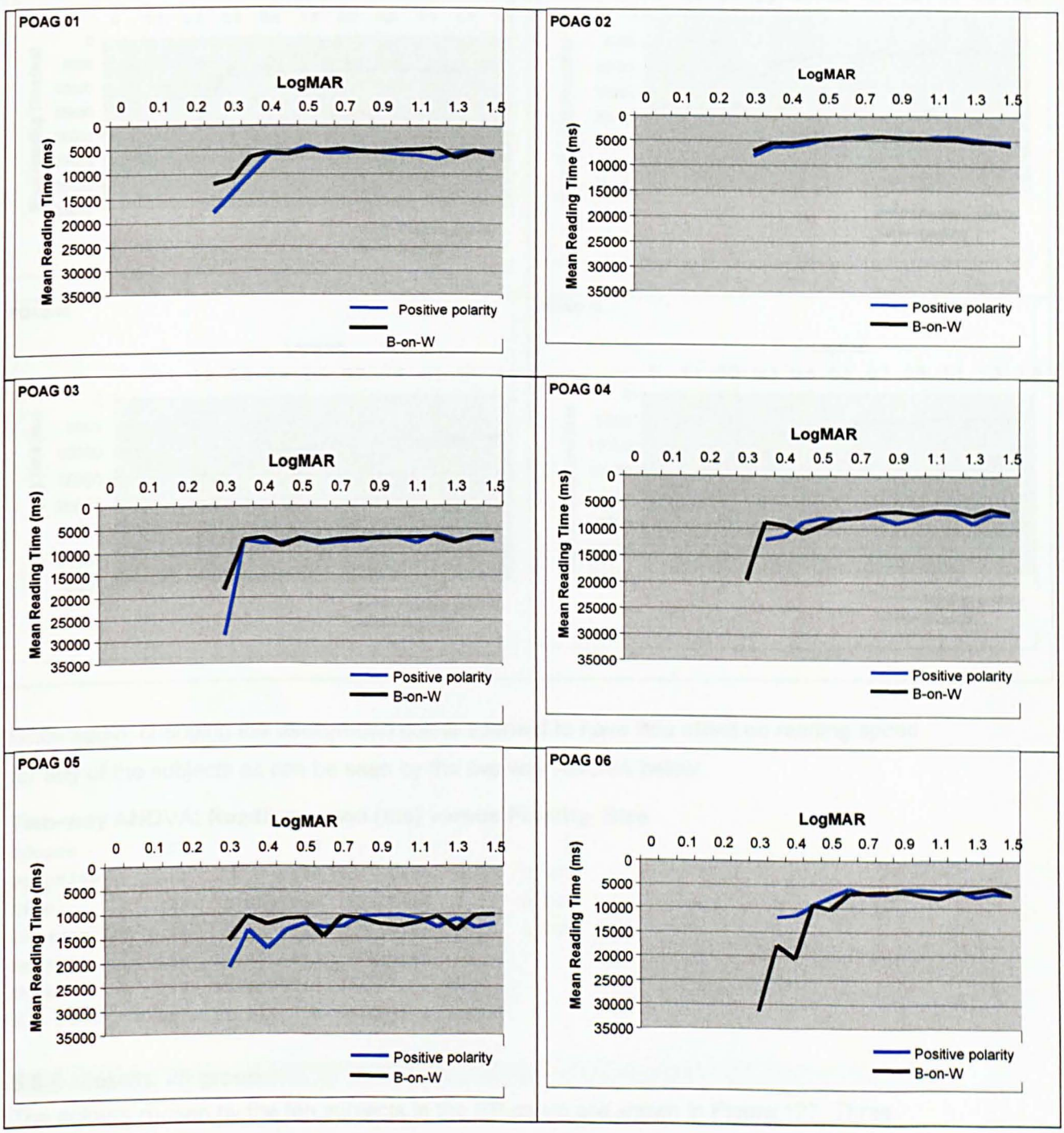
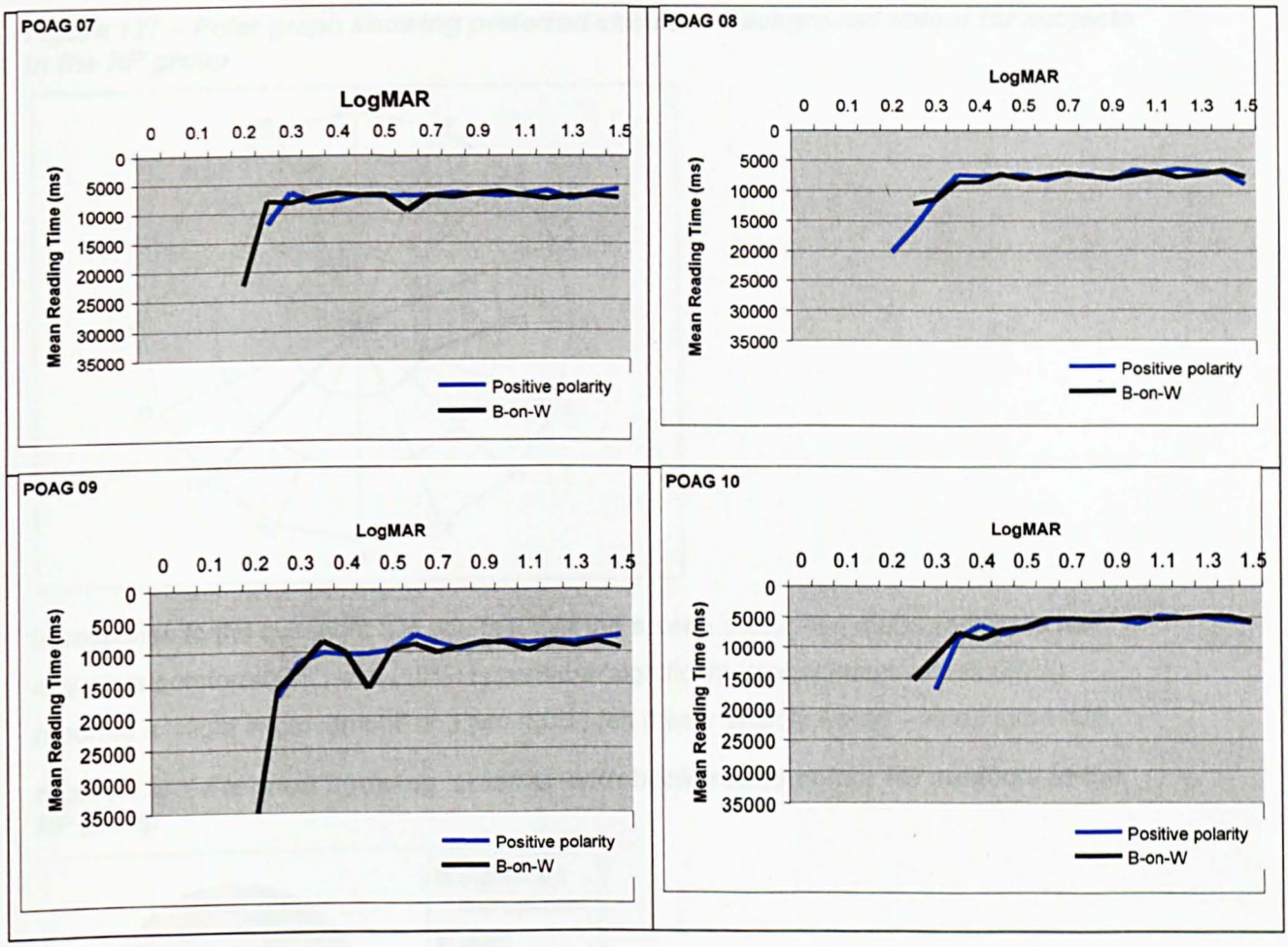


Figure 126 shows reading speed as a function of font size (logMAR) for black on white and black on preferred colour for each subject in the POAG group.

Figure 126 – Reading speed as a function of font size (LogMAR) for white background and preferred colour background for subjects in the POAG group





Once again, changing the background colour seemed to have little effect on reading speed for any of the subjects as can be seen by the two way ANOVA below.

Two-way ANOVA: Reading speed (ms) versus Polarity, Size

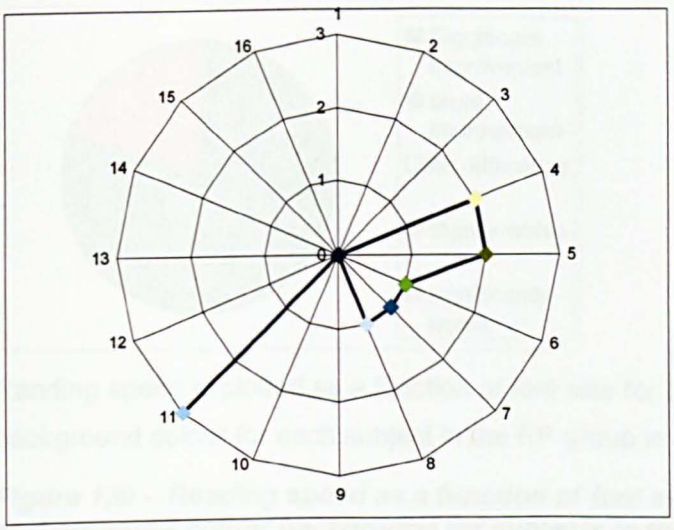
Source	DF	SS	MS	F	P
Polarity	1	6490	6490	0.00	0.973
Size	13	170592564	13122505	2.33	0.006
Interaction	13	7209339	554565	0.10	1.000
Error	252	1419016819	5631019		
Total	279	1596825212			

S = 2373 R-Sq = 11.14% R-Sq(adj) = 1.61%

5.8.4 Results: RP group

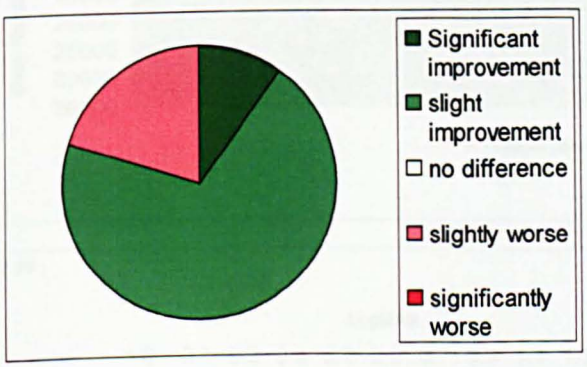
The colours chosen by the ten subjects in the RP group are shown in Figure 127. Three subjects chose the pale blue, two subjects chose beige while the other subjects each selected a different colour.

Figure 127 – Polar graph showing preferred choice of background colour for subjects in the RP group



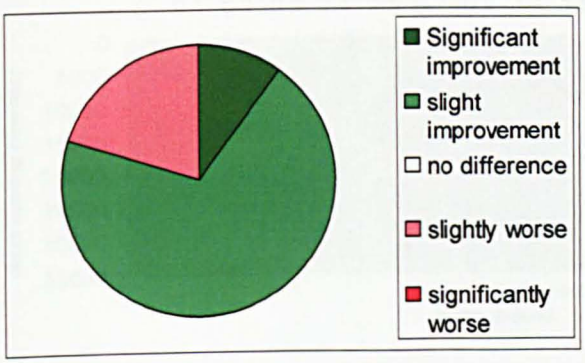
In response to the question: "Do you feel that the screen colour has made your eyes feel any more comfortable?", one (10%) reported a 'significant improvement, seven (70%) reported a 'slight improvement' and two (20%) felt it was 'slightly worse' – see Figure 128.

Figure 128 – Pie chart showing 'comfort' with background colour for subjects in the RP group



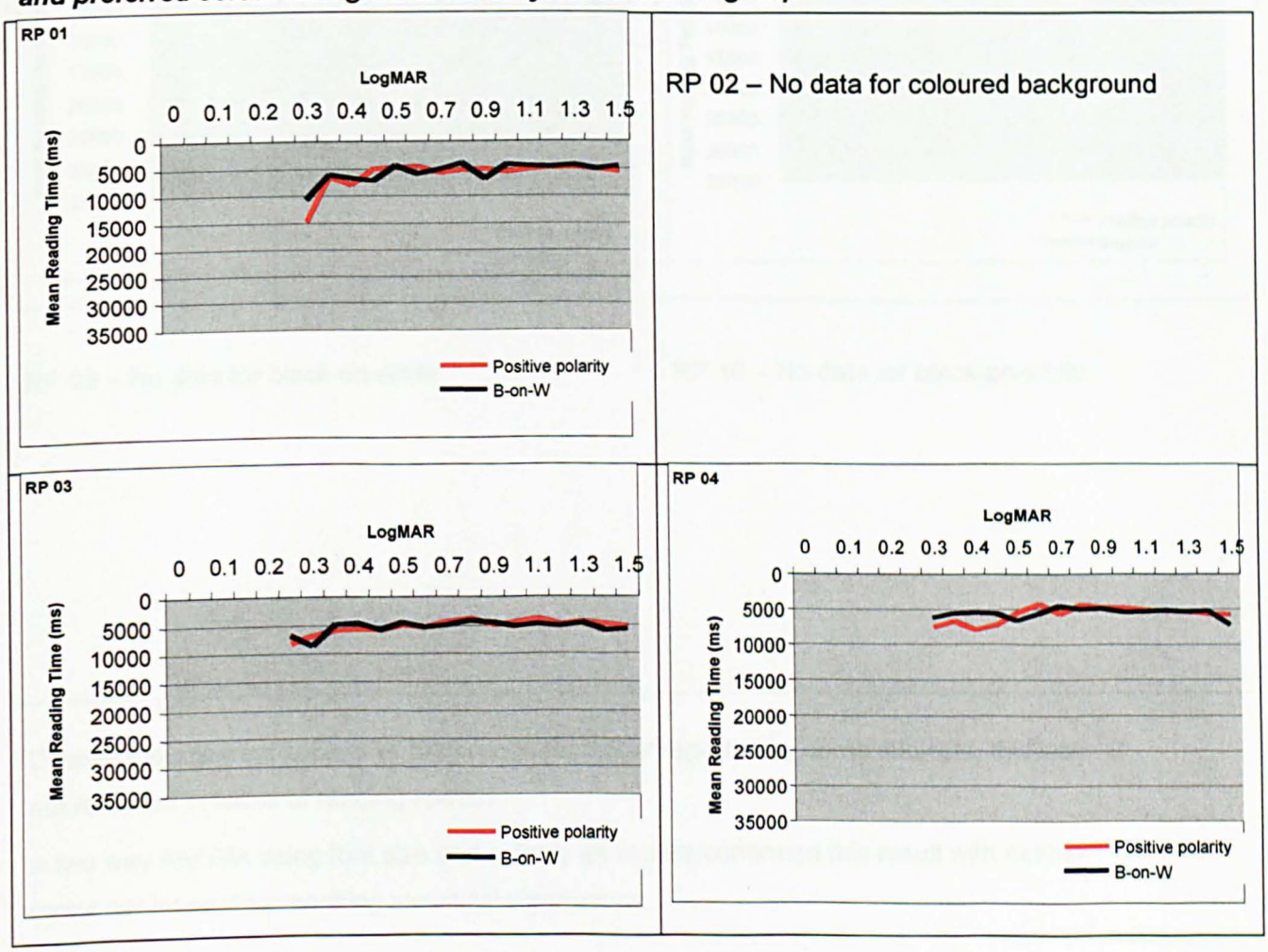
In response to the question: "Do you feel that the screen colour has made it any easier for you to read text on the computer?", one reported a 'significant improvement', seven reported a 'slight improvement' and two felt it had made reading 'slightly worse' – see Figure 129.

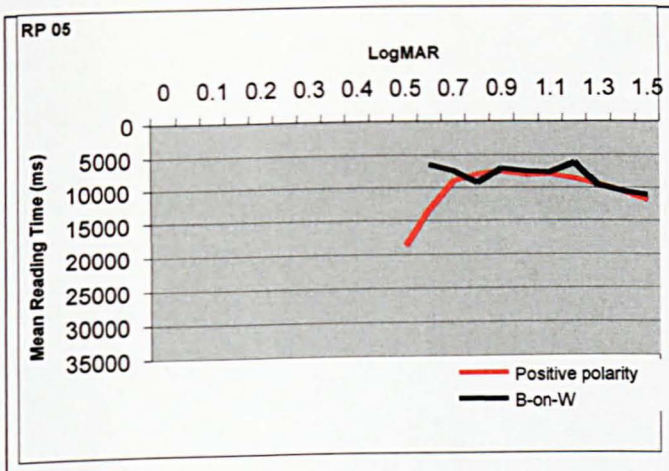
Figure 129 – Pie chart showing 'ease of reading' with background colour for subjects in the RP group

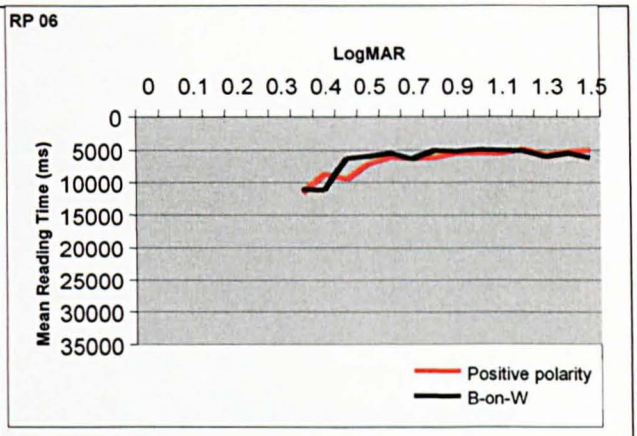


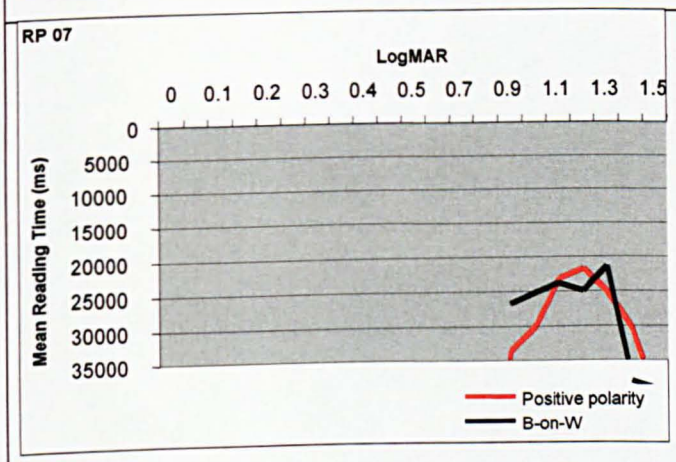
Reading speed is plotted as a function of font size for black on white and black on preferred background colour for each subject in the RP group in Figure 130.

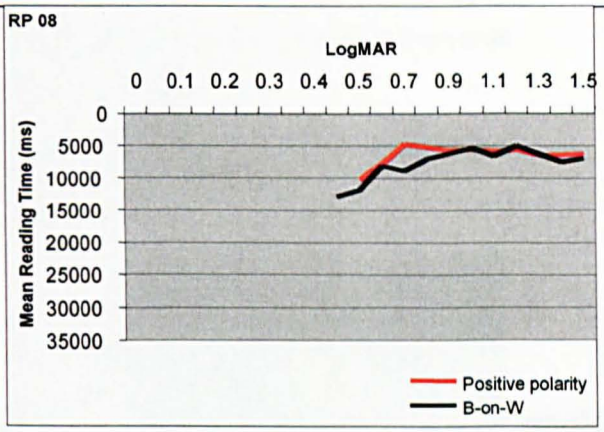
Figure 130 – Reading speed as a function of font size (LogMAR) for white background and preferred colour background for subjects in the RP group











RP 09 – No data for black-on-white

RP 10 – No data for black-on-white

Despite the apparent subjective preference for colour reported by some subjects, this was not reflected in terms of reading speed.

A two way ANOVA using font size and polarity as factors confirmed this result with neither factor nor interaction reaching statistical significance.

Two-way ANOVA: Reading speed (ms) versus Polarity, Size

Source	DF	SS	MS	F	P
Polarity	1	1877337	1877337	0.03	0.865
Size	6	166221549	27703592	0.43	0.859
Interaction	6	11157994	1859666	0.03	1.000
Error	112	7262058496	64839808		
Total	125	7441315377			

S = 8052 R-Sq = 2.41% R-Sq(adj) = 0.00%

5.8.5 Summary: positive polarity

The mean reading time for each of the different groups of subjects is shown as a function of letter size in Figures 131 and 132 for black on white and black on preferred colour displays. This graph shows the familiar effect of letter size on reading speed but suggests that overall changing background colour has no significant effect on reading speed.

Figure 131 – Reading speed as a function of font size (LogMAR) for white background and preferred colour background for all groups of visual impairment

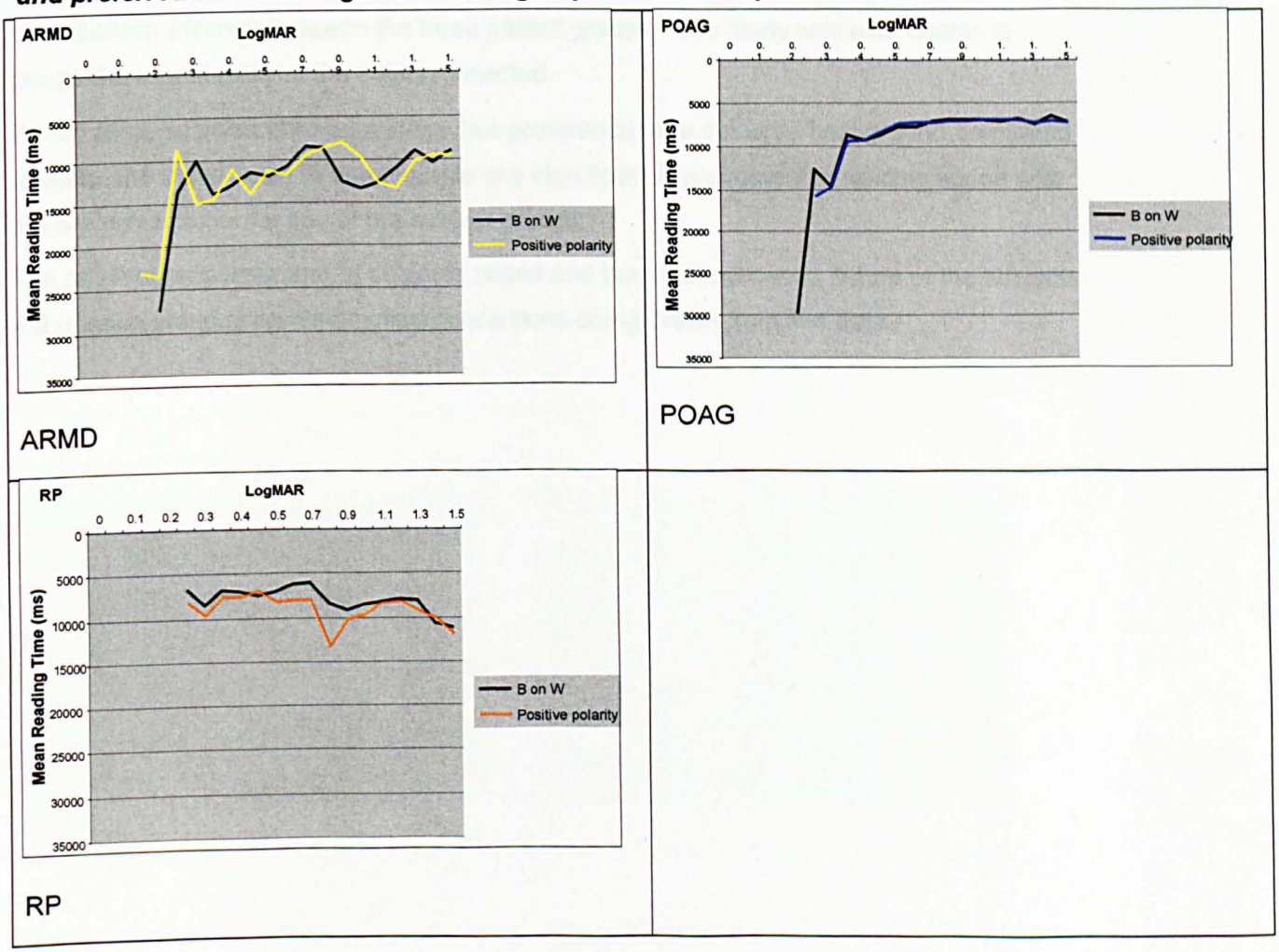
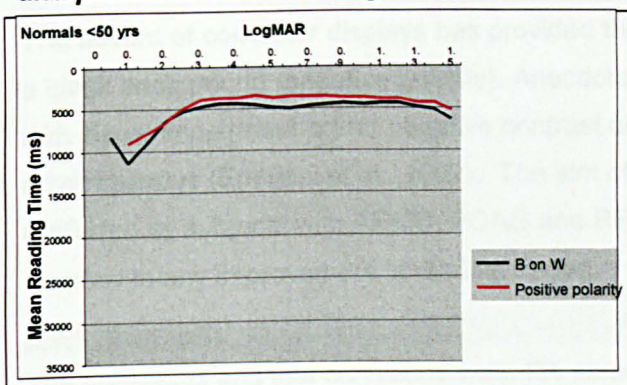
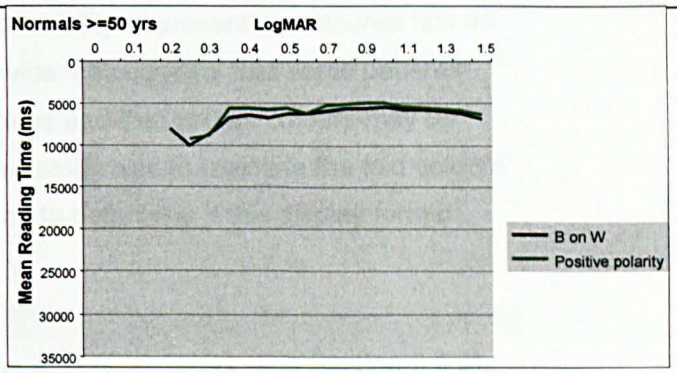


Figure 132 – Reading speed as a function of font size (LogMAR) for white background and preferred colour background for all normal subjects



Normals <50 yrs



POAG

5.8.6 Conclusions for positive polarity colours

The preferred background colour chosen in this study was idiosyncratic and showed no clear pattern within or between the three patient groups. The study was also unable to gauge the repeatability of the colours selected.

Whilst some subjects showed a subjective preference for a coloured background compared to white, the study failed to demonstrate any significant improvement in reading speed with the preferred colour for any of the subject groups.

The relatively small number of subjects tested and the heterogeneous nature of the subjects within each group prevents any firm conclusions being drawn from this data.

5.9 The effect of text colour on reading speed

The advent of computer displays has provided the possibility of presenting coloured text on a black background (negative polarity). Anecdotal evidence suggests that some patients with visual impairment prefer negative contrast displays and that certain colours may be advantageous (Eperjesi et al., 2002). The aim of this study was to examine the text colours preferred by subjects with ARMD, POAG and RP and to determine if this display format resulted in any improvement in reading speed.

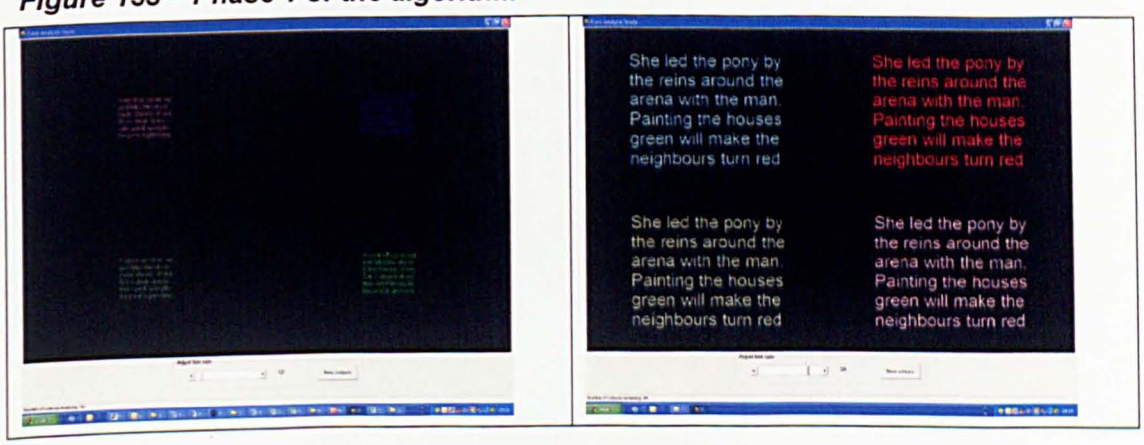
5.9.1 Methods

The apparatus and test conditions were the same as described above (see Section 5.5.3). The same 16 colours employed in the previous experiment were used (see Section 4.3). However, as text displayed in these colours looked rather desaturated in colour, eight extra colours were added to phase one of the algorithm.

- Red (255, 0, 0)
- Green (0, 255, 0)
- Blue (0, 0, 255)
- Yellow (255, 255, 0)
- Pink (255, 0, 255)
- Turquoise (0, 255, 255)
- Orange (255, 127, 0)
- Purple (127, 0, 255)

The same algorithm as described in Section 5.8.1 was used to determine the preferred colour. Again, subjects were permitted to adjust the font size so that it could be read easily before commencing the colour selection procedure (see Figure 133).

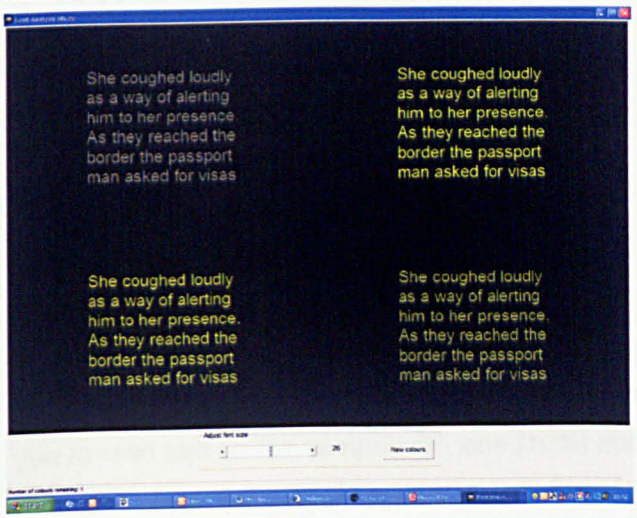
Figure 133 – Phase 1 of the algorithm



The preferred colour was determined by a process of elimination as described for the previous experiment. Having determined the preferred colour, the text was displayed at four

saturations of this colour and the subject was asked to choose the preferred saturation (see Figure 134).

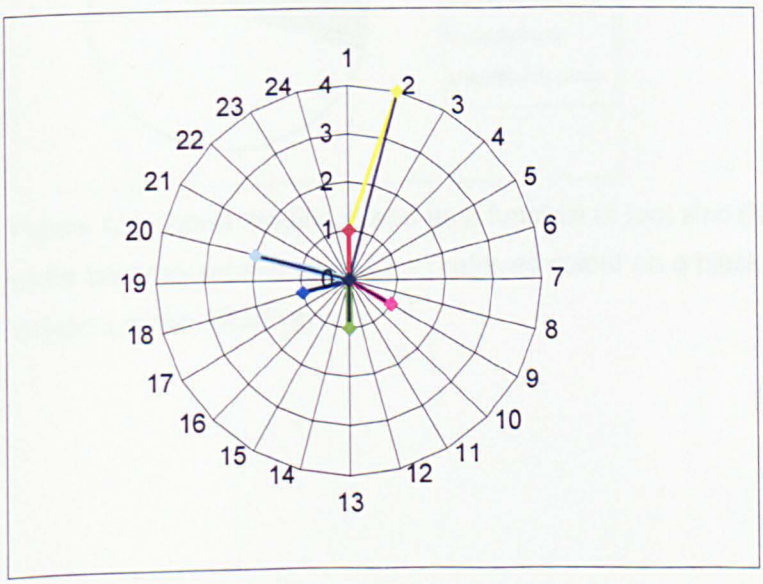
Figure 134 – Phase 2 of the algorithm showing different saturations of the remaining colour



5.9.2 Results: ARMD group

The distribution of preferred text colour for the 10 subjects in the ARMD group is shown in Figure 135. Four subjects chose yellow, two chose pale blue while the other subjects each chose different colours.

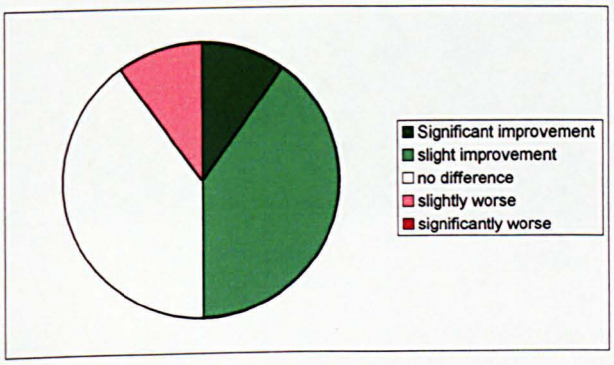
Figure 135 – Polar graph showing preferred text colour against a black background for subjects in the ARMD group



In response to the question: "Do you feel that the screen colour has made your eyes feel any more comfortable?", one (10%) subject reported a 'significant improvement, four (40%)

reported a 'slight improvement', four (40%) felt there was 'no difference' and one (10%) felt it was 'slightly worse' – see Figure 136.

Figure 136 – Pie chart showing 'comfort' with coloured text on a black background for subjects in the ARMD group



In response to the question: "Do you feel that the screen colour has made it any easier for you to read text on the computer?", one (10%) subject reported a 'significant improvement', two (20%) reported a 'slight improvement', five (50%) felt there was no difference and two (20%) felt it had made reading 'slightly worse' – see Figure 137.

Figure 137 – Graph showing 'ease of reading' with coloured text on a black background for subjects in the ARMD group

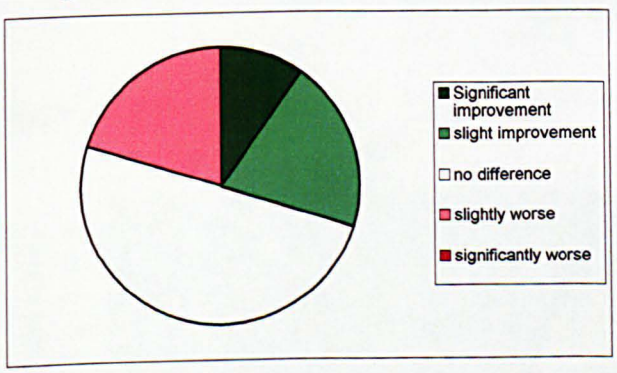
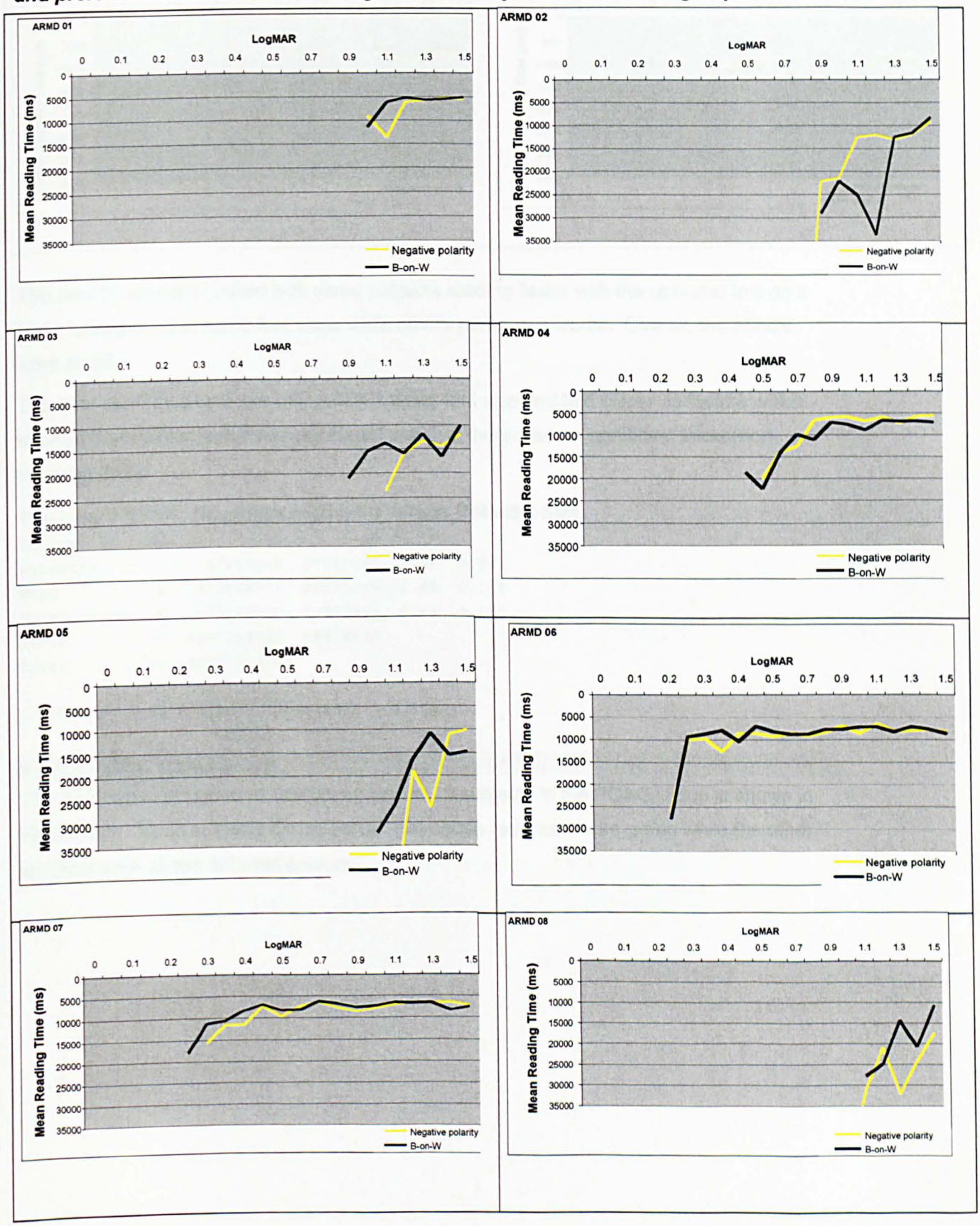
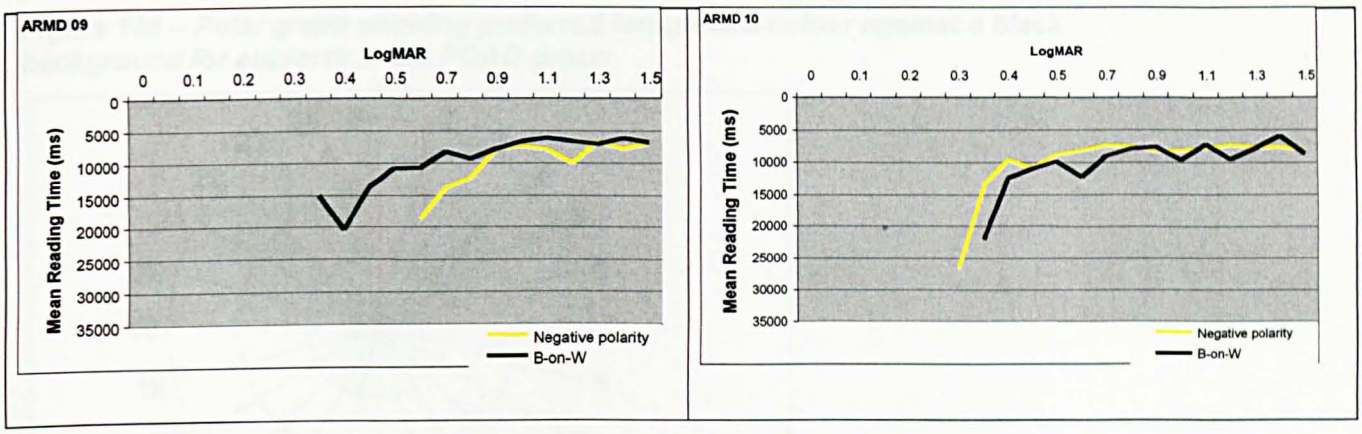


Figure 138 shows reading speed as a function of font size (logMAR) for black text on a white background and text of the preferred colour on a black background for each of the ten subjects in the ARMD group.

Figure 138 – Reading speed as a function of font size (LogMAR) for black on white and preferred colour on a black background for subjects in the ARMD group





The results are rather mixed with some subjects reading faster with the coloured text on a black background at some font sizes while others performed worse. Overall, the effects were small.

This was confirmed by a two way ANOVA using font size and text colour as factors which showed that neither factor was significant and that there was no significant interaction between them.

Two-way ANOVA: Reading speed (ms) versus Polarity, Size

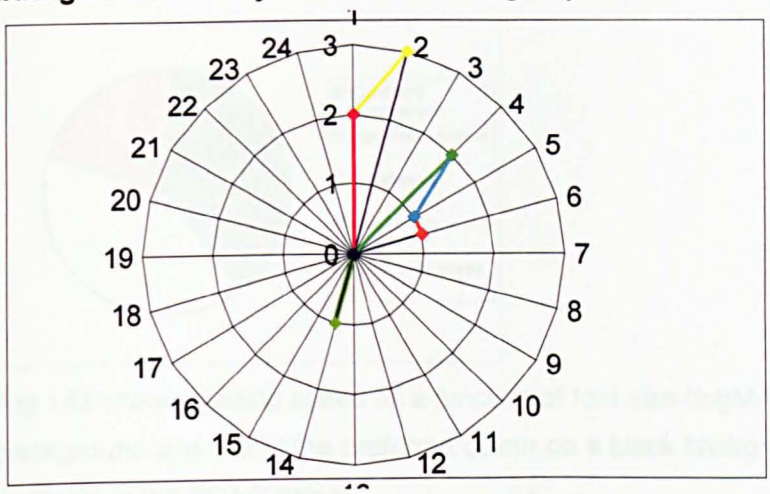
Source	DF	SS	MS	F	P
Polarity	1	67217042	67217042	1.39	0.242
Size	4	325806779	81451695	1.68	0.161
Interaction	4	79109759	19777440	0.41	0.802
Error	90	4357243669	48413819		
Total	99	4829377248			

S = 6958 R-Sq = 9.78% R-Sq(adj) = 0.75%

5.9.3 Results: POAG group

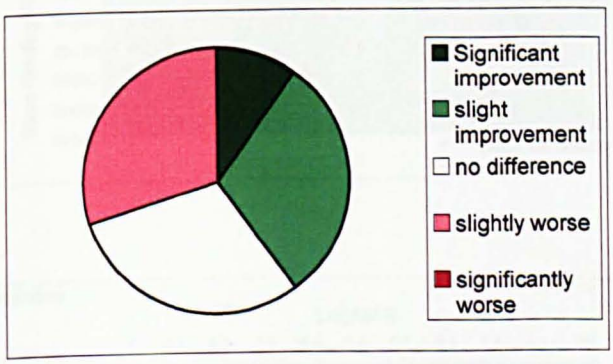
The distribution of preferred text colour for the 10 subjects in the POAG group is shown in Figure 139. Three subjects chose yellow, two chose red, two chose green while the other subjects each chose different colours.

Figure 139 – Polar graph showing preferred foreground colour against a black background for subjects in the POAG group



In response to the question: "Do you feel that the screen colour has made your eyes feel any more comfortable?", one reported a 'significant improvement, three reported a 'slight improvement', three felt there was 'no difference' and three felt it was 'slightly worse' – see Figure 140.

Figure 140 – Pie chart showing 'comfort' with coloured text on a black background colour for subjects in the POAG group



In response to the question: "Do you feel that the screen colour has made it any easier for you to read text on the computer?", two subjects reported a 'significant improvement', two reported a 'slight improvement', four felt there was no difference and two felt it had made reading 'slightly worse' – see Figure 141.

Figure 141 – Graph showing 'ease of reading' with coloured text on a black background for subjects in the POAG group

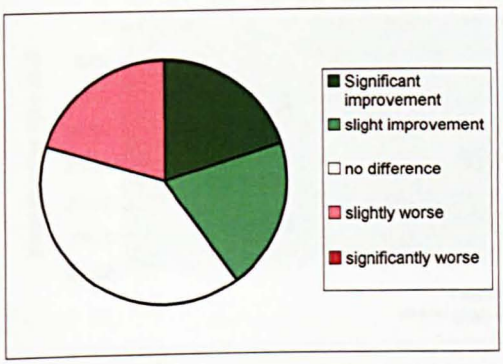
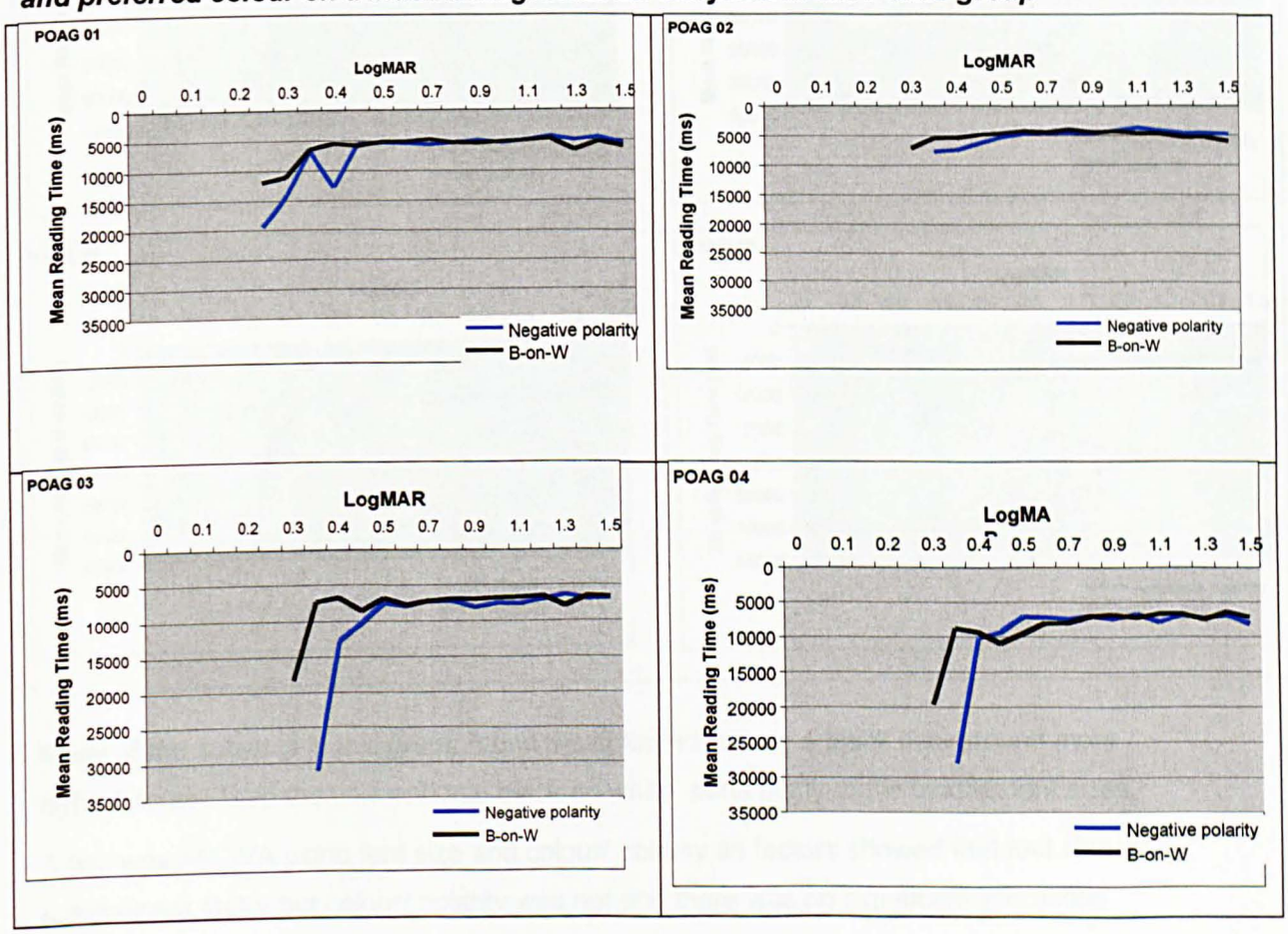
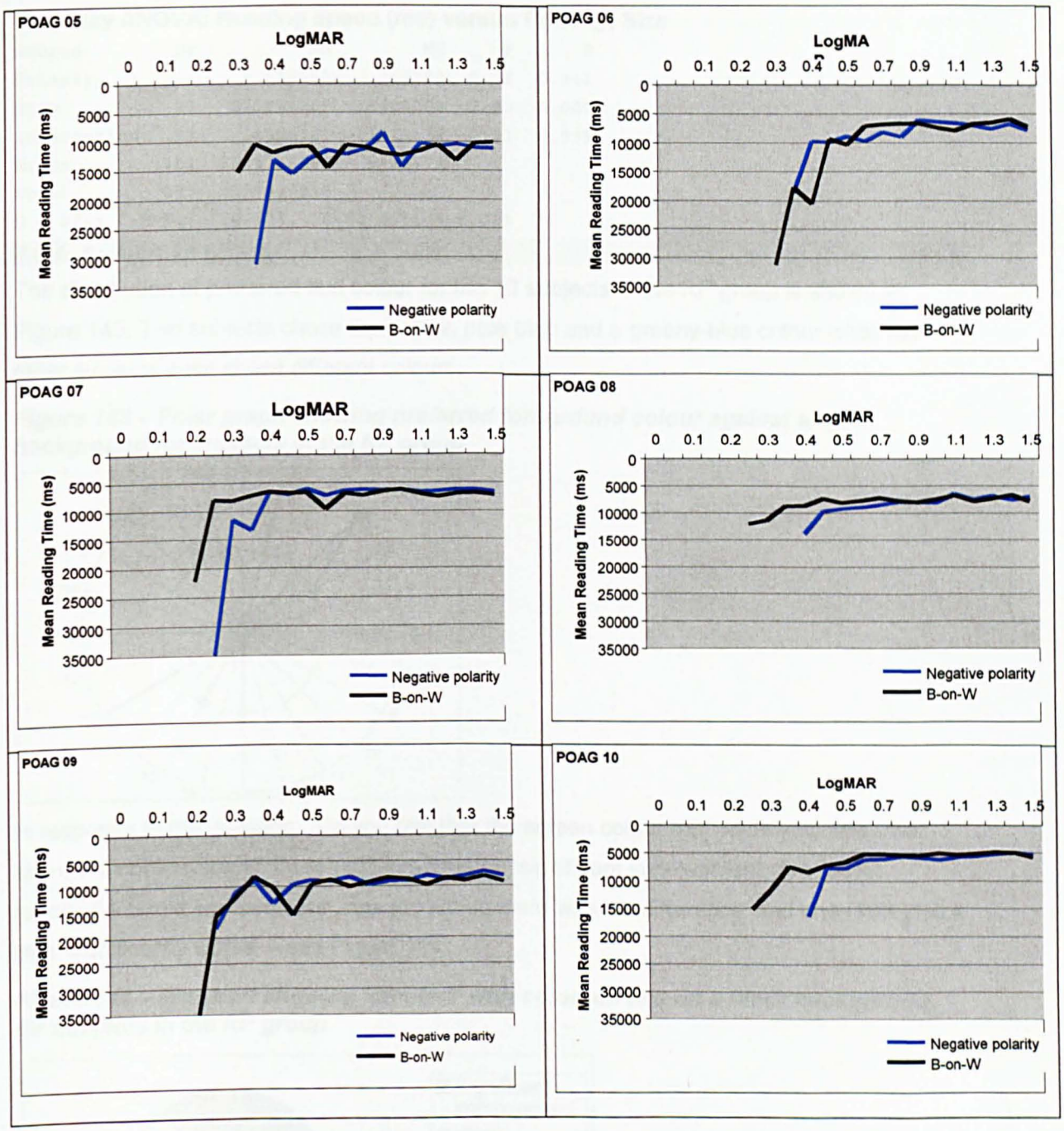


Fig 142 shows reading speed as a function of font size (logMAR) for black text on a white background and text of the preferred colour on a black background for each of the ten subjects in the POAG group.

Figure 142 – Reading speed as a function of font size (LogMAR) for black on white and preferred colour on a black background for subjects in the POAG group





Many of the subjects in this group found the coloured text on a black background more difficult to see than the conventional black on white, particularly at the smaller font sizes.

A two way ANOVA using font size and colour/ polarity as factors showed that font size was a significant factor but colour/ polarity was not and there was no significant interaction between the factors.

Two-way ANOVA: Reading speed (ms) versus Polarity, Size

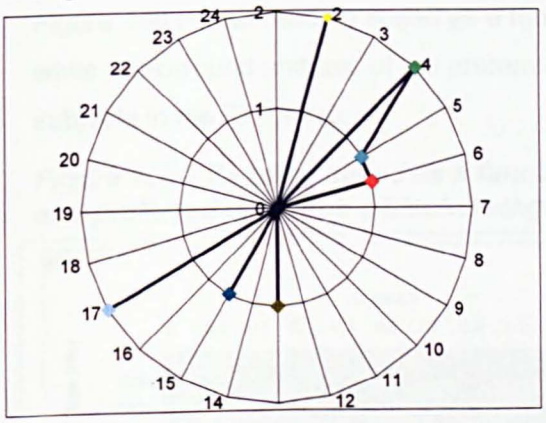
Source	DF	SS	MS	F	P
Polarity	1	219352	219352	0.04	0.841
Size	13	213304109	16408008	3.03	0.000
Interaction	13	14579761	1121520	0.21	0.999
Error	252	1366716688	5423479		
Total	279	1594819910			

S = 2329 R-Sq = 14.30%, R-Sq(adj) = 5.12%

5.9.4 Results: RP group

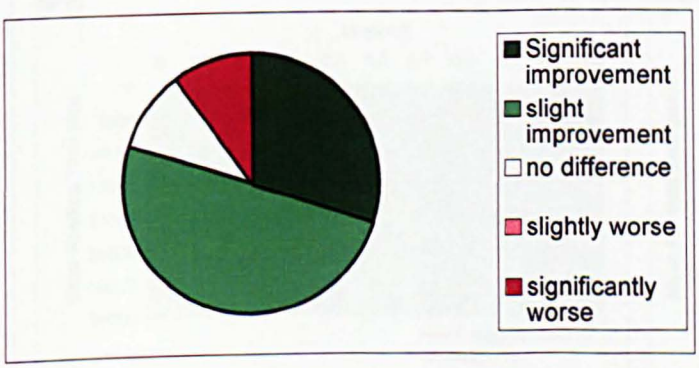
The distribution of preferred text colour for the 10 subjects in the RP group is shown in Figure 143. Two subjects chose the yellow, pale blue and a greeny-blue colour while the other subjects each chose different colours.

Figure 143 – Polar graph showing preferred foreground colour against a black background for subjects in the RP group



In response to the question: "Do you feel that the screen colour has made your eyes feel any more comfortable?", three (30%) reported a 'significant improvement, five (50%) reported a 'slight improvement', one (10%) felt there was 'no difference' and one (10%) felt it was 'significantly worse' – see Figure 144.

Figure 144 – Pie chart showing 'comfort' with coloured text on a black background for subjects in the RP group



In response to the question: "Do you feel that the screen colour has made it any easier for you to read text on the computer?", two (20%) subjects reported a 'significant improvement',

seven (70%) reported a 'slight improvement' and one (10%) felt it had made reading 'slightly worse' – see Figure 145.

Figure 145 – Graph showing 'ease of reading' with coloured text on a black background for subjects in the RP group

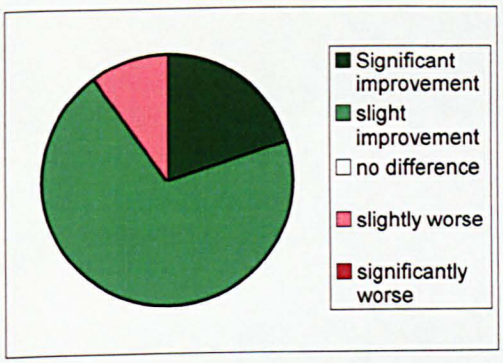
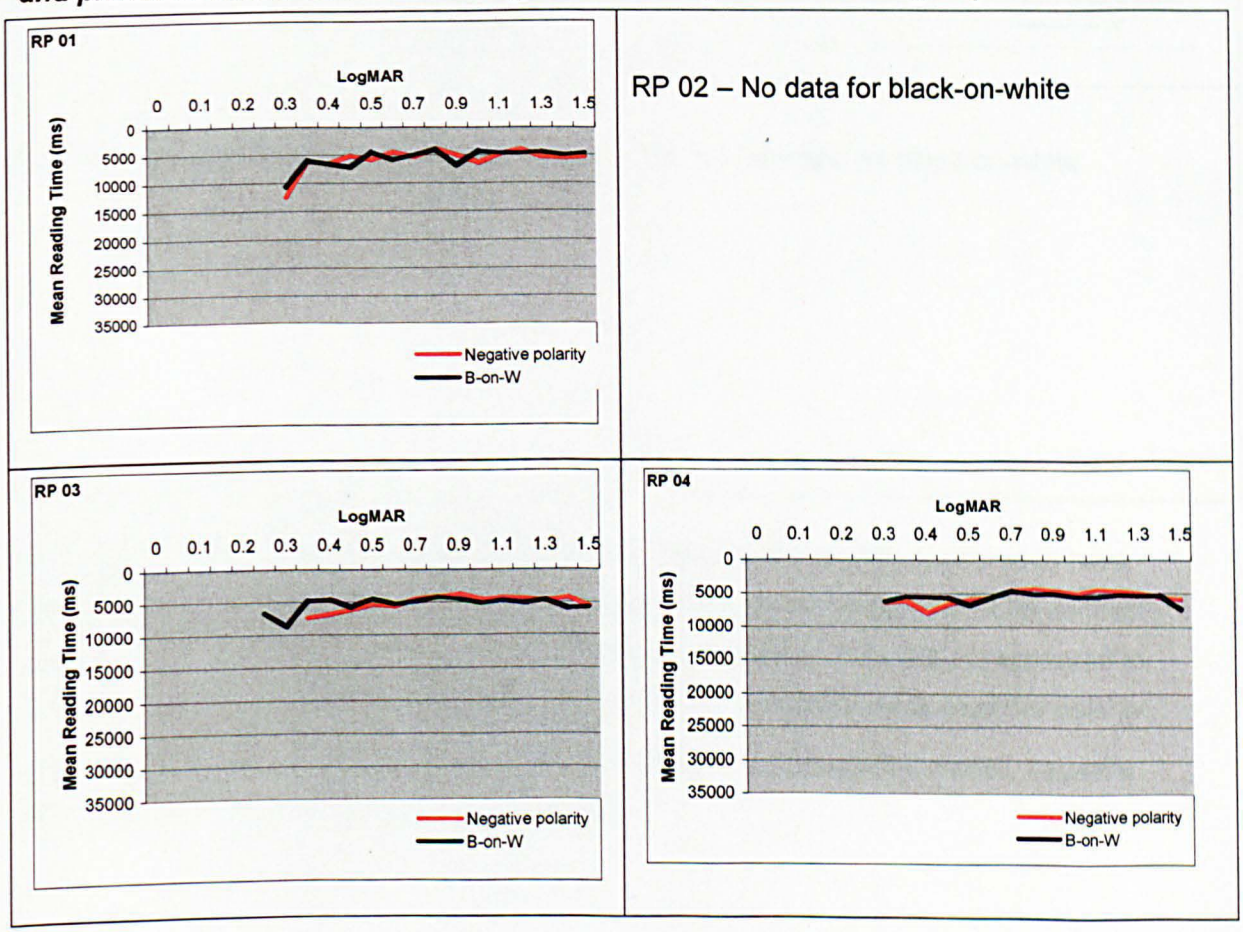
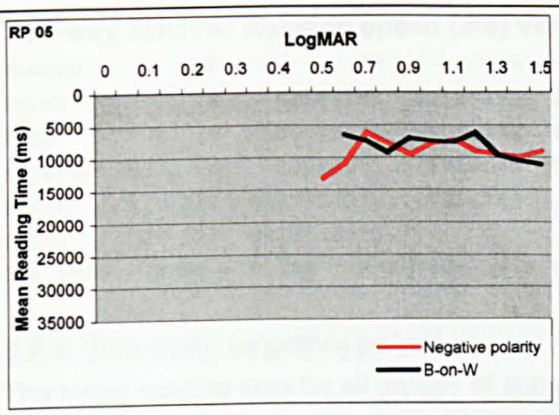
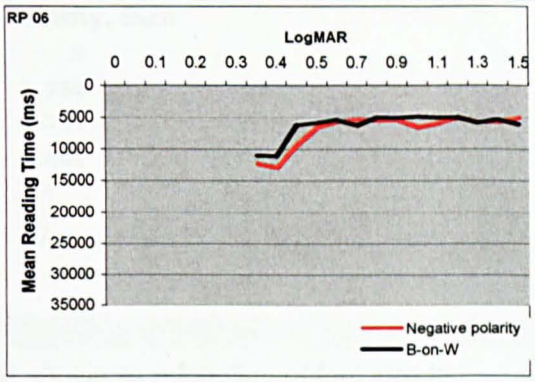


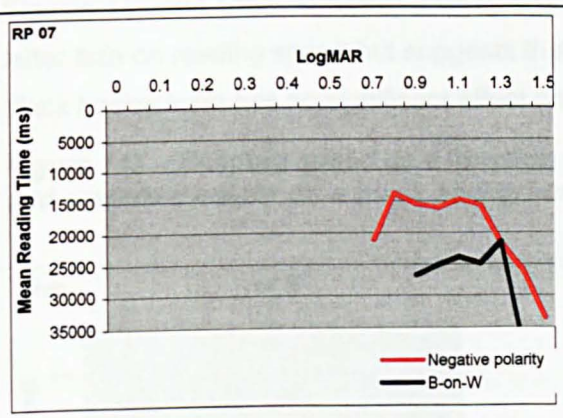
Figure 146 shows reading speed as a function of font size (logMAR) for black text on a white background and text of the preferred colour on a black background for each of the ten subjects in the RP group.

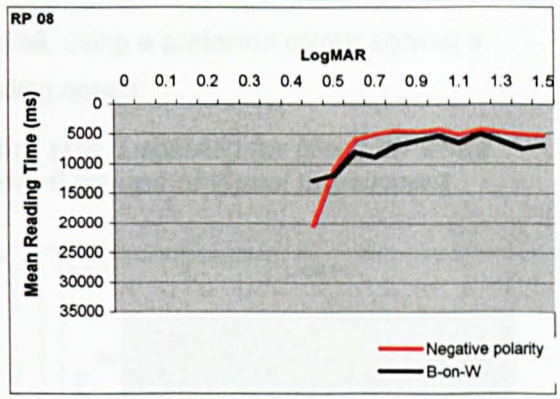
Figure 146 – Reading speed as a function of font size (LogMAR) for black on white and preferred colour on a black background for subjects in the RP group











RP 09 – No data for black-on-white

RP 10 – No data for black-on-white

With the exception of one subject (RP 07), the use of negative polarity appeared to have little effect on reading speed. RP 07 had the worst binocular VA (0.58), the worst contrast sensitivity (0.45) and the longest duration of disease (35 years). This subject appeared to not only read quicker, but also to be able to read smaller font sizes using negative polarity.

A two way ANOVA using font size and polarity as factors confirmed that overall, negative polarity did not have an effect on reading speed.

Two-way ANOVA: Reading speed (ms) versus Polarity, Size

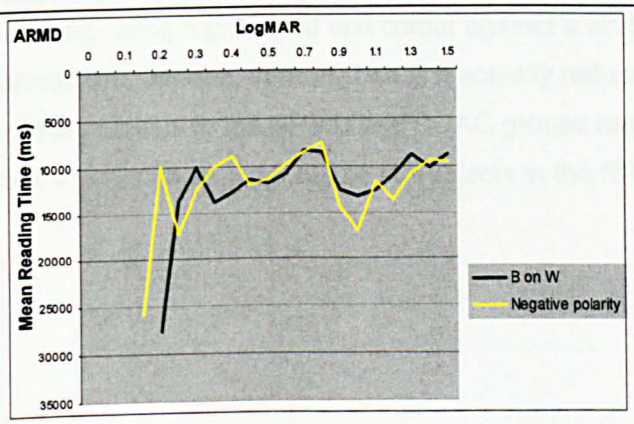
Source	DF	SS	MS	F	P
Polarity	1	62183193	62183193	1.33	0.252
Size	6	156340676	26056779	0.56	0.764
Interaction	6	10264071	1710679	0.04	1.000
Error	112	5247731976	46854750		
Total	125	5476519915			

S = 6845 R-Sq = 4.18% R-Sq(adj) = 0.00%

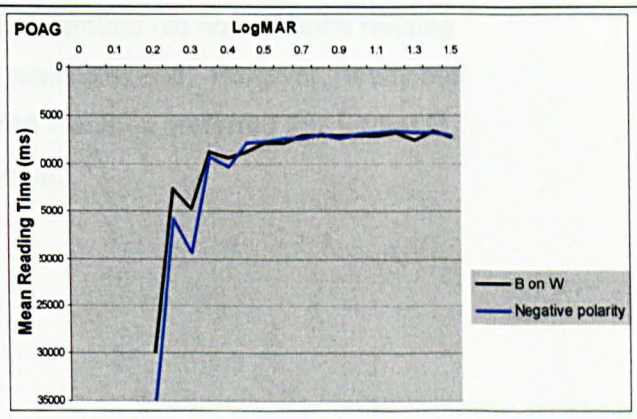
5.9.5 Summary: negative polarity

The mean reading time for all groups of subjects is shown as a function of font size in Figures 147 and 148 for positive polarity displays. This graph shows the familiar effect of letter size on reading speed but suggests that overall, using a preferred colour against a black background has no significant effect on reading speed.

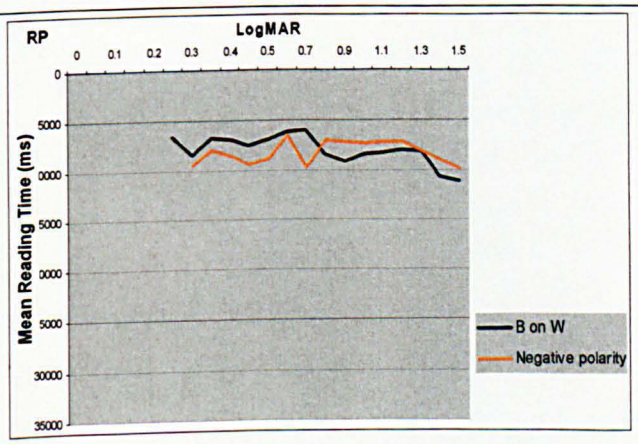
Figure 147 – Reading speed as a function of font size (LogMAR) for black on white and preferred colour on a black background for all groups of visual impairment



ARMD

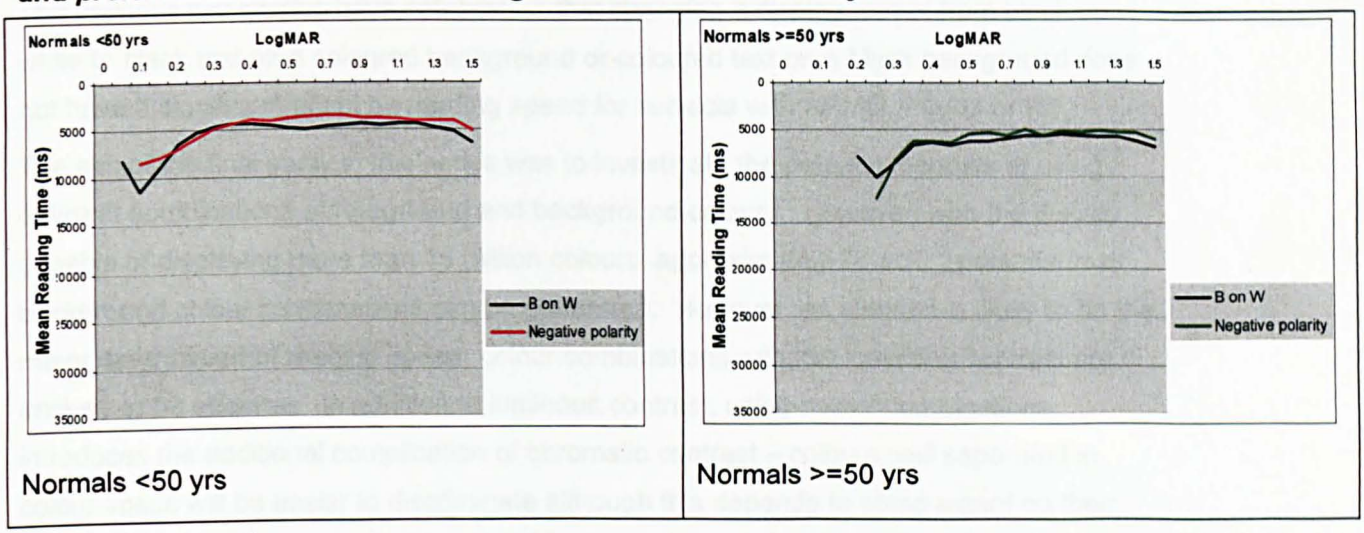


POAG



RP

Figure 148 – Reading speed as a function of font size (LogMAR) for black on white and preferred colour on a black background for all normal subjects



5.9.6 Conclusions for negative polarity colours

Overall, using a preferred text colour against a white background did not enhance reading speed and, indeed, in many cases it actually reduced reading speed. However, nearly half of the subjects in the ARMD and POAG groups reported that they preferred this format to black on white as did 9 out of 10 subjects in the RP group.

5.10 Colour combinations

The previous two studies have established that changing a display format from black on white to black text on a coloured background or coloured text on a black background does not have a significant effect on reading speed for subjects with ARMD, POAG or RP.

The aim of the final study in this series was to investigate the potential benefits of using different combinations of foreground and background colours. However, with the display capable of displaying more than 16 million colours, approximately 28×10^{12} potential text/ background colour combinations can be generated. However, as contrast is likely to be the major determinant of reading speed, colour combinations with low luminous contrast are unlikely to be effective. In addition to luminous contrast, using colour combinations introduces the additional complication of chromatic contrast – colours well separated in colour space will be easier to discriminate although this depends to some extent on their position within colour space.

To circumvent this problem for this study, 48 different combinations (see Table 27) were selected on the basis of their subjective appeal in a brief pilot study. Combinations with poor contrast were excluded (e.g. pale colours on pale colours). In addition, certain combinations which have been reported to aid reading in those with visual impairment were included (Lindner et al., 1999). It was not possible to equalise luminance or contrast for these colour combinations.

Table 27 – Colours used for foreground/background combinations

Colour	Background RGB	Foreground RGB	Colour
1	128, 0, 0	255, 0, 0	XXXXX
2	128, 0, 0	255, 255, 0	XXXXX
3	128, 0, 0	0, 0, 255	XXXXX
4	128, 0, 0	0, 255, 0	XXXXX
5	128, 0, 0	0, 255, 255	XXXXX
6	128, 0, 0	255, 255, 255	XXXXX
7	128, 0, 0	255, 102, 0	XXXXX
8	128, 0, 0	255, 0, 255	XXXXX
9	0, 0, 128	255, 0, 0	XXXXX
10	0, 0, 128	255, 255, 0	XXXXX
11	0, 0, 128	0, 0, 255	XXXXX
12	0, 0, 128	0, 255, 0	XXXXX
13	0, 0, 128	0, 255, 255	XXXXX
14	0, 0, 128	255, 255, 255	XXXXX
15	0, 0, 128	255, 102, 0	XXXXX
16	0, 0, 128	255, 0, 255	XXXXX

Colour	Background RGB	Foreground RGB	Colour
17	0, 51, 0	255, 0, 0	XXXXX
18	0, 51, 0	255, 255, 0	XXXXX
19	0, 51, 0	0, 0, 255	XXXXX
20	0, 51, 0	0, 255, 0	XXXXX
21	0, 51, 0	0, 255, 255	XXXXX
22	0, 51, 0	255, 255, 255	XXXXX
23	0, 51, 0	255, 102, 0	XXXXX
24	0, 51, 0	255, 0, 255	XXXXX
25	255, 0, 0	128, 0, 0	XXXXX
26	255, 255, 0	128, 0, 0	XXXXX
27	0, 0, 255	128, 0, 0	XXXXX
28	0, 255, 0	128, 0, 0	XXXXX
29	0, 255, 255	128, 0, 0	XXXXX
30	255, 255, 255	128, 0, 0	XXXXX
31	255, 102, 0	128, 0, 0	XXXXX
32	255, 0, 255	128, 0, 0	XXXXX
33	255, 0, 0	0, 0, 128	XXXXX
34	255, 255, 0	0, 0, 128	XXXXX
35	0, 0, 255	0, 0, 128	XXXXX
36	0, 255, 0	0, 0, 128	XXXXX
37	0, 255, 255	0, 0, 128	XXXXX
38	255, 255, 255	0, 0, 128	XXXXX
39	255, 102, 0	0, 0, 128	XXXXX
40	255, 0, 255	0, 0, 128	XXXXX
41	255, 0, 0	0, 51, 0	XXXXX
42	255, 255, 0	0, 51, 0	XXXXX
43	0, 0, 255	0, 51, 0	XXXXX
44	0, 255, 0	0, 51, 0	XXXXX
45	0, 255, 255	0, 51, 0	XXXXX
46	255, 255, 255	0, 51, 0	XXXXX
47	255, 102, 0	0, 51, 0	XXXXX
48	255, 0, 255	0, 51, 0	XXXXX

The same algorithm as described in Sections 5.8.1 and 5.9.1 was used except there were no variations in saturation for the final choice of colour.

Figure 149 – Figure showing screenshot of the colour combinations



5.10.1 Results: ARMD group

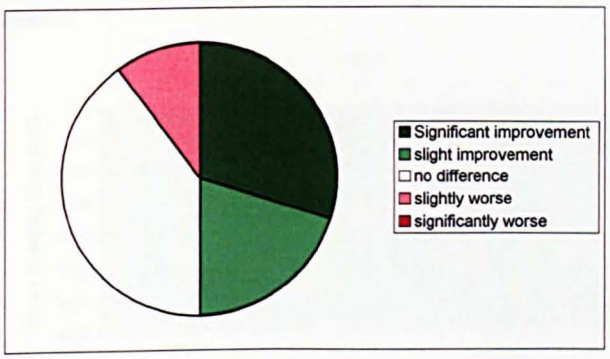
Table 28 shows the colour combinations chosen by each of the subjects in the ARMD group. One subject selected blue on yellow, one subject selected yellow on blue, three subjects in total chose a blue background and five subjects (50%) chose white on dark green as their preferred colour combination.

Table 28 – Table showing the foreground/background combinations selected by each subject in the ARMD group

ARMD	RGB value text/background	
1	0,0,128 255,255,0	XXXXXXXXXXXX
2	255,255,0 0,51,0	XXXXXXXXXXXX
3	0,255,255 0,0,128	XXXXXXXXXXXX
4	255,255,255 0,0,128	XXXXXXXXXXXX
5	255,255,255 0,51,0	XXXXXXXXXXXX
6	255,255,0 0,0,128	XXXXXXXXXXXX
7	255,255,255 0,51,0	XXXXXXXXXXXX
8	255,255,255 0,51,0	XXXXXXXXXXXX
9	0,51,0 255,255,255	XXXXXXXXXXXX
10	255,255,255 0,51,0	XXXXXXXXXXXX

In response to the question: "Do you feel that the screen colour has made your eyes feel any more comfortable?", three subjects reported a 'significant improvement, two reported a 'slight improvement', four felt it made no difference and one subject reported that it was 'slightly worse' – see Figure 150.

Figure 150 – Graph showing 'comfort' with preferred colour combinations for subjects in the ARMD group



In response to the question: "Do you feel that the screen colour has made it any easier for you to read text on the computer?", three reported a 'significant improvement', one reported a 'slight improvement', five felt it made no difference and one subject felt it had made reading 'slightly worse' – see Figure 151.

Figure 151 – Graph showing 'ease of reading' with preferred colour combinations for subjects in the ARMD group

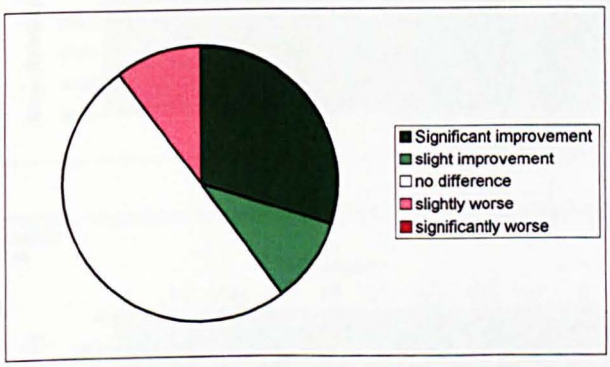
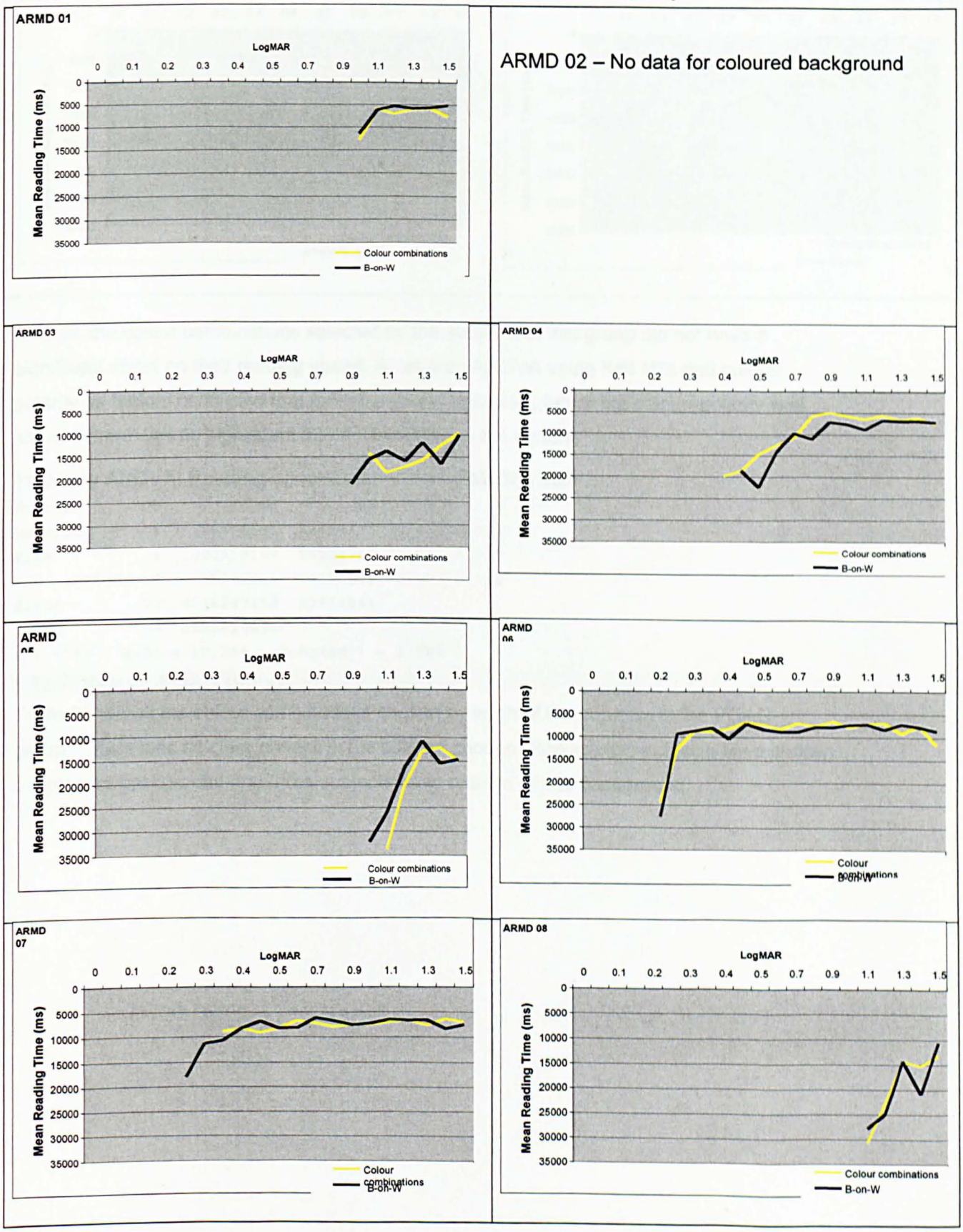
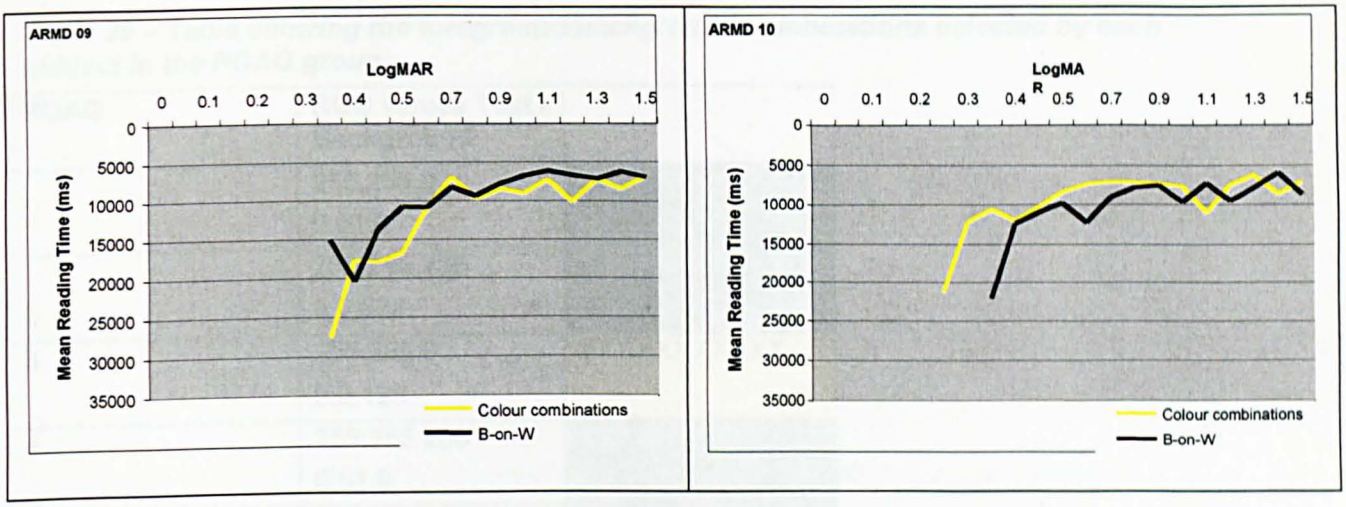


Figure 152 shows reading speed as a function of font size (logMAR) for black text on white background and the preferred text and background colour combination for each of the ten subjects in the ARMD group.

Figure 152 – Reading speed as a function of font size (LogMAR) for preferred foreground/background combinations for subjects in the ARMD group





Overall, the colour combinations selected by the subjects in this group did not have a significant effect on their reading speed. A two way ANOVA using font size and colour/ polarity as factors confirmed that font size was a significant factor but colour/ polarity was not and there was no significant interaction between the factors.

Two-way ANOVA: Reading speed (ms) versus Polarity, Size

Source	DF	SS	MS	F	P
Polarity	1	13665591	13665591	0.41	0.525
Size	4	300819197	75204799	2.24	0.070
Interaction	4	30082249	7520562	0.22	0.924
Error	90	3016247459	33513861		
Total	99	3360814496			

S = 5789 R-Sq = 10.25% R-Sq(adj) = 1.28%

5.10.2 Results: POAG group

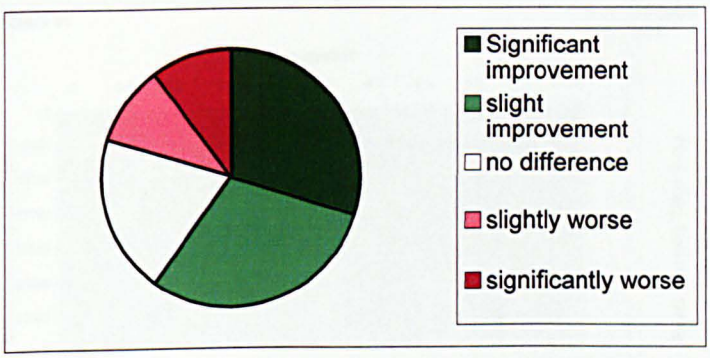
Table 29 shows the colour combinations chosen by each of the subjects in the POAG group. There was no clear pattern in the colours chosen although two subjects have chosen a turquoise background and three subjects have chosen a blue background.

Table 29 – Table showing the foreground/background combinations selected by each subject in the POAG group

POAG	RGB values Text / Background	
1	255,255,0 0,51,0	XXXXXXXXXXX
2	255,255,255 0,0,128	XXXXXXXXXXX
3	255,255,0 0,0,128	XXXXXXXXXXX
4	255,255,255 0,51,0	XXXXXXXXXXX
5	255,0,255 0,0,128	XXXXXXXXXXX
6	0,0,128 0,255,255	XXXXXXXXXXX (Dark blue)
7	0,51,0 0,255,255	XXXXXXXXXXX (Dark green)
8	255,102,0 0,51,0	XXXXXXXXXXX
9	0,51,0 255,0,0	XXXXXXXXXXX
10	0,255,255 0,0,128	XXXXXXXXXXX

In response to the question: "Do you feel that the screen colour has made your eyes feel any more comfortable?", three reported a 'significant improvement, three reported a 'slight improvement', two felt it made no difference, one reported that it was 'slightly worse' and one subject reported that it was 'significantly worse' – see Figure 153.

Figure 153 – Pie chart showing 'comfort' with preferred colour combinations for subjects in the POAG group



In response to the question: "Do you feel that the screen colour has made it any easier for you to read text on the computer?", three reported a 'significant improvement', three reported a 'slight improvement', three felt it made no difference and one subject felt it had made reading 'significantly worse' – see Figure 154.

Figure 154 – Graph showing 'ease of reading' with preferred colour combinations for subjects in the POAG group

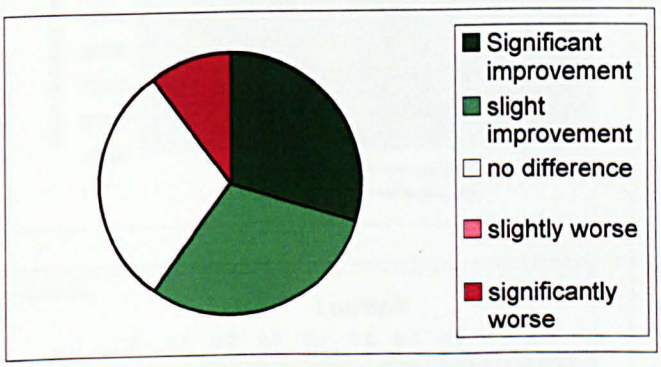
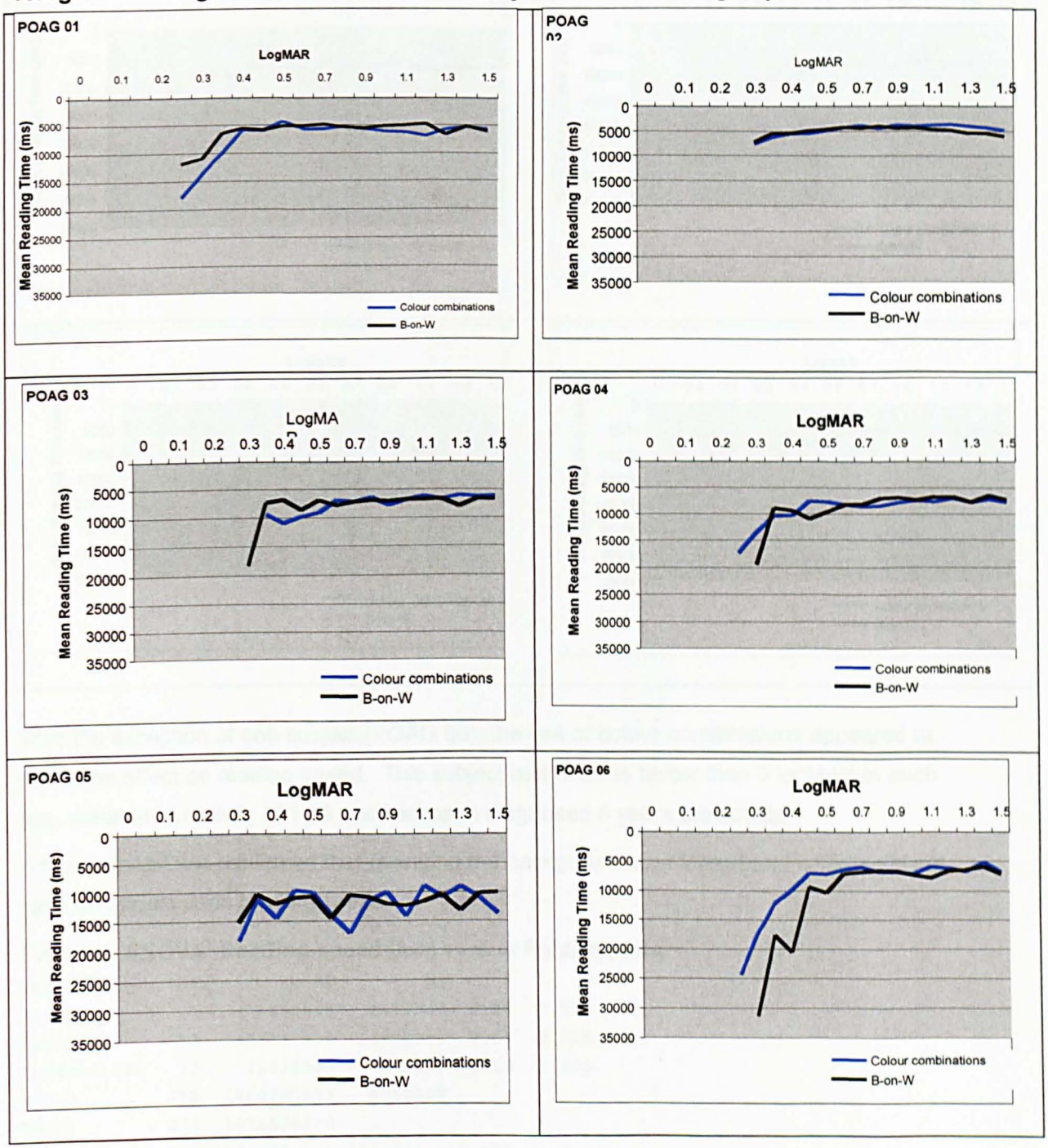
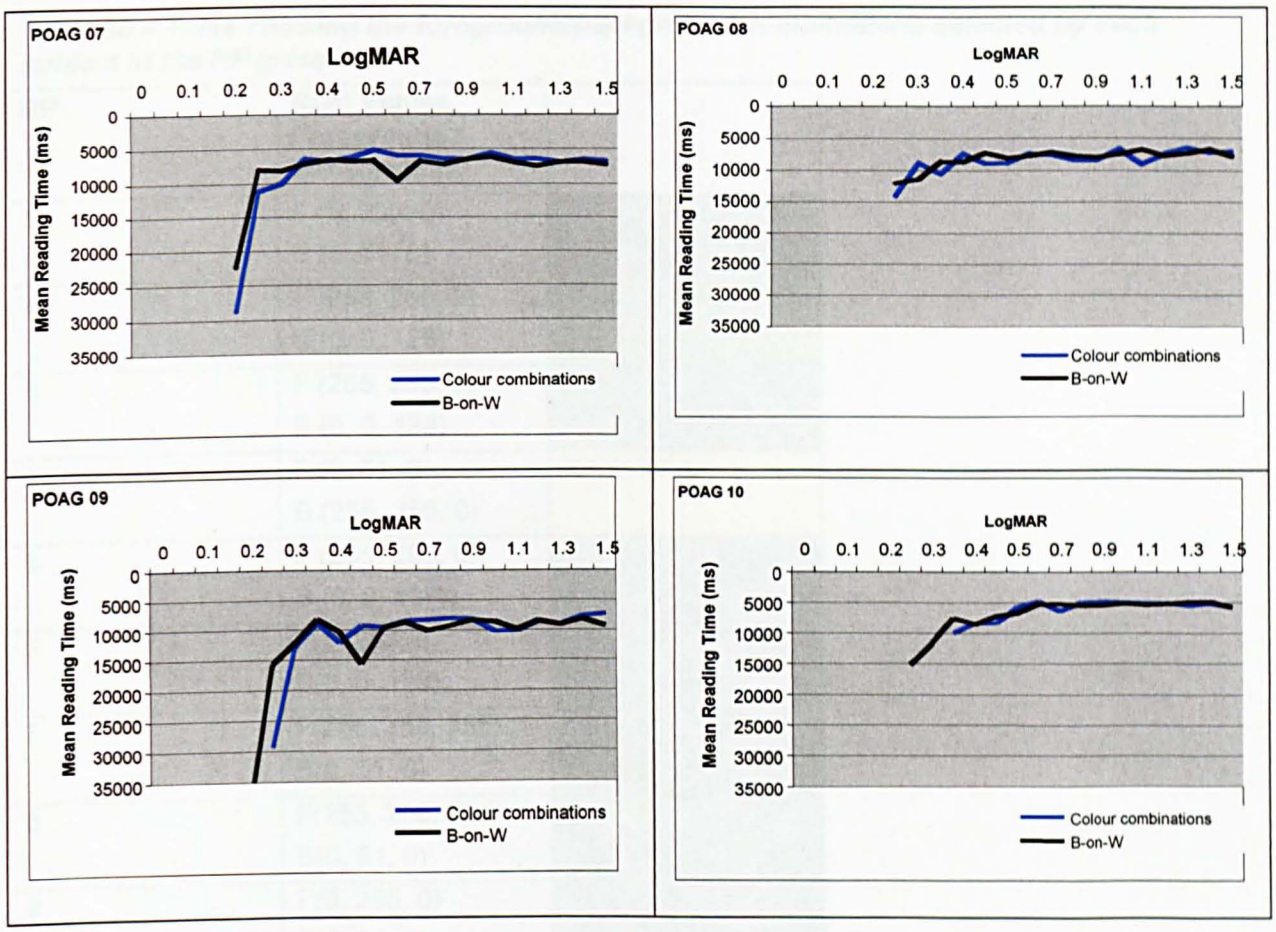


Figure 155 shows reading speed as a function of font size (logMAR) for black text on a white background and the preferred text and background colour combination for each of the ten subjects in the POAG group.

Figure 155 – Reading speed as a function of font size (LogMAR) for preferred foreground/background combinations for subjects in the POAG group





With the exception of one subject (POAG 06), the use of colour combinations appeared to have little effect on reading speed. This subject had acuities better than 0 logMAR in each eye, contrast sensitivity of 1.65 and had been diagnosed 8 years previously.

A two way ANOVA confirmed that changing the background and foreground colours did not have an impact upon reading speed.

Two-way ANOVA: Reading speed (ms) versus Polarity, Size

Source	DF	SS	MS	F	P
Colour	1	1655349	1655349	0.28	0.598
Size	13	161447238	12419018	2.09	0.015
Interaction	13	11415940	878149	0.15	1.000
Error	252	1500107653	5952808		
Total	279	1674626180			

S = 2440 R-Sq = 10.42% R-Sq(adj) = 0.82%

5.10.3 Results: RP group

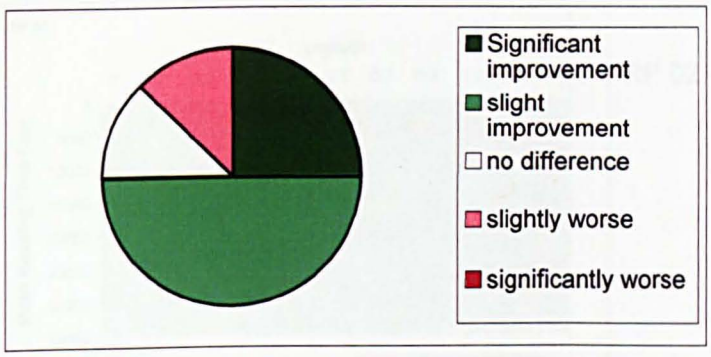
Table 30 shows the colour combinations chosen by each of the subjects in the RP group. Half of the subjects chose a dark green background whilst three chose a blue background.

Table 30 – Table showing the foreground/background combinations selected by each subject in the RP group

RP	RGB Values Foreground / Background	
1	F (0, 255, 0) B (0, 51, 0)	XXXXXXX
2	F (255, 255, 0) B (0, 0, 128)	XXXXXXX
3	F (255, 255, 0) B (0, 0, 128)	XXXXXXX
4	F (0, 51, 0) B (255, 255, 0)	XXXXXXX
5	F (255, 255, 0) B (0, 0, 128))	XXXXXXXX
6	F(0, 255, 0) B(0, 0, 128)	XXXXXXXX
7	F(255, 255, 255) B(0, 51, 0)	XXXXXXXX
8	F(255, 255, 0) B(0, 51, 0)	XXXXXXXX
9	F(0, 255, 0) B(0, 51, 0)	XXXXXXXX
10	F(0, 255, 255) B(0, 51, 0)	XXXXXXXX

In response to the question: "Do you feel that the screen colour has made your eyes feel any more comfortable?", two reported a 'significant improvement, four reported a 'slight improvement', one felt it made no difference and one subject reported that it was 'slightly worse' – see Figure 156.

Figure 156 – Pie chart showing 'comfort' with preferred colour combinations for subjects in the RP group



In response to the question: "Do you feel that the screen colour has made it any easier for you to read text on the computer?", one reported a 'significant improvement', six reported a 'slight improvement' and one subject felt it made no difference – see Figure 157.

Figure 157 – Pie chart showing 'ease of reading' with preferred colour combinations for subjects in the RP group

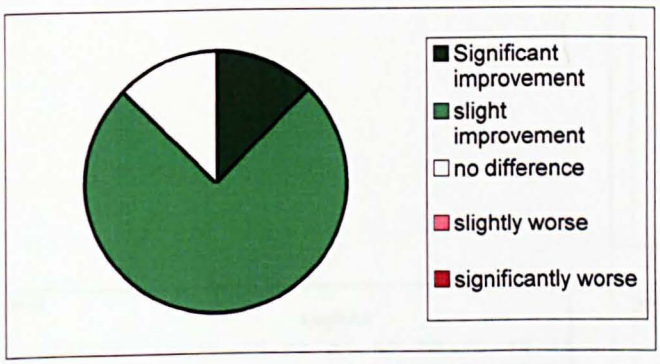
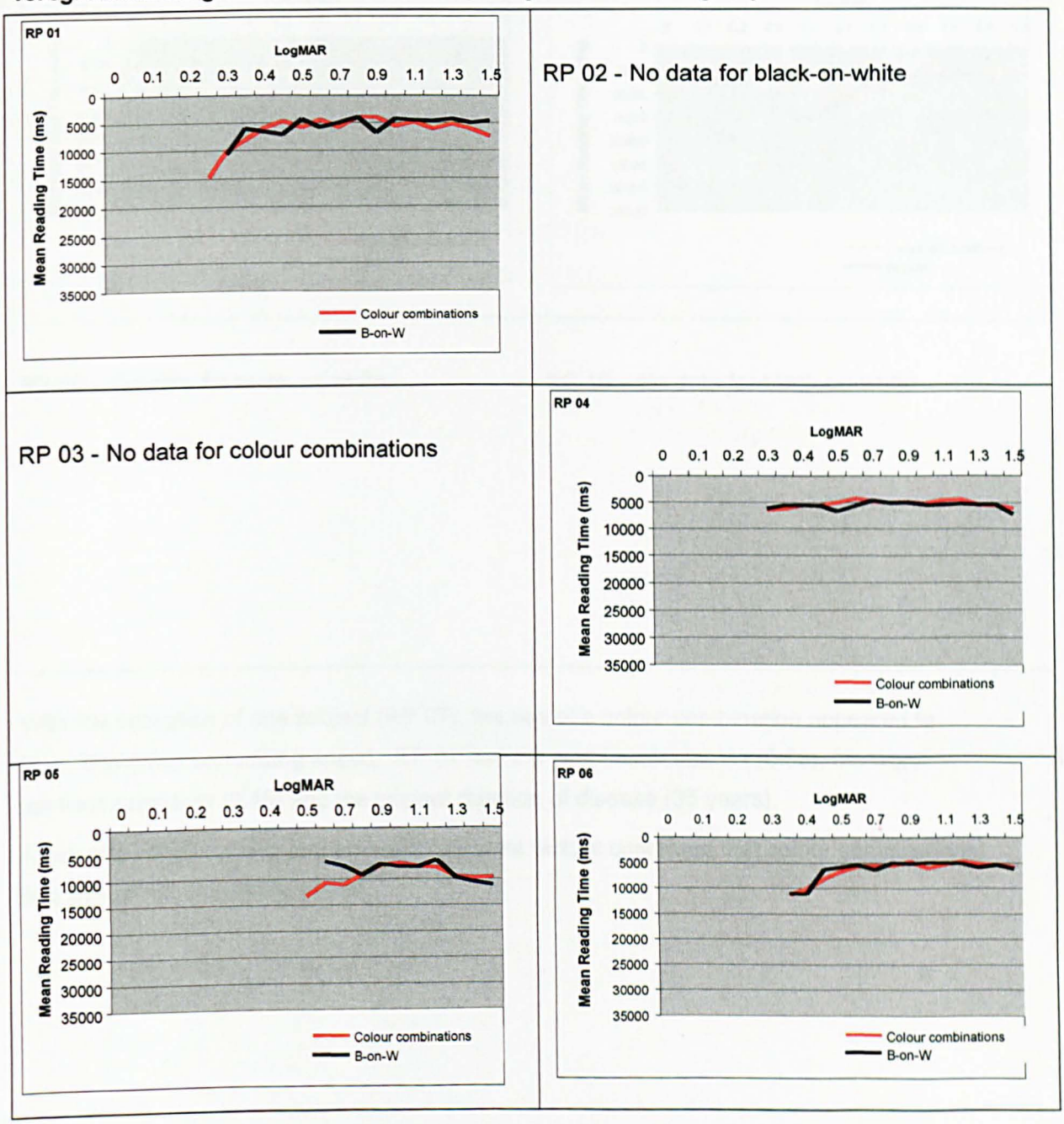
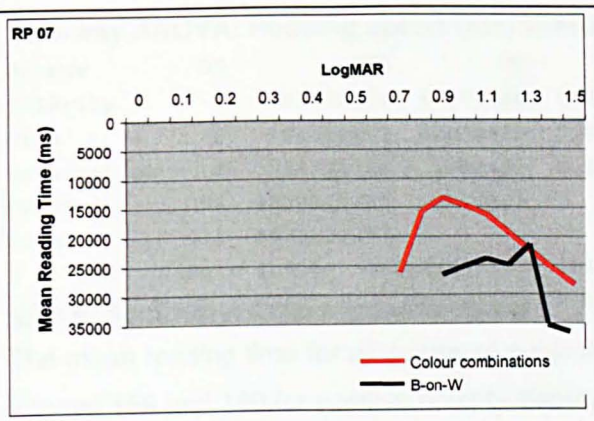
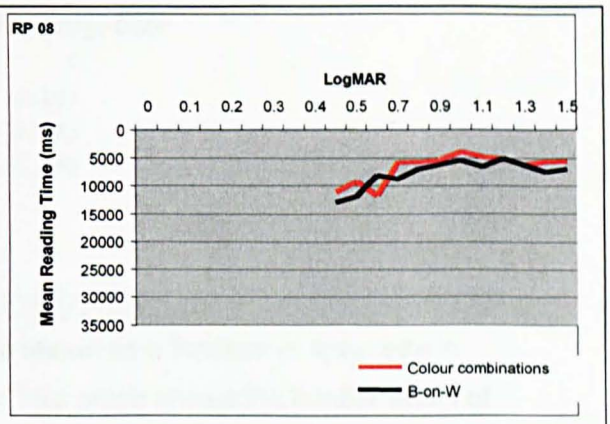


Figure 158 shows reading speed as a function of font size (logMAR) for black text on a white background and the preferred text and background colour combination for each of the ten subjects in the RP group.

Figure 158 – Reading speed as a function of font size (LogMAR) for preferred foreground/background combinations for subjects in the RP group







RP 09 – No data for black-on-white

RP 10 – No data for black-on-white

With the exception of one subject (RP 07), the use of a colour combination appeared to have little effect on reading speed. RP 07 had the worst binocular VA (0.58), the worst contrast sensitivity (0.45) and the longest duration of disease (35 years).

A two way ANOVA using font size and colour as factors confirmed that colour combinations had little effect on reading speed.

Two-way ANOVA: Reading speed (ms) versus Polarity, Size

Source	DF	SS	MS	F	P
Polarity	1	65578864	65578864	1.33	0.251
Size	6	164856201	27476033	0.56	0.763
Interaction	6	19394739	3232457	0.07	0.999
Error	98	4829273487	49278301		
Total	111	5079103292			

S = 7020 R-Sq = 4.92% R-Sq(adj) = 0.00%

5.10.4 Summary: Colour combinations

The mean reading time for all groups of subjects is shown as a function of letter size in Figures 159 and 160 for positive polarity displays. This graph shows the familiar effect of letter size on reading speed but suggests that changing the foreground and background colour has no effect on reading speed.

Figure 159 – Reading speed as a function of font size (LogMAR) for preferred foreground/background combinations for all groups of visual impairment

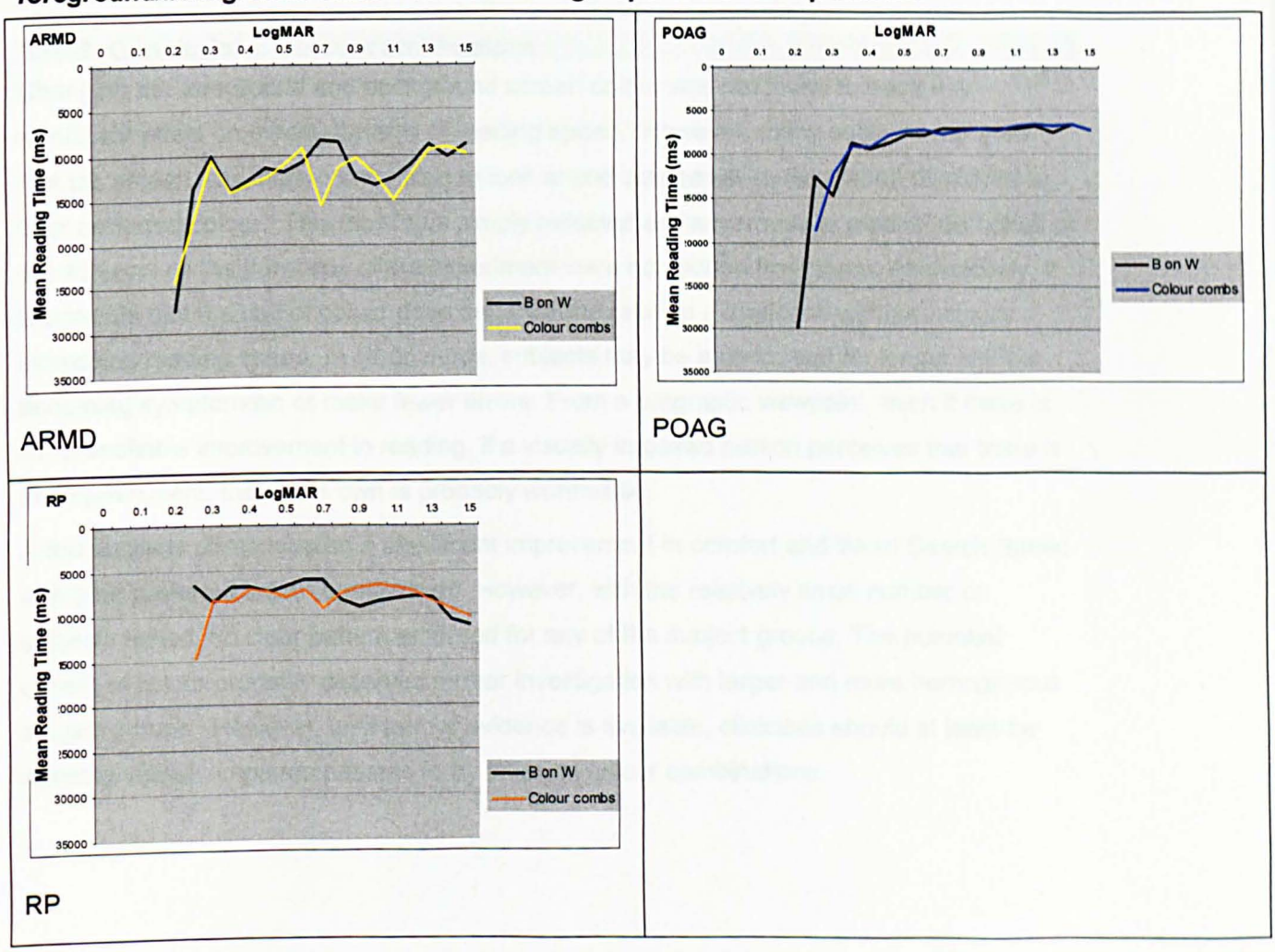
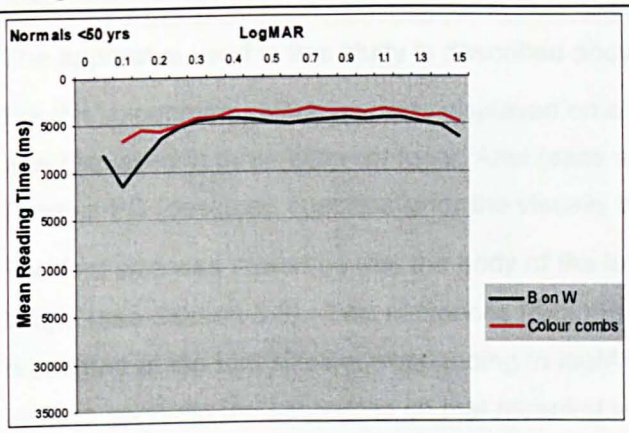
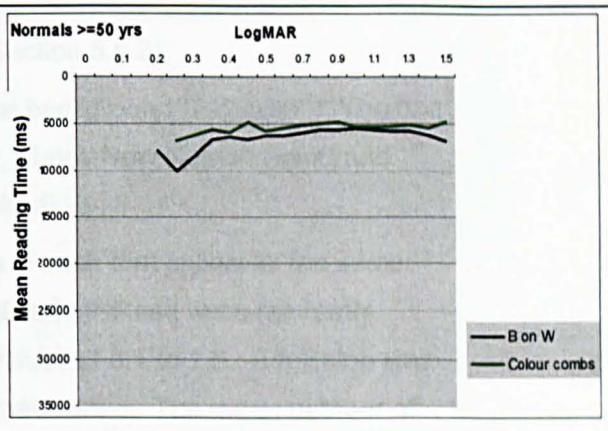


Figure 160 – Reading speed as a function of font size (LogMAR) for preferred foreground/background combinations for all groups of visual impairment



Normals <50 yrs



Normals >=50 yrs

5.10.5 Conclusions: Colour combinations

Changing the foreground and background screen colour was not found to have any significant effect on measurements of reading speed. However, many subjects reported that the screen was more comfortable to look at and was easier to read when displayed in their preferred colour. This may have simply reflected an "eagerness to please" on behalf of the subjects as the purposes of the experiment were not hidden from them. Alternatively, it is possible that the use of colour does enhance the reading experience without actually increasing reading speed. In other words, subjects may be able to read for longer without becoming symptomatic or make fewer errors. From a pragmatic viewpoint, even if there is no quantifiable improvement in reading, if a visually impaired person perceives that there is an improvement, this on its own is probably worthwhile.

A few subjects demonstrated a significant improvement in comfort and Word Search Speed with their preferred colour combination. However, with the relatively small number of subjects tested, no clear pattern emerged for any of the subject groups. The potential benefit of colour probably deserves further investigation with larger and more homogenous subject groups. However, until further evidence is available, clinicians should at least be advising visually-impaired patients to try different colour combinations.

5.11 Experiment to examine the effect of font style on reading speed

5.11.1 Methods

The apparatus used in this study is described above (Section 5.5.3).

For this experiment, black text was displayed on a white background (212 cdm^{-2}). The text was displayed in three different fonts: Arial (sans serif), Times New Roman (serif) and Tiresias PC (designed specifically for the visually impaired).

The font size was scaled so that the body of the letters in each font style was the same height (see Section 3.3). Two sentences from the modified MNRead were randomly presented at ten font sizes corresponding to logMAR values of 0.1 to 1.5. A full stop was used to separate the sentences so that meaning was maintained. The mean number of words for each sentence was ten. Font sizes were presented in descending order only as all subjects had some form of visual impairment. The order of the fonts was randomised to balance for order effects.

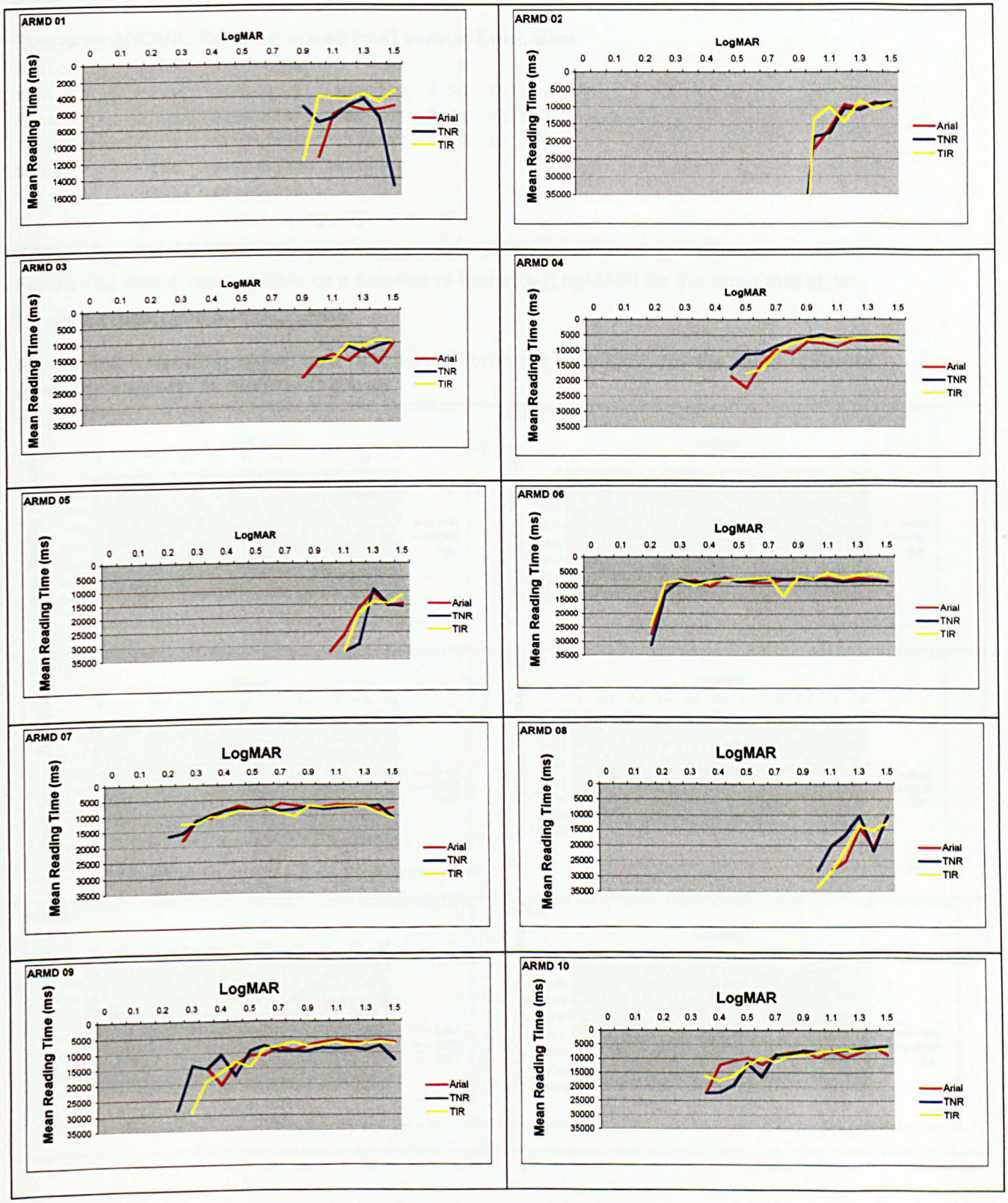
The screen contrast was set at maximum (approximately 400:1). The test was performed in a room with subdued lighting and free from distractions.

Following an audible cue, the sentences were displayed and the observer was instructed to read the sentences aloud as quickly as possible. On completing both sentences, the examiner (PJD) pressed a stop key.

5.11.2 Results: ARMD group

Figure 161 shows reading time as a function of font size (LogMAR) for the three font styles, for each subject in the ARMD group.

Figure 161 – Reading speed as a function of font size (LogMAR) for the three different fonts for subjects in the ARMD group



Reading speed was remarkably unaffected by font style for subjects in the ARMD group. This is shown by a two way ANOVA using font size and style as factors which confirmed

that font size was a significant factor but font style was not and there was no significant interaction between them.

Two-way ANOVA: Reading speed (ms) versus Font, Size

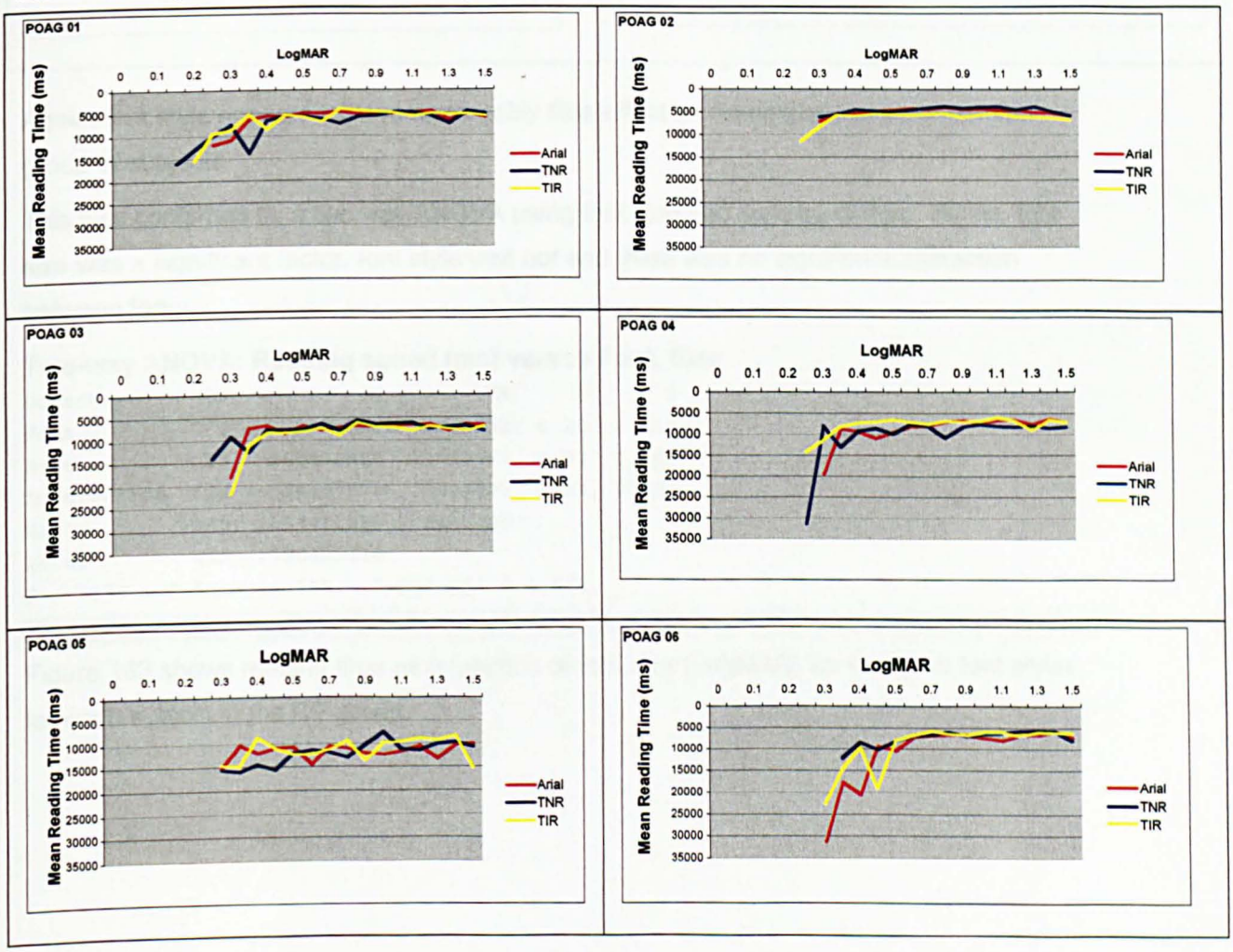
Source	DF	SS	MS	F	P
Font	2	19150464	9575232	0.30	0.743
Size	4	299828782	74957195	2.33	0.059
Interaction	8	17119100	2139887	0.07	1.000
Error	135	4343543492	32174396		
Total	149	4679641837			

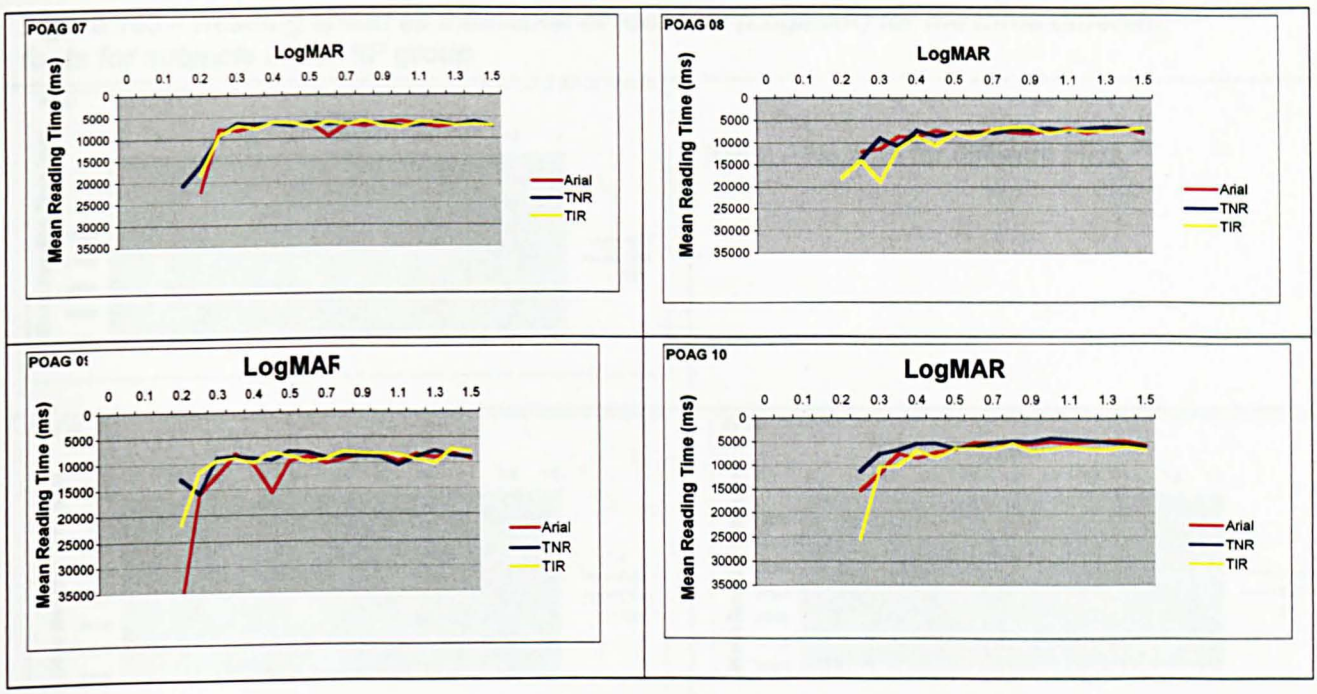
S = 5672 R-Sq = 7.18% R-Sq(adj) = 0.00%

5.11.3 Results: POAG group

Figure 162 shows reading time as a function of font size (LogMAR) for the three font styles, for each subject in the POAG group.

Figure 162 – Reading speed as a function of font size (LogMAR) for the three different fonts for subjects in the POAG group





Again, font style appears to have remarkably little effect on reading speed amongst this group of subjects.

This was confirmed by a two way ANOVA using font size and style as factors. Whilst, font size was a significant factor, font style was not and there was no significant interaction between them.

Two-way ANOVA: Reading speed (ms) versus Font, Size

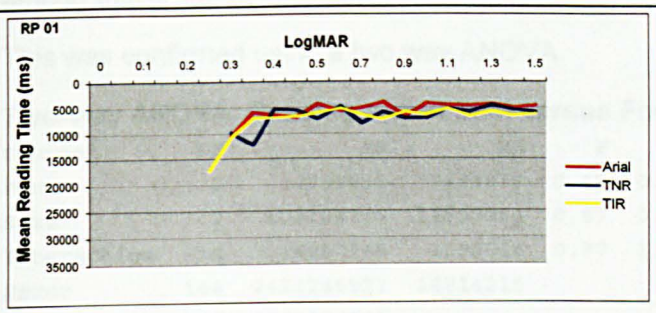
Source	DF	SS	MS	F	P
Font	2	2183863	1091932	0.20	0.818
Size	13	284838617	21910663	4.03	0.000
Interaction	26	46407573	1784907	0.33	0.999
Error	378	2057051256	5441935		
Total	419	2390481310			

S = 2333 R-Sq = 13.95% R-Sq(adj) = 4.61%

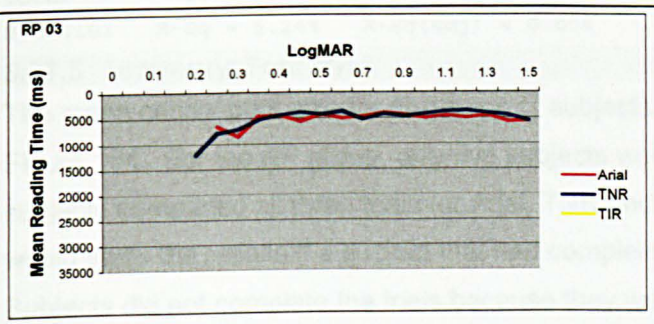
5.11.4 Results: RP group

Figure 163 shows reading time as a function of font size (LogMAR) for the three font styles, for each subject in the RP group.

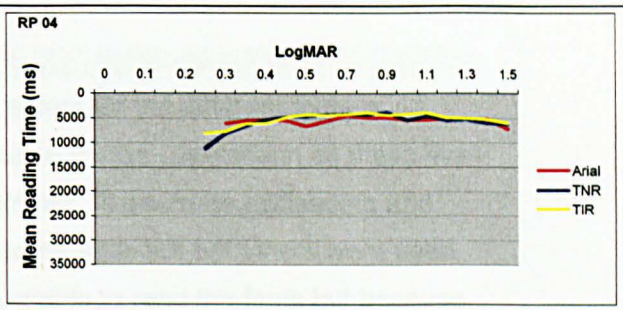
Figure 163 – Reading speed as a function of font size (LogMAR) for the three different fonts for subjects in the RP group

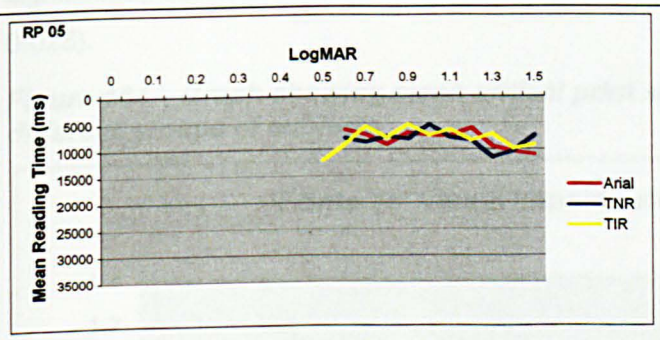


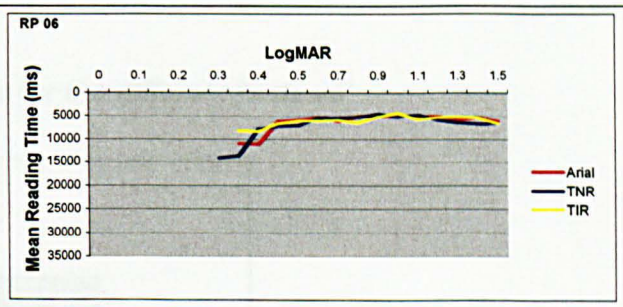
RP02 – No data for different fonts

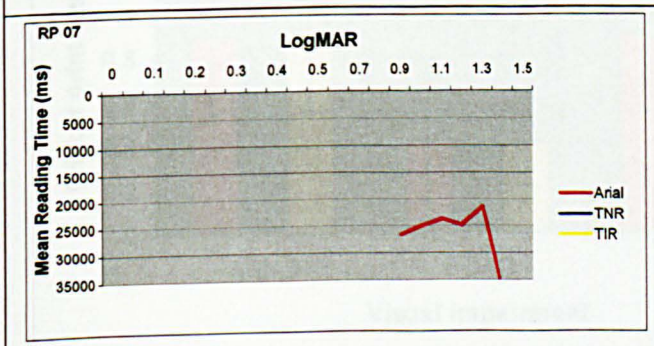


RP 03 – No data for Tiresias

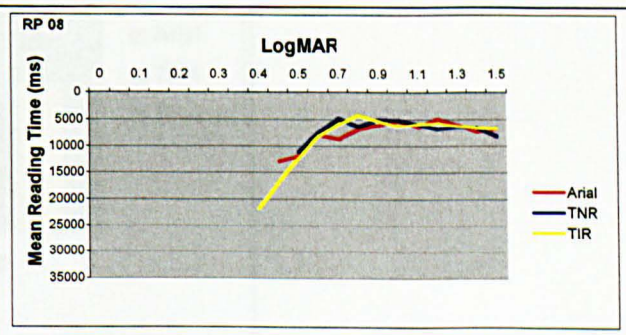








RP07 – No data for TNR or Tiresias



RP09 – No data for different fonts

RP10 – No data for different fonts

Once more, the choice of font style appears to have little or no effect on reading speed among this group of subjects.

This was confirmed using a two way ANOVA.

Two-way ANOVA: Reading speed (ms) versus Font, Size

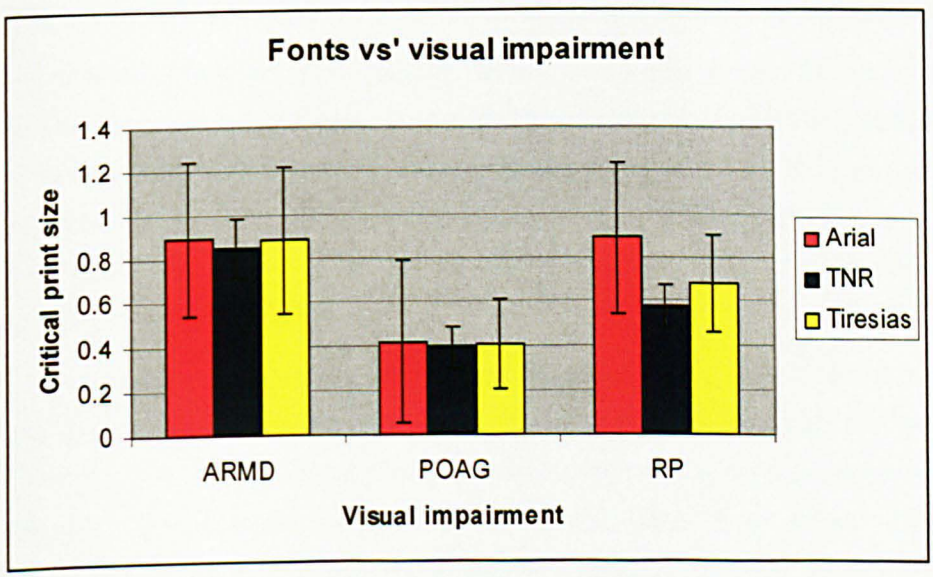
Source	DF	SS	MS	F	P
Font	2	14989635	7494818	0.45	0.641
Size	7	102199745	14599964	0.87	0.533
Interaction	14	16660248	1190018	0.07	1.000
Error	144	2421246927	16814215		
Total	167	2555096555			

S = 4101 R-Sq = 5.24% R-Sq(adj) = 0.00%

5.11.5 Summary: Font style

The mean critical print size for all groups of subjects is shown for the different fonts in Figure 164. For the RP group, only five subjects were used for the comparison as these five subjects completed all three trials for Arial, TNR and Tiresias. It would be misleading and would skew the results if a subject that had completed some trials but not others were used. Subjects did not complete the trials because they were unable to read the fonts but because they were tired from testing on the other experiments. Times New Roman was found to be significantly easier to read than Arial for subjects with retinitis pigmentosa (paired t-test; p = 0.025).

Figure 164 – Graph showing mean critical print size for the different fonts vs' different groups of subjects



5.11.6 Conclusions: Font style

Overall, font style appears to have surprisingly little effect on reading speed. A small but significant difference was found between TNR and Arial for the RP group. However, with such a small sample group, a degree of caution is required in the interpretation of this result.

5.12 Discussion

Anecdotal evidence and "clinical wisdom" suggests that the use of coloured filters can enhance visual function in individuals with various forms of visual impairment although previous research in this area is equivocal. The experiments described in this chapter were carried out as a pilot study to determine whether colour has a useful role to play in improving reading for those with visual impairment with a view to conducting a larger study if the results were positive.

The study looked at three separate populations with different visual impairments. The first group (ARMD) involves central visual field loss, POAG classically involves mid-peripheral field loss with central field loss in the later stages and RP tends to start mid-peripherally extending outwards and only affecting central vision in the very late stages.

5.12.1 Discussion: ARMD group

As ARMD involves central visual field loss, it would be expected that reading would be most affected with this patient group. This was supported by the finding that the worse the binocular VA and also the lower the contrast sensitivity, the slower the mean reading speed. As ARMD is a progressive disease which has huge variations between individuals, it was not surprising to find a weak correlation between "years since diagnosis" and reading speed.

Reversing the contrast on the display (white on black), caused a decrease in mean reading speed overall although this was not significant. However, three subjects read more than 10% faster with contrast reversal confirming the large variations between subjects.

There was no significant increase in reading speed with a coloured background and subjectively, subjects reported mixed views on whether a coloured background made text easier and more comfortable to read. Approximately one third of subjects reported a definite improvement; about one third felt it made no difference and approximately one third felt it made things worse. This would suggest that changing the background colour is not helpful for subjects with ARMD.

There was no significant increase in reading speed with coloured text on a black background although subjectively, subjects reported that this made text easier and more comfortable to read. Fifty per cent of subjects reported a definite improvement, 40% felt it made no difference and ten per cent (n = 1) felt it made things worse. This would suggest that changing the foreground colour may be helpful for subjects with ARMD.

There was no significant increase in reading speed with colour combinations although interestingly, fifty per cent of subjects chose white on dark green as their preferred colour combination. Possibly, this is because it was the combination with the highest contrast. Fifty per cent of subjects reported a definite improvement, 40% felt it made no difference

and ten per cent (n = 1) felt it made things worse. This would suggest that changing to mixed colours may have some benefit for subjects with ARMD.

The results for the ARMD group are inconclusive overall. This is probably due to the small sample size, the variation between subjects as they were all at differing stages of their disease. Also, no consideration was given to whether the subjects had 'wet' or the 'dry' form of the disease and how much of the macula was affected. Two eyes of the same patient may be affected differently and this study did not account for this.

5.12.2 Discussion: POAG group

As POAG affects the mid-peripheral visual field in the early stages, it would not be expected to have a major effect on reading speed. This was borne out by the data which showed no correlations between contrast sensitivity, VA, years of diagnosis and reading speed. The POAG group had almost normal acuities for distance and near and good contrast sensitivity.

Changing the screen colour and polarity had no significant effect on reading speed for this group. However, subjectively a number of participants reported that a coloured background improved "comfort" and "ease of reading". Six of the ten subjects reported that colour combinations improved reading and comfort although there was no obvious pattern to choice of colour.

It is not surprising that the POAG group was inconclusive. Of the three subject groups, POAG is the only disease with a relatively successful treatment regime which maintains good visual function.

5.12.3 Discussion: RP group

A number of studies have suggested that the visual performance of patients with RP can be enhanced by using coloured filters (Lindner et al., 1999; Van Den Berg, 1989). This group included subjects at a wide range of stages of progression of the disease and it is not surprising, therefore, that the results were quite variable within the group. Overall, changing screen colour and polarity had no significant effect on reading speed. However, some subjects within the group did perform much better when the screen was coloured. Subjectively, at least 75% of subjects reported improvements using colour both in terms of comfort and ease of reading. Interestingly, blues and greens seemed to be the most popular choice of colours although it is impossible to draw any meaningful conclusions from such a small sample.

For the RP subjects, the lower the recorded contrast sensitivity, the slower the reading speed. Similarly, the worse the VA, the slower the reading speed. Increasing number of years since diagnosis was also shown to be negatively correlated with reading speed.

The RP group had inconclusive results. Perhaps one of the reasons for this was the large disparity in the progression of the disease. In conjunction with this, no consideration was given to where the greatest field loss had occurred. For example, a patient with significant inferior field loss would find it more difficult to read than someone with a predominantly superior field loss. Also, with the tunnel vision effect, if the subject has a severely reduced field then only a small section of text can be viewed at any one time irrespective of colour.

5.13 Conclusions

The relatively small number of subjects in each sample group and the diversity of subjects within the groups limit the scope of any conclusions that may be drawn from these studies.

Overall, there was no evidence that changing screen colours and contrast polarity improves reading speed in patients with ARMD, POAG or RP. However, a number of subjects showed some improvement and many subjects reported that they could read more comfortably when the screen was coloured even when this did not translate into an improvement in reading speed. The colours chosen were idiosyncratic with no clear favourites emerging. It is also worth pointing out that it would be worth investigating whether subjects chose the same colour on another day to ascertain just how repeatable the results are.

Until evidence emerges from a larger study, the best advice that can be proffered from this data is that patients with these conditions should be encouraged to experiment with various screen parameters; specifically font size and style and foreground and background colour. Unfortunately, changing these settings is not absolutely straightforward on modern computers.

To facilitate this process, a computer program was developed as part of this project which will be made freely available via the internet.

6. Conclusions

6.1 Conclusions

This thesis has examined systematically the effects of different screen parameters on reading speed by looking at both subjective and objective evaluations. It has done this by looking at different groups of subjects which naturally divide into those whose vision is normal and those who have some form of visual impairment. In addition, it has focused on parameters which can be explored by users themselves.

6.2 Main findings

The first part of the thesis explored the effects of contrast and polarity on reading speed. It found that for young, normal subjects, reading speed is maintained for contrast levels down to approximately 30%. Beyond this, if larger fonts are used, reading speeds can be preserved with contrasts as low as 6%. Most display screens have contrast of over 90% (with black on white) so any variations between displays are unlikely to have much effect on reading speed. However, this is not to say that reading at low contrast levels would be 'comfortable' for a display screen user.

For normal subjects (<50 years and >=50 years), there was no difference in mean reading speed using reverse polarity.

The second part of this thesis looked at the effects of different fonts on reading speed. Subjects tended to rate sans serif fonts as more 'attractive' to look at and 'easier to read' than their serif counterparts. Objectively, sans serif fonts were read on average slightly quicker than serif fonts although this was not statistically significant. This is interesting for display screen users as it essentially means that choice of font does not affect reading speed although some fonts may be perceived as being 'more comfortable' to look at than others.

The effects of letter spacing and anti-aliasing were also examined. Again, these did not affect reading speed although 'no spacing' affected reading speed when the letters were large (i.e. 1.5 logMAR).

The third part of the thesis looked at the effects of screen colour on reading speed in normal display screen users. Subjectively, 97.5% of participants preferred a coloured background compared to a white background. There were no trends for choice of colour and, with the objective tasks, there was no significant improvement in performance. This may well reflect the tasks used. Interestingly though, the prevalence and frequency of asthenopic symptoms appeared to be reduced following the use of a coloured screen for a minimum of one week.

Whilst this may be a perceived effect rather than a quantifiable effect, it still bears significance on general well-being of display screen users.

The final part of this thesis examined the effects of colour on reading speed in a sample of individuals with various forms of visual impairment (i.e. ARMD, POAG and RP). The study showed that whilst there were some quite large individual improvements to be found using colour, the sample sizes were too small to draw any meaningful conclusions.

6.3 Future work

With so many people now using computers at work and at home, small improvements in user efficiency and comfort are worth exploring. By and large, the studies described in this thesis have demonstrated that the design and visual characteristics of modern displays are close to optimal in terms of efficiency. However, a high proportion of computer users still complain of eye problems associated with viewing a display. The causes of these problems are probably multifactorial. However, results described in this thesis do suggest that a significant proportion of computer users would be more comfortable using a display screen with a background colour other than white. Further work to develop the most efficient algorithms for establishing the optimum colour and to quantify the benefits is warranted.

The benefits of screen customization for those with various types of visual impairment could not be clearly established due to the small sample sizes and heterogeneous nature of the subjects used in this study. However, the versatility of modern display screens does open up exciting possibilities in this area and certainly warrants further investigation.

In the meantime, software has been developed to assist normal and visually-impaired computer users to readily change key display parameters. It is hoped that this will encourage users to at least experiment with display formats other than the default settings.

7. Publications arising from this thesis

7.1 Peer reviewed publications resulting from this thesis

D'Ath, P.J., Thomson, W.D. & Wilkins, A. 2007, "Memory for the Color of Non-Monochromatic Lights", *Color Research and Application*, Vol 32, No. 4, pp11-15.

D'Ath PJ, Wilkins A, Owens N & Thomson WD (2007), "The effects of screen colour on asthenopic symptoms and visual performance in a normal population of display screen users and a sample of individuals with visual stress".

To be submitted in the near future to Ophthalmic and Physiological Optics for publication.

D'Ath PJ, Myint JH, Johnston EK, Thomson WD (2008), "The effects of screen colour on reading speed in subjects with visual impairment".

In preparation

Memory for the Color of Non-Monochromatic Lights

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Abstract: The aim of this work was to explore the limits of memory for the hue of coloured illumination using nonspectral colours. Eighty-four undergraduate optometry students with normal colour vision as assessed by the Ishihara 38 plate test, were given 10 s to memorize the hue of a luminous surface (luminance 120 cd m^{-2}), subtending 22 by 18 degrees in an otherwise unlit room. The sample hue was one of 12 samples with chromaticity spaced evenly every 30 degrees around a hue circle in the CIE UCS diagram. The circle, radius 0.06, was centered at the chromaticity of D65 (u' = 0.198, v' = 0.468). The hue was displaced randomly by between 40 and 100 degrees, and the participants were required to use one of two keys to return the hue to its original appearance. The keys changed CIE 1976 hue angle (h_{uv}) by 1 degree, one in a clockwise and the other in a counterclockwise direction, but left the CIE 1976 saturation (s_{uv}) and the luminance unchanged. Each participant saw the to-be-memorized hue once only and made subsequent adjustments without seeing it again. Four adjustments were made immediately, four after 1 h, and a further four after 1 week. The second and the fourth in each set of four were preceded by a clockwise displacement of hue angle and the remaining two by an anticlockwise displacement. The CIE 1976 UCS chromaticity of the standard and the chromaticity of the very first adjustment performed immediately after the presentation of the standard were separated by 0.0210 (s.d. 0.0178) averaged across hues. One hue (purple) was more readily nameable than the others and was more accurately reproduced. There was no evidence of stable individual differences in observers' memory: observers' accuracy in reproducing one colour was not significantly correlated with their accuracy in reproducing another. Adjustments made after an interval of 1 h were worse than those undertaken immediately, but no better than those performed after 1 week. The variability of hue memory under these conditions was similar to the variability of coloured surfaces under common sources of illumination.
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Key words: colour memory; nonspectral colours; individual differences

INTRODUCTION

Memory for colours is usually considered in relation to surface colours—colours of meaningless patches[1] or real objects.[2,3] Memory is influenced by how readily a colour can be named, and how useful the name is in discriminating the colour from others in the experiment.[4] Colour memory is rarely measured under conditions in which the eyes have a chance to adapt to the colour, as when coloured light is used as a light source. Seliger,[5] however, has obtained measurements of the ability of observers to remember and reproduce monochromatic light. He presented light from a monochromator for 0.2–3 s, then changed the wavelength by at least 30–40 nm and required observers to turn a knob to reproduce the colour immediately. He measured the error in terms of the standard deviation in nanometers. The standard deviation varied with wavelength but was generally about twice the threshold at which one wavelength can be discriminated from another. When replotted in terms of the CIE UCS space, the standard deviation of the difference in chromaticities that can reliably be discriminated averages 0.0368 (s.d. = 0.0224). The difference in chromaticity of a surface of uniform spectral reflectance under incandescent light (CIE Standard illuminant A) and under fluorescent light (CIE Type F2) is 0.0434 and between a fluorescent (F2) source and daylight (CIE Standard illuminant D65) is

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0.0385. The largest such difference is between daylight and incandescent light (0.087). All these differences lie within 2 standard deviations of the difference in chromaticities that can reliably be discriminated. It would make sense in evolutionary terms if memory for the colour of illumination has a precision commensurate to the variability with which changes in illuminant chromaticity are normally encountered. It seems plausible to expect the visual system to be insensitive to differences in illuminant colour that are of little survival value, including differences that are typically "discounted" in order to maintain "colour constancy." Seliger's measurements were undertaken using monochromatic light, and were therefore of maximum saturation and limited to spectral colours. The present study extended the measurements to nonspectral colours of low saturation in order to see whether memory for these colours was equally poor.

The study was motivated not only by a desire to determine the precision with which nonspectral colours can be remembered, but also in part by the effects of colour on reading speed. It has been shown that at least 5% of the general school population read printed text more quickly with an optimal background colour that is not white.[6] Certain individuals habitually wear coloured glasses to improve reading speed and reduce visual stress.[7] In these individuals, reading speed has been shown to increase when the text is illuminated with coloured light. The reading speed decreases consistently with departures from optimal colour, whether in respect of hue or saturation, and does so in a way similar from one individual to another. In general, there is little benefit of the colour on reading speed,[7] once the UCS chromaticity differs from optimum by a chromaticity difference of 0.076. The question therefore arises as to the extent to which accuracy in the representation of the colour of lighting within the visual system is playing a role in the measurement of the effects of coloured light on reading speed, and the extent to which this is revealed by measurements of memory for the colour of light.

METHOD

Apparatus

A liquid crystal display (Flatron 4710B flatscreen) measuring 340 mm horizontally by 270 mm vertically was controlled by a program on a personal computer that used a look-up table based on interpolation between 42 points calibrated with a Minolta Chroma Meter II. It was possible to display any chromaticity on the perimeter of a circle in the CIE 1976 UCS diagram. The circle had a center with chromaticity $u' = 0.198$, $v' = 0.468$ (that of CIE standard illuminant D65), and a radius of 0.06. In other words the display was of constant luminance and could vary in CIE 1976 hue angle (h_{uv}) without an associated change in the CIE 1976 saturation (s_{uv}). The luminance at the center of the screen was 120 cd m^{-2}, and it decreased toward the perimeter by no more than 20%. The computer program allowed the hue angle to be varied in a clockwise or anticlockwise direction at the touch of one of two keys. A single depression of a key changed the hue angle by 1 degree.

TABLE I. Chromaticities of the standard (to-be-remembered) colours used in experiment 1.

hue (deg)	u'	v'
0	0.258	0.468
30	0.250	0.498
60	0.228	0.520
90	0.198	0.528
120	0.168	0.520
150	0.146	0.498
180	0.138	0.468
210	0.146	0.438
240	0.168	0.416
270	0.198	0.408
300	0.228	0.416
330	0.250	0.438

Participants

Thiry-one male and 65 female undergraduate optometry students and staff at City University aged 18–44 years (mean 21) took part. All participants had normal colour vision, as assessed by the Ishihara 38-plate test.[8] A subset of 60 participants undertook the experiment more than once, the trials separated by at least 1 week. The data for the second trial were considered separately.

Procedure

Each individual was seated at a distance of 0.84 m from the screen in an otherwise darkened room, at which distance the screen subtended 22 by 18 degrees. They adapted to the darkened room for 5 min. They were then given 10 s to observe and memorize the hue of the screen and were told they would be required to retain the colour in memory for 1 week. The screen displayed one of 12 hues selected at random as the to-be-remembered colour. The 12 hues were spaced 30 degrees apart on a hue circle in the CIE UCS diagram, as described above. The chromaticities are listed in Table I.

Immediately following the 10 s observation period the hue angle was displaced by between 40 and 100 degrees hue angle in a anticlockwise direction. The displacement was random, sampled with equal probability between 40 and 100 degrees. The change in colour was instantaneous. The participant was required to use the two keys until he or she was confident that the screen was once again displaying the original colour, whereupon he or she pressed the space bar. The computer then changed the colour, again by between 40 and 100 degrees but in the opposite direction to that previously used. Four such trials were completed. For trials 1 and 3 the displacement of colour was anticlockwise on the hue circle and for trials 2 and 4 it was clockwise. After an interval of an hour, a further four such trials were undertaken, and these were repeated again after an interval of 1 week. The standard (to-be-memorized) colour was pre-

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sented once only at the outset of the trials. Participants saw only one colour per trial lasting 1 week.

An additional six participants from City University, all female, aged 21–35 years (mean 27), were asked to observe the screen while they used the cursor keys to adjust the colour of the screen so that it displayed the best example of each of the following colours: red, orange, green, blue, yellow, purple, and pink. The colours were requested in the above order, and the participants made four adjustments for each colour in turn. Each of the 12 standard colours listed in Table I were then presented in clockwise order beginning with a hue angle of zero, then 330 degrees etc., and the participant was required to name the colour, and to rate the acceptability of the name they had provided using a 7-point Likert scale (1 = very poor; 7 = very good).

RESULTS

Overall Accuracy of Naïve Observers

The mean errors (in degrees visual angle) with respect to sign for the first four settings were respectively +16.1, +2.3, +13.9, and +0.6. The initial setting was an "undershoot," in other words, observers failed to fully restore the hue to its original value. Subsequent settings erred in the same direction, despite the fact that settings 2 and 4 were from a displacement that was in the opposite direction. This suggests that the first setting may have biased the remaining settings. The first setting that participants made—that immediately after the demonstration of the to-be-remembered hue—was not affected by previous settings. The following analysis was therefore conducted on this first setting. The data were obtained from 96 participants, a minimum of 7 per hue and a maximum of 9. The mean separation of the UCS chromaticities between the standard and the adjustment was 0.0210 (s.d. 0.0178) across participants and across hues. On the basis of the work of MacAdam and others,[9] this corresponds to a difference of about 50 times the colour difference that can just be discerned (i.e. about 50 jnds), although such interpretation must be qualified in view of the residual nonuniformity of the CIE 1976 UCS diagram.

Overall Accuracy of the Group

Given that the settings of some participants erred in one hue direction and others in the opposite direction, the average hue difference with respect to sign between the standard and the very first setting gives an indication of how close the group as a whole came to replicating the standard immediately after it was shown. The mean was 16.8 degrees (s.d. 21.5), corresponding to a separation in UCS chromaticity of 0.0165 (s.d. 0.0211) between the standard and the group average. The colour difference was in a clockwise direction from the standard, i.e., in a direction similar to that of the change in hue, suggesting that observers tended to underestimate the adjustment required.

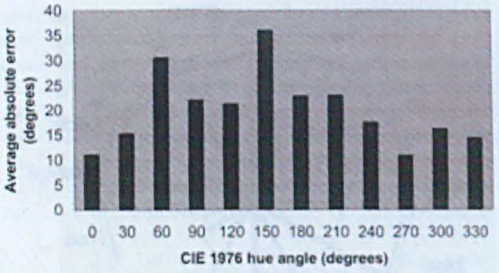


FIG. 1. Average error in degrees as a function of the sample hue.

Differences as a Function of Hue

Since the direction of the error may have been influenced by the direction of the change of the hue, the data set was enlarged to include all the four settings that immediately followed the initial presentation of the sample. The absolute value of the error was calculated for each of the four settings per hue and averaged for each participant. The direction of the change of hue was balanced across settings, and the average across settings better reflected the effect of the sample hue as opposed to the effect of both the sample hue and the change of hue. The mean errors are shown in Fig. 1. One-way analysis of variance revealed a significant difference between hues ($F_{(11,84)} = 2.46$, $P = 0.01$). Post hoc comparisons using the method of Bonferroni revealed significant differences between 150 and 0 and 150 and 270 degrees.

A subsidiary study was undertaken in order to check whether the error scores were related to the ability to name the shade of colour shown in the to-be-remembered sample. Six observers were asked to name each of the 12 colours shown and to rate the acceptability of the name they gave. The data in Fig. 1 have been replotted in polar coordinates in Fig. 2 and are shown by the continuous curve. The length of the bold radial lines in Fig. 2 is proportional to the number of participants (0–6) reporting their chosen name as acceptable. The longer the line the easier the shade of colour was to capture in a colour name.

As can be seen, the hue angle of 150 was difficult to name and difficult to remember. The hue angle of 270 was easy to name and easy to remember. However the hue angle of 0 was easy to remember but difficult to name, presumably because two alternatives (red and orange) were equally valid.

The six participants were asked to adjust the hue to create the best shade of red, orange, green, blue, yellow, purple, and pink. Around the perimeter of the figure are the ranges of hue angles (mean − 1 s.d. to mean + 1 s.d.) of the settings. The setting for purple averaged 268 degrees and had the lowest standard deviation of the settings (6.7). This is consistent with the hue of 270 degrees being easy to name and remember. The setting for green was 73 degrees (s.d. 21) and for blue 208 degrees (s.d. 24) which might explain

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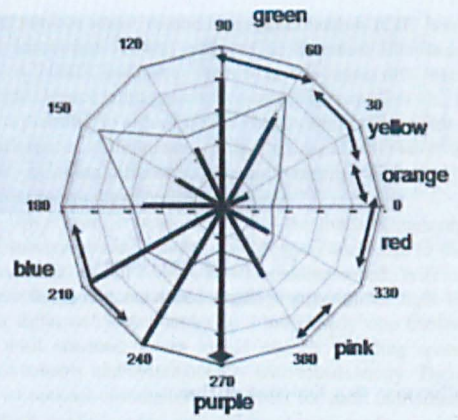


FIG. 2. The continuous curve shows the accuracy of reproduction of the sample from memory as a function of hue angle. The radius of the plot corresponds to 40 degrees hue angle. The lengths of the radial bold lines are proportional to the number of participants naming the hue with satisfaction. The length of the lines on the perimeter correspond to the range of settings (mean ± 1 s.d.) of hue angle when participants were asked to set the hue to the colour shown by the colour name beside the line.

why 150 degrees (blue/green) is difficult to name and remember. The border between the settings for nominal "red" and "orange" lies close to 0 degrees, which might explain why this hue is difficult to name, but there remains the question as to why it is easy to remember.

Consistency Within Observers

Sixty individuals were examined twice, more than one week apart, on each occasion with different hues, the hues usually spaced 60 degrees apart. Figure 3 shows the errors obtained by each individual on the two sessions. There is no significant correlation between the error on the two sessions ($r = 0.03$), and therefore nothing to suggest that some individuals were consistently more accurate than others.

Stability Over Time

The sample was presented once at the outset, and the observer attempted to replicate its colour four times at each of three occasions: immediately following the presentation, again after 1 h, and again after a week had elapsed. The mean of the absolute values of the errors on the four settings are shown as a function of time in Fig. 4. The difference between immediate memory and that at 1 h was highly significant ($t_{(113)} = 5.7$, $P = 0.000$); the difference between 1 h and 1 week was not ($t < 1$).

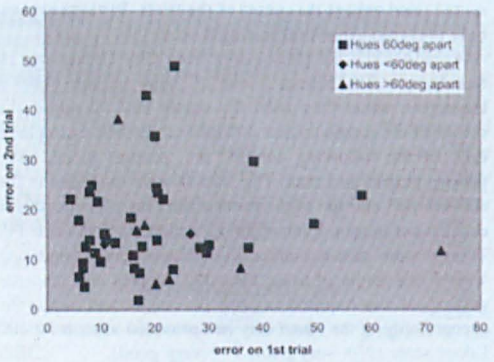


FIG. 3. Mean absolute error in degrees hue angle on one trial plotted against the error on a second trial with different hue angle. The difference in hue angle between the two trials is shown in the legend. The data show a negligible and nonsignificant correlation ($r = 0.03$).

DISCUSSION

Participants were given the opportunity of immediately reproducing a colour they had just seen but their ability to do so was more than 50 times worse than their ability to match colours that are simultaneously visible, according to the data of MacAdam.[10] Phillips[11] has shown that immediate memory for an arbitrary spatial configuration (of a random checkerboard, for example) is greatly impaired by the interpolation of a similar, but different, configuration, known as a mask. In the present work, the presence of a sample colour different from that observers were required to remember presumably provided interference with sensory memory similar to that provided by a mask. The method of adjustment that was used here, though rapid, carried the disadvantage that the mask was variable.

The standard deviation of the chromaticity difference was 0.0178, and therefore similar to the figure of 0.0368 obtained by Seliger.[5] It is of interest that in both the present study and that of Seliger, the standard deviation of the difference in colour that can be discerned from memory (given an interpolated mask) is similar to the difference in the chromaticity of a white surface under different common sources of illumination. The difference in chromaticity of a

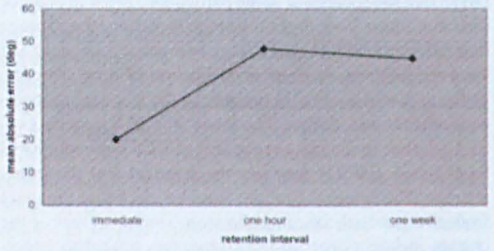


FIG. 4. Average error in degrees as a function of time.

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white surface under incandescent illumination (CIE Standard Illuminant A) and under (CIE Standard Illuminant D65) is 0.0807, and this is likely to be the largest difference in light source chromaticity customarily experienced. It seems plausible to argue that the visual system is insensitive to differences in illuminant colour that are of little survival value, including differences that are typically "discounted" in order to maintain "colour constancy."

In this respect, it is of interest that the limits of memory performance obtained in the current study are close to the limits within which colours benefit reading speed. Wilkins *et al.*[7] repeatedly measured reading speed under light of many different chromaticities in 5 individuals who habitually used coloured lenses to aid reading. Reading speed varied reliably and systematically with chromaticity. There was an optimal chromaticity, different for each individual, at which reading speed was maximal, and reading speed decreased with departures from this optimum, whether in hue or saturation. A chromaticity difference of 0.076 was sufficient to remove most of the gain in reading speed that resulted at the optimal chromaticity. It seems unlikely that the effects of colour on reading speed were cognitively mediated and resulted because participants had a "favorite" colour that they remembered. Even if participants were to have remembered the colour sufficiently well (which is most unlikely, given the retention intervals involved), they would also have had to have remembered the speed with which they read with that colour. It seems more likely that the similarity between the limits on memory for colour and the limits of the improvements in reading speed that colour can confer both reflect the insensitivity of the visual system to differences in illuminant chromaticity under conditions of colour adaptation.

Seliger[5] showed that the wavelength dependence of delayed matching of spectral colours exhibited the least variation at the same wavelengths as those reported for maximal colour discrimination measured by bipartite wavelength matching, that is, at the wavelengths of the intersections of cone spectral sensitivities. In the present study, the UCS space was used, and the differences in discriminability of stimulus colours have therefore been approximately equated. Nonspectral (unsaturated) colours were used, and this would have further reduced any differences due to cone spectral sensitivities. Unsurprisingly, the present data show no hue angle differences that are traceable to the intersection of cone spectral sensitivities.

ACKNOWLEDGMENT

This work was supported by the PACCIT program of the ESRC.

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7.3 The effects of screen colour on asthenopic symptoms and visual performance in a normal population of display screen users and a sample of individuals with visual stress

To be submitted shortly

The effects of screen colour on asthenopic symptoms and visual performance in a normal population of display screen users and a sample of individuals with visual stress.

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Key words: Colour, computer, Asthenopia, visual stress, Meares-Irlen Syndrome

ABSTRACT

***Aims* - To explore the effects of screen colour on asthenopic symptoms and visual performance in a normal population of display screen users and a sample of individuals with visual stress.**

Methods – 40 office-based computer users were recruited for the first study and 32 participants with a previous diagnosis of Meares-Irlen Syndrome were recruited for the second study. The same methods was used for both studies. Participants were asked to complete a symptom questionnaire before completing a pre-determined algorithm for selecting screen background colour. Participants then had to complete a series of visual performance tasks with their optimum colour and also against a white background. The order of testing (white and coloured background) was balanced to minimise possible order effects. After baseline readings were obtained, the background colour of each participant's computer screen was then changed to the colour determined in the test using software developed for the study for a minimum of 5 days. Participants were then reassessed between 5 and 15 days later.

Results – **Study 1:** 92.5% of participants reported one or more symptoms associated with using their computer at baseline. 69.2% reported that changing the background screen colour made their eyes feel more comfortable. 38.5% of participants experienced symptoms of asthenopia 'often' or 'most of the time' at baseline and this reduced to 25.6% by customising the background colour. One month after the follow up appointment, 46.2% of participants were still using their chosen screen colour.

Study 2:

The mean time for participants to complete the Rate of Reading test against a white background was 222 s (s.d. = 89s) and against the optimum coloured background, 208 s (s.d. = 91s) ($t(31) = 2.36$, $p = 0.025$). There were no significant differences with colour for the other visual performance tasks. All participants (N = 32, 100%) reported positive benefits from using their optimum screen colour compared to baseline.

INTRODUCTION

Developments in display technology combined with improvements in the design of computer interfaces have greatly improved the legibility of computer displays over recent years. Despite this, complaints of eye problems associated with viewing computer displays are still surprisingly common (Ustinaviciene and Januskevicius

(2006). Symptoms frequently include eye-strain, tired eyes, redness, soreness, dry eyes, transient blurring and headaches. In some cases, these symptoms relate to uncorrected refractive errors or binocular vision problems. In other cases, environmental factors such as the organization of the workstation, poor lighting or inappropriate work practices are responsible. However, for some individuals these symptoms appear to persist even when these issues are addressed, suggesting that the nature of the display itself may play a part.

There is now good evidence that a significant proportion of the population read printed documents faster when the background colour is other than white. Wilkins *et al.*, (2001) reported that 5% of their sample of school children read more quickly when using a coloured overlay in front of the text. Evans and Joseph (2002) found a similar result amongst adults, with 38% of their sample reading more than 5% faster with a coloured overlay. The chromaticity at which reading speed is maximal differs from one individual to another (Wilkins et al., 2004) and can be quite specific. The effects of colour can in certain individuals be surprisingly large - sometimes individuals read more than three times as fast when the background is coloured (Wilkins *et al.*, 2001; 1994).

The effects of colour seem to be particularly marked for individuals who experience "visual stress" when reading. The term "visual stress" is used to describe a condition in which individuals experience a range of visuo-perceptual distortions when viewing certain patterns including text. Symptoms may include the perception of movement, flicker, "glare" or general discomfort when reading. Such symptoms tend to reduce Word Search Speed and speed and may impact on educational development and progress (Cole, 1997). The condition is also known as Meares-Irlen Syndrome (MIS). Individuals are often unaware that they are suffering from this condition, assuming that their perception of printed text is entirely normal (Irlen, 1983).

In some cases, these symptoms can be alleviated or eliminated by the use of colour. For reading printed text, this is usually achieved by using coloured overlays or tinted spectacle lenses.

One aspect of the design of the computer user interface that has received surprisingly little attention is colour. Studies which have investigated the use of colour on displays have tended to explore the possibility that one colour combination (text and background) may be optimum for all users rather than testing the hypothesis that the optimum colours may be idiosyncratic and vary between individuals (Lightstone et al, 1999). Despite the huge gamut of colours available to users of modern computers, few adopt screen colours other than the

default black on white. This may be due to the complexity of achieving this or simply because of the familiarity of the black on white format.

As colour seems to be of benefit to a proportion of the normal population when reading printed text, it is of interest to know if a similar benefit can be demonstrated by customising computer display colours. It is also of interest to know if individuals with visual stress who already use coloured overlays obtain a similar benefit by changing the background colour of a computer display.

AIMS AND HYPOTHESES

The aims of this study were to investigate the effects of customising the background colour of computer displays on the symptomatology and task efficiency of a sample of normal computer users and a sample of individuals who suffer from symptoms of visual stress.

METHODS

All tests were carried out using a Samsung P10 laptop computer. The screen dimensions were 0.285m horizontally and 0.215m vertically. The chromaticity of white was u' = 0.199, v' = 0.473 and the space-averaged screen luminance was 212 $cd.m^{-2}$. Software was written specifically for the study using Visual Basic 6.

Determining optimum screen colour

The first stage of the test involved determining the optimum screen colour for each participant. To achieve this, two passages of black text (consisting of randomly ordered common words), were displayed on either side of the vertical midline of the screen. In the first phase of the algorithm, the background of one half of the screen was coloured whilst the other half remained white. The participants were required to look at the text on either side of the screen and report if the words were easier/ more comfortable to read with the coloured or white background. Sixteen different colours were presented; the colour appearing on the left or right hand half of the screen at random.

The 16 colours were all of a similar luminance (50 – 78 $cd.m^{-2}$; mean 60 $cd.m^{-2}$) and were distributed in a circle within CIE 1976 Uniform Colour Space centred on the screen white (u' = 0.199, v' = 0.473). The hue angles were, therefore, separated by 22.5 degrees (CIE h_{uv}) and the saturation (CIE s_{uv}) was maintained approximately constant. Chromaticities and luminance were calibrated using a Minolta Chroma Meter II.

If at this stage, the participant preferred white to all of the sixteen colours, the program terminated and the participant was not included in the trial.

However, if the participant preferred one of more of the colours to the white, the algorithm went into a second phase. In this phase, two of the 16 colours were presented

simultaneously on either half of the screen and the participant was "forced" to declare their preference. In order to avoid large colour differences and possible adaptation effects, colours were paired so that colours next to each other in the hue circle were compared. Colours that were chosen in the first round were then compared and the process repeated until four colours remained. At this stage, a single passage of text was displayed in the centre of the screen and the entire screen background was coloured. Colours were then presented successively in pairs with each colour being presented for 3s. This process was repeated until an overall 'winner' emerged.

The entire screen was then presented with the preferred colour in the background and the subject was given the opportunity to vary the saturation and luminance of the chosen colour to optimise the appearance. The RGB values and the corresponding chromaticity were then recorded.

Task performance tests

Three task performance tests were developed for the study. These were designed to simulate tasks commonly carried out by computer users and thereby quantify any change in performance resulting from the optimisation of screen colour.

The Rate of Reading test

This was based on the Rate of Reading test developed by Wilkins (1996). The conventional test consists of a paragraph of printed text comprising ten lines. Each line has the same fifteen commonly-used monosyllabic words in random order. The participant is required to read the words out loud as quickly and accurately as possible whilst the examiner records the number of errors. The time required to complete the paragraph or the number of words read within one minute is used to calculate the rate of reading in words/minute. This test has been shown to be sensitive to changes in reading performance brought about by the use of colour (Wilkins, 2002).

In the computer adaptation, the examiner clicked a button to keep a tally of errors and another button to record completion of the task. The rate of reading was calculated automatically.

Nonsense Sentences Test

This task was based on a test developed by Baddeley et al. (1992), and was designed to asses reading, comprehension and visuo-motor skills. A list of 20 simple sentences (e.g. dogs have six legs) were presented on the screen. The participant was required to read the sentences silently and classify them as 'true' or 'false' by clicking on the corresponding button at the end of each sentence. There were four versions of this test so no subject read

the same sentences more than once. The accuracy of the responses and the time taken to complete the task was recorded.

Spreadsheet test

A 10x10 array of single digit random numbers was displayed on the screen. The participant was required to count the number of occurrences of a given digit in the array. The accuracy of the count and the time taken were recorded. The mean of 5 trials was calculated.

STUDY 1

Forty office-based computer users (15 males and 25 females) were recruited for the study.

Before commencing the study, each participant was asked a series of questions relating to symptoms which they associated with using their computer. Participants were asked: "over the **last month**, have you suffered from any of the following when using your **computer**?" The list of asthenopic symptoms included: sore eyes, itchy eyes, gritty eyes, burning eyes, dry eyes, tired eyes, eye strain, double vision and headaches. Participants were required to tick: "Never, rarely, sometimes, often or most of the time" to each symptom.

The tests were conducted in each participant's office and care was taken to minimise influences from the ambient environment such as glare, screen reflections or other distractions. Participants viewed the laptop screen from approximately 40cm and wore their normal spectacles/ contact lenses if required.

The preferred screen colour for each subject was determined using the procedure described above. Participants who showed a preference for at least one colour undertook the task performance test described above with the screen background colour to white and their preferred colour. The order of testing (white and coloured background) was balanced to minimise possible order effects.

The background colour of each participant's computer screen was then changed to the colour determined in the test using software developed for the study. Participants were then reassessed between 5 and 15 days later. At the follow-up assessment, participants were asked to complete the symptom questionnaire used previously and the task performance tests were repeated.

RESULTS STUDY 1

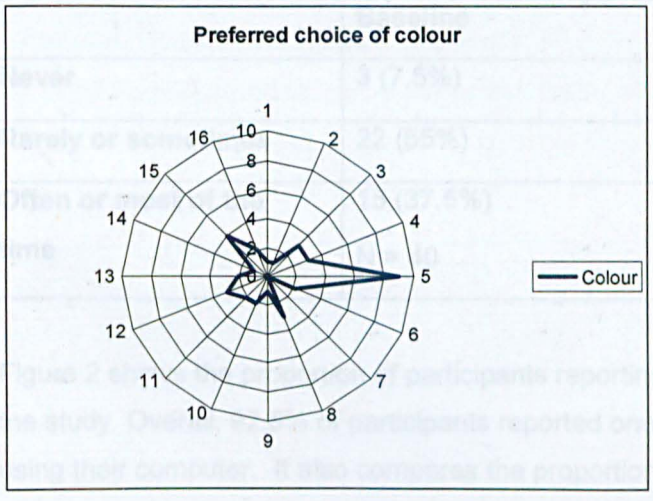
Of the 40 participants tested, one preferred a white screen to a coloured screen and was therefore excluded from the rest of the study.

Figure 1 – Table showing the u'v' co-ordinates of the colours chosen by each of the participants

Colour	R	G	B	N
1	246	171	196	1
2	248	183	172	1
3	255	208	165	3
4	222	212	130	3
5	219	229	145	9
6	192	227	147	2
7	171	239	182	0
8	142	228	196	3
9	110	219	206	1
10	137	215	241	2
11	168	200	255	2
12	190	179	247	3
13	209	162	255	2
14	228	149	248	1
15	255	149	249	4
16	237	149	207	1

Figure 1 shows the u'v' co-ordinates of the colours chosen by each of the participants. As can be seen from Figure 1, colours 5 (green) and 15 (pink) were chosen more frequently than any of the other colours.

Figure 1 – Graphical representation of preferred choice of colour



Symptoms

Figure 2 – Graphical representation of all asthenopic symptoms at baseline compared with follow up

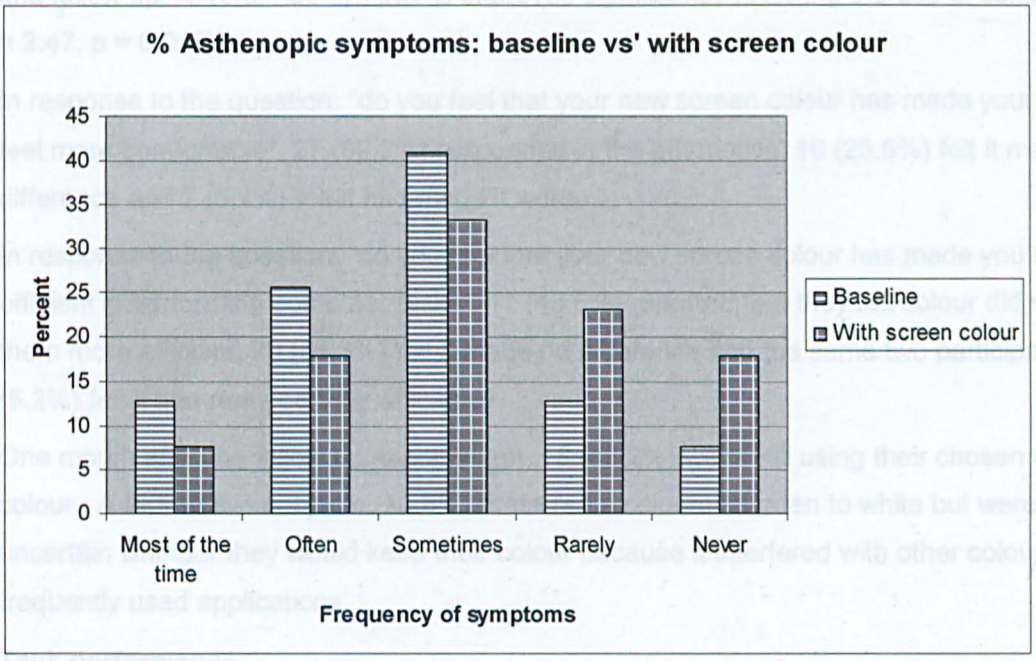


Table 1 – Results for all symptoms of asthenopia

Asthenopia – All symptoms		
	Baseline	**Follow up**
Never	3 (7.5%)	7 (17.9%)
Rarely or sometimes	22 (55%)	22 (56.4%)
Often or most of the time	15 (37.5%) N = 40	10 (25.6%) N = 39

Figure 2 shows the proportion of participants reporting various symptoms at the outset of the study. Overall, 92.5% of participants reported one or more symptoms associated with using their computer. It also compares the proportion of participants who experienced symptoms with their normal white background and after using their optimum screen colour for a minimum of one week. Only three (7.7%) participants 'never' experienced any symptoms of asthenopia with the white background whereas seven (17.9%) were asymptomatic with the coloured background. Fifteen (38.5%) participants experienced

symptoms of asthenopia 'often' or 'most of the time' at baseline and this reduced to 10 (25.6%) by customising the background colour. Symptoms of asthenopia were scored between 0 ('never') 4 ('most of the time') and the results were compared between baseline and follow up. Overall, Ss symptoms improved significantly following the use of colour ($t(38) = 2.47$, $p = 0.018$).

In response to the question: "do you feel that your new screen colour has made your eyes feel more comfortable", 27 (69.2%) responded in the affirmative, 10 (25.6%) felt it made no difference and 2 (5.2%) felt it had made it worse.

In response to the question: "do you feel that your new screen colour has made you more efficient in performing computer tasks", 17 (43.6%) reported that they felt colour did make them more efficient, 20 (51.3%) felt it made no difference and the same two participants (5.2%) felt it had reduced their efficiency.

One month after the follow up appointment, 18 (46.2%) were still using their chosen screen colour. A further five subjects (12.8%) preferred a coloured screen to white but were uncertain whether they would keep their colour because it interfered with other colours in frequently used applications.

Task performance

Table 2 summarises the results for the task performance tests. There were no significant differences in any of the task performances with and without a preferred colour. With the Rate of Reading test, 21 (53.8%) participants read faster with a coloured screen whilst 18 (46.2%) read slower. For the Spreadsheet Analysis, 19 (48.7%) participants read faster with a coloured screen whilst 20 (51.3%) read slower. With the Nonsense sentences, 27 participants performed slower, 9 performed faster and 3 remained the same.

Table 2 – Mean time, s.d. and range in seconds for each of the performance tasks at baseline and at follow up.

Rate of Reading	White	Coloured
Baseline: mean time (s.d.; range)	108.8 (18.1; 74 - 171)	106.8 (19.4; 65 - 171)
Follow up: mean time (s.d.; range)	107.1 (16.8) (16.8; 69 – 159)	107.5 (16.6; 66 - 162)
Spreadsheet Analysis		
Baseline: mean of 5 trials (s.d.; range)	19.4 (4.5; 10.8 – 27.8)	19.2 (4.6; 10.4 – 27.6)
Follow up: mean of 5 trials (s.d.; range)	18.8 (4.1; 12.0 – 28.8)	19.3 (4.1; 11.8 – 28.0)
Nonsense sentences		
Baseline: mean time (s.d.; range)	36.7 (10.4; 23 - 66)	40.4 (13.9; 24 - 90)
Follow up: mean time (s.d.; range)	38.0 (10.1; 25 - 69)	40.4 (10.9; 27 - 69)

STUDY 2 : METHODS

32 participants (16 males and 16 females) were recruited from the orthoptics department at Brighton Hospital, Sussex (mean age = 15 yrs; range = 7 to 40 years). All participants had been previously diagnosed with visual stress and regularly used coloured overlays of coloured spectacles. Prior to entry into the study, all volunteers underwent a full orthoptic assessment which included visual acuity assessment, prism cover test, ocular motility, convergence, prism fusion range and stereopsis. Any participants with significant binocular vision anomalies were excluded from the study. In keeping with the Declaration of Helsinki (2000), ethical approval was obtained from both the City University Research and Ethical Committee and the Local Research Ethics Committee (LREC) for Brighton, Mid Sussex and East Sussex.

The same questionnaire as used in Study 1 was used for this sample although an extra set of questions were included. Ss were asked: "Over the **last month** have you suffered from any of the following when using your **computer**?" Ss had to rate "Do the words appear to move, wobble or flicker?", "Do the words go in and out of focus?", "Do the words look too close together?", "Does the page look too bright or dazzling?" and "Does it hurt your eyes

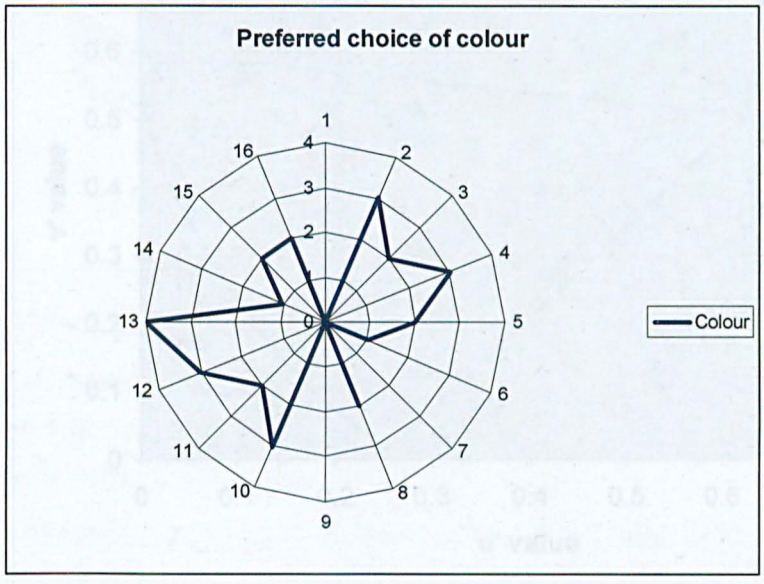
when you look at the page?" on a scale of "never, rarely, sometimes, often, most of the time".

All participants were tested using the same tests and protocol described for Study 1.

RESULTS

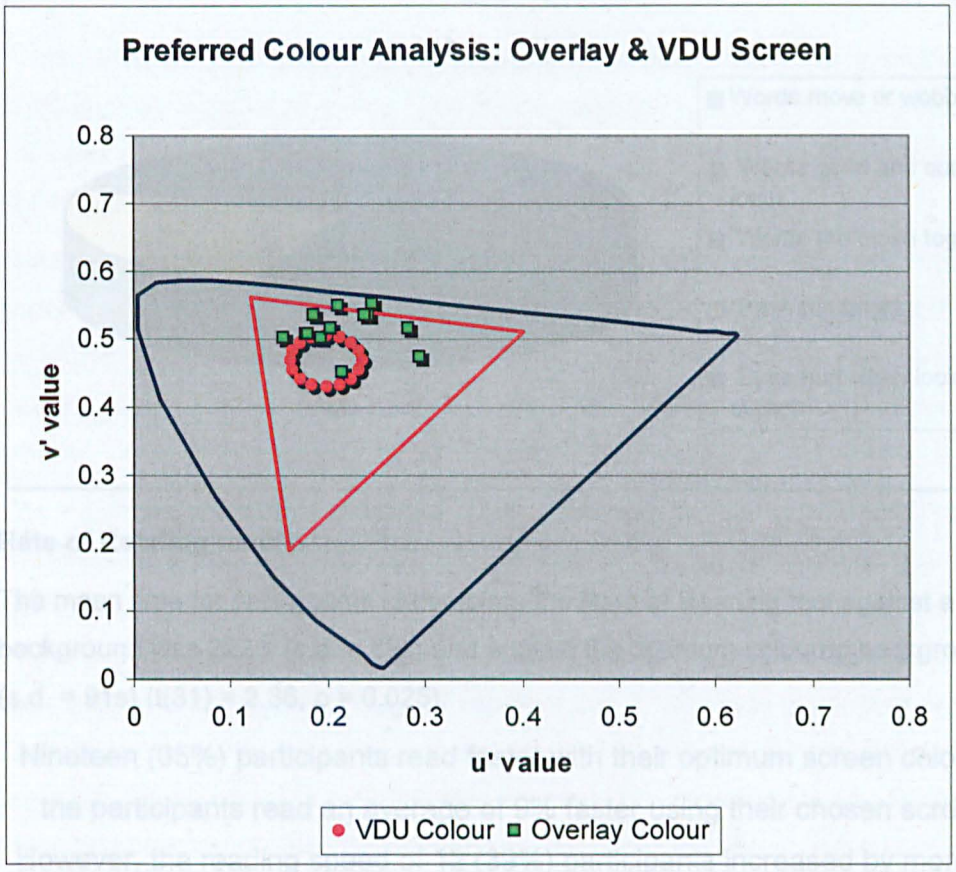
All Ss (100%) chose a coloured background compared to a white background. Figure 3 shows the distribution of u'v' colours chosen by the participants.

Figure 3 – Graphical representation of preferred choice of colour



The u'v' values for the Irlen overlays, and the u'v' values for the algorithm colour chosen by the subjects on the computer screen and plotted on a CIE u'v' diagram are shown in Fig 4.

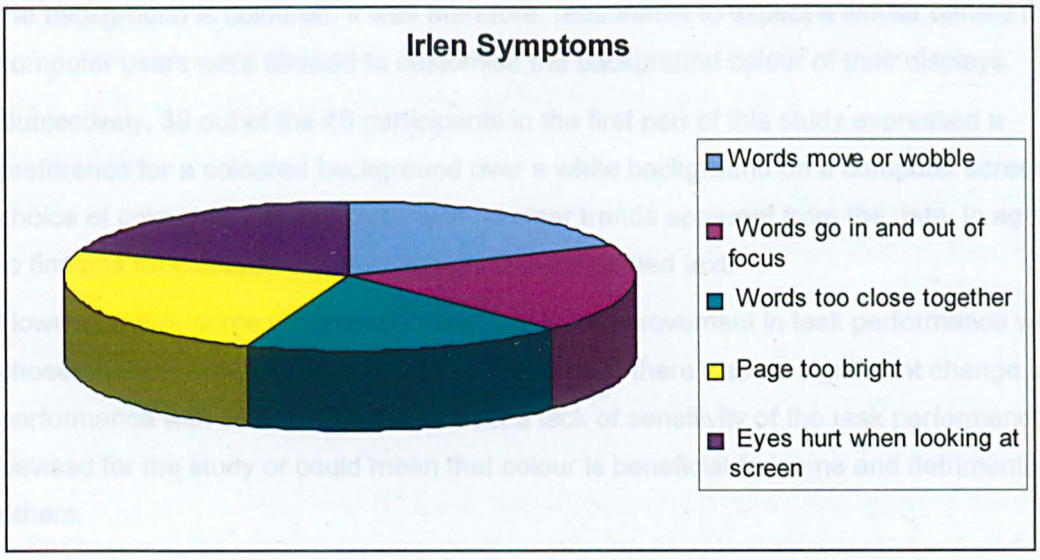
Figure 4 – Graphical representation comparing u'v' values between Irlen overlay colour and VDU screen tint plotted against the CIE chromaticity diagram



As Figure 4 shows, the values for the colour of the computer screen algorithms are uniformly distributed in a circle, 22.5 degrees apart on the perimeter of a circle in the CIE UCS diagram. This particular circle has a radius of 0.0369 and a centre with chromaticity $u' = 0.1978$, $v' = 0.4683$. However, the overlay colours do not form a circle around a point, and do not show equal separations between the colours. Therefore, a direct comparison between the two colours chosen by each subject would not provide a result of use.

All participants (N = 32, 100%) reported positive benefits from using their optimum screen colour compared to baseline when the most common symptom of visual stress reported then was that participants complained that their 'page was too bright'

Fig 5 – Pie chart showing frequency of visual stress symptoms in response to the questionnaire



Rate of Reading results

The mean time for participants to complete the Rate of Reading test against a white background was 222 s (s.d. = 89s) and against the optimum coloured background, 208 s (s.d. = 91s) ($t(31) = 2.36$, $p = 0.025$).

Nineteen (65%) participants read faster with their optimum screen colour. Overall, the participants read an average of 9% faster using their chosen screen colour. However, the reading speed of 12 (39%) participants increased by more than 10%.

Spreadsheet Analysis

The mean time for participants to complete the Spreadsheet Analysis against a white background was 29.2 s (s.d. = 13.0s) and against a coloured background, 29.2 s (s.d. = 11.0s) ($t(30) = 0.04$, $p = 0.965$). The number of errors was not significantly different with the preferred colour (mean errors: white = 1.72, colour = 1.58).

Nonsense Sentences

The mean time for participants to complete the Nonsense Sentences task against a white background was 105.1 secs (s.d. = 81.9s) and against a coloured background, 95.6 secs (s.d. = 73.0s) ($t(31) = 1.96$, $p = 0.059$). The number of errors was not significantly different with the preferred colour (mean errors: white = 0.97, colour = 0.55).

Twenty (62.5%) of the participants increased their task speed with use of the coloured screen. Eighteen (56.2%) participants increased their task speed by more than 10%.

DISCUSSION

There is growing evidence that a proportion of the population read printed text faster when the background is coloured. It was therefore, reasonable to expect a similar benefit if computer users were allowed to customise the background colour of their displays.

Subjectively, 39 out of the 40 participants in the first part of this study expressed a preference for a coloured background over a white background on a computer screen. The choice of colour was idiosyncratic with no clear trends apparent from the data, in agreement to findings for coloured overlays/spectacles and printed text.

However, while some subjects demonstrated an improvement in task performance with their chosen colour, others performed worse and overall there was no significant change in task performance with colour. This may reflect a lack of sensitivity of the task performance tests devised for the study or could mean that colour is beneficial for some and detrimental to others.

The subjective preference shown for a coloured background was supported by a significant reduction in the prevalence and frequency of asthenopic symptoms when participants' worked at displays set up with their preferred colour for a minimum of one week. Twenty seven of the 39 subjects reported that changing the background colour had "made their eyes feel more comfortable" while 17 reported that it had made them more efficient in performing computer tasks. The fact that 18 (46.2%) participants were still using their preferred screen colour one month after the study is compelling support for the benefits. Of those that reverted to white, some reported that they had done so reluctantly because the demands of the tasks that they were doing (desktop publishing, web-design).

This perceived benefit of colour, even if not supported by attempts to quantify the effects, is significant and could have major implications in terms of the prevalence of symptoms and general sense of well-being among computer users.

The benefits of customising screen colour were even more apparent among the group of participants who suffered from visual stress. All participants reported a reduction in symptoms with their chosen screen colour and many demonstrated a significant increase in their rate of reading. This is in agreement with the literature showing that reading from hard copy is improved with the use of coloured overlays (Bouldoukian et al, 2002; Evans et al, 2002; Wilkins, 2002; Wilkins et al, 2001 &1994; Tyrrell et al, 1995; Robinson & Conway, 1994; Kyd et al, 1992; Irlen, 1983).

However customising screen colour did not produce a significant improvement in the spreadsheet and nonsense sentence tasks.

This contrary to the findings of Tyrell et al (1995), Evans et al (1994) and Wilkins and Neary (1991) who showed an improvement in visual search performance with coloured filters. Whiting et al (1994, 1988) showed that comprehension improved in 70-90% of participants using coloured overlays. Other studies have reported similar findings (Robinson & Conway, 1994, 1990; O'Connor et al 1990; Hannell et al, 1989; Irlen, 1983).

Conclusions

Although the sample size in this study is relatively small, the results suggest that allowing computer users to customise the background colour of their displays may be beneficial in terms of visual comfort and perceived efficiency. Users who suffer from symptoms of visual stress are likely to gain significant benefit.

Further studies on a larger number of computer users are required to confirm these findings. However, with an increasing proportion of the population now using computers for a large part of the working day, these findings have significant implications in terms of the well-being of computer users and productivity.

We are currently developing software which will allow computer users to quickly and accurately identify their optimum screen colour and apply this colour to all applications used on their own computer.

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