Visual discomfort whilst viewing 3D stereoscopic stimuli

by

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Doctoral Thesis
Submitted in partial fulfilment of the requirements
for the award of

Doctor of Philosophy of Loughborough University

March 31, 2015

Abstract

3D stereoscopic technology intensifies and heightens the viewer's experience by adding an extra dimension to the viewing of visual content. However, with expansion of this technology to the commercial market concerns have been expressed about the potential negative effects on the visual system, producing viewer discomfort. The visual stimulus provided by a 3D stereoscopic display differs from that of the real world, and so it is important to understand whether these differences may pose a health hazard. The aim of this thesis is to investigate the effect of 3D stereoscopic stimulation on visual discomfort. To that end, four experimental studies were conducted.

In the first study two hypotheses were tested. The first hypothesis was that the viewing of 3D stereoscopic stimuli, which are located geometrically beyond the screen on which the images are displayed, would induce adaptation changes in the resting position of the eyes (exophoric heterophoria changes). The second hypothesis was that participants whose heterophoria changed as a consequence of adaptation during the viewing of the stereoscopic stimuli would experience less visual discomfort than those people whose heterophoria did not adapt. In the experiment an increase of visual discomfort change in the 3D condition in comparison with the 2D condition was found. Also, there were statistically significant changes in heterophoria under 3D conditions as compared with 2D conditions. However, there was appreciable variability in the magnitude of this adaptation among individuals, and no correlation between the amount of heterophoria change and visual discomfort change was observed.

In the second experiment the two hypotheses tested were based on the vergence-accommodation mismatch theory, and the visual-vestibular mismatch theory. The vergence-accommodation mismatch theory predicts that a greater mismatch between the stimuli to accommodation

and to vergence would produce greater symptoms in visual discomfort when viewing in 3D conditions than when viewing in 2D conditions. An increase of visual discomfort change in the 3D condition in comparison with the 2D condition was indeed found; however the magnitude of visual discomfort reported did not correlate with the mismatch present during the watching of 3D stereoscopic stimuli.

The visual-vestibular mismatch theory predicts that viewing a stimulus stereoscopically will produce a greater sense of vection than viewing it in 2D. This will increase the conflict between the signals from the visual and vestibular systems, producing greater VIMS (Visually-Induced Motion Sickness) symptoms. Participants did indeed report an increase in motion sickness symptoms in the 3D condition. Furthermore, participants with closer seating positions reported more VIMS than participants sitting farther away whilst viewing 3D stimuli.

This suggests that the amount of visual field stimulated during 3D presentation affects VIMS, and is an important factor in terms of viewing comfort.

In the study more younger viewers (21 to 39 years old) than older viewers (40 years old and older) reported a greater change in visual discomfort during the 3D condition than the 2D condition. This suggests that the visual system's response to a stimulus, rather than the stimulus itself, is a reason for discomfort. No influence of gender on viewing comfort was found.

In the next experiment participants' fusion capability, as measured by their fusional reserves, was examined to determine whether this component has an impact on reported discomfort during the watching of movies in the 3D condition versus the 2D condition. It was hypothesised that participants with limited fusional range would experience more visual discomfort than participants with a wide fusion range. The hypothesis was confirmed but only in the case of convergent and not divergent eye movement. This observation illustrates that participants capability to convergence has a significant impact on visual comfort.

The aim of the last experiment was to examine responses of the accommodation system to changes in 3D stimulus position and to determine whether discrepancies in these responses (i.e. accommodation overshoot, accommodation undershoot) could account for visual discomfort experienced during 3D stereoscopic viewing. It was found that accommodation discrepancy was larger for perceived forwards movement than for perceived backwards movement. The discrepancy was slightly higher in the group susceptible to visual discomfort than in the group not susceptible to visual discomfort, but this difference was not statistically significant.

When considering the research findings as a whole it was apparent that not all participants experienced more discomfort whilst watching 3D stereoscopic stimuli than whilst watching 2D stimuli. More visual discomfort in the 3D condition than in the 2D condition was reported by 35% of the participants, whilst 24% of the participants reported more headaches and 17% of the participants reported more VIMS.

The research indicates that multiple causative factors have an impact on reported symptoms. The analysis of the data suggests that discomfort experienced by people during 3D stereoscopic stimulation may reveal binocular vision problems. This observation suggests that 3D technology could be used as a screening method to diagnose untreated binocular vision disorder. Additionally, this work shows that 3D stereoscopic technology can be easily adopted to binocular vision measurement.

The conclusion of this thesis is that many people do not suffer adverse symptoms when viewing 3D stereoscopic displays, but that if adverse symptoms are present they can be caused either by the conflict in the stimulus, or by the heightened experience of self-motion which leads to Visually-Induced Motion Sickness (VIMS).

KEYWORDS: 3D, visual discomfort, heterophoria adaptation, vergence-accommodation mismatch, visual-vestibular mismatch, fusional vergence, accommodation discrepancy (overshoot, undershoot).

Acknowledgements

The present thesis would never have materialized without the support I received from the amazing people I had the chance, luck and honour to meet on my way.

Firstly, I would like to express my sincere gratitude to my supervisor Dr Peter Howarth for the opportunity of doing research in such an interesting area of science. His support and guidance have been invaluable throughout the years of my PhD.

Many thanks go to Prof. Neil Mansfield, Prof. George Havenith and Dr Simon Hodder for their support during my time as a PhD student. I would also thank all members of EERC for the sociable atmosphere and for being good friends.

My sincere acknowledgements to Prof. James Wolffsohn and Dr Thomas Drew (Aston University, UK) for the equipment support (the Power Refractor) and much useful advice.

I would also like to thank the CS MSU Graphics & Media Lab team (Lomonosov Moscow State University, Russia), especially Alexander Voronov for help in analysing 3D stereoscopic movie characteristics.

Sincere thanks must go to all of the volunteers who took part in the research reported in this thesis, without them there would have been no thesis to write.

My special thanks go to Dr Wendy Jones - your support meant so much to me. I do not think words can quite portray how much I appreciate it.

I am very grateful to Daniel Collins and Christina Kokoroskou for their friendship, always open house and for offering help whenever needed.

And of course not forgetting my wonderful parents, Teresa and Andrzej; my siblings, Patrycja and Tomek; and grandma Olga, for all of their love, support and encouragement throughout my education.

Finally, I would like to thank my other half Michal Krawczynski for his love, motivation and advice. Thank you that I could share with you all my ups and downs during this journey. You are a great inspiration to me and without your help I wouldn't be where I am today.

Thank you all, so much.

Publications

Journal publication:

Karpicka, E. & Howarth, P. A. (2013), "Heterophoria adaptation during the viewing of 3D stereoscopic stimuli", *Ophthalmic and Physiological Optics* 33(5), 604-610.

The article was featured as a "Story of the week" by Practice Update (Elsevier)

Conference proceedings:

Karpicka, E. & Howarth, P. A. (2013), "The viewing of 3D stereoscopic films" *in* "Proceedings of the 4th International Symposium on Visual IMage Safety (VIMS2013)", Stratford-upon-Avon, UK,

Karpicka, E. & Howarth, P. A. (2014), "Accommodation discrepancy whilst viewing 3D stereoscopic stimuli", British Congress of Optometry and Visual Science, Cardiff, UK, *Ophthalmic and Physiological Optics* 34, 690.

Prize for poster presentation:

Karpicka, E. & Howarth, P. A. (2013), "Perceived discomfort during the viewing of 3D stereoscopic stimuli" Loughborough University Research Conference 2013, Loughborough University, UK.

First prize for best poster presentation

International oral presentation:

The results of the experiment described in Chapter 3 was presented at the Vision Performance Institute, Forest Grove, Oregon, USA (03.02.2012).

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Chapter 1

Introduction

1.1 Motivation

Over recent years, the use of three dimensional (3D) technology has become widespread across different media devices. Cinema, blu-ray players, televisions and even mobile phones are available in this format. There is no doubt that we are witnessing the renaissance of 3D technology.

Due to technological advancement for the first time 3D has become available not only in cinemas but also in our homes. According to Informa Telecoms & Medias forecasts for the 3D TV sector the global penetration of 3D TV sets is growing. In 2010 only 0.2% of households had been equipped with a 3D ready TV set. Level of market penetration increased to 3.4% at the end of 2012 and it is expected to rise to 28.2% by the end of 2017 (Thomas 2013). From 2013 to 2018 TechNavios analysts forecast the Global 3D market will grow at a CAGR of 35.85% (PRNewswire 2014). This increase is mainly driven by the fact that 3D is now a standard feature of many new TV sets. Similar observations can be made in relation to 3D enabled cinemas. The number of 3D cinemas worldwide increased by a factor of around 251 from 258 in 2006 to 64,905 in 2014 (Statista 2014).

With the increasing accessibility to 3D stereoscopic technology many concerns and warnings about the health hazards of viewing 3D stimuli have been expressed. In 2010 it was reported that the Italian government confiscated 7000 sets of 3D glasses because they "did not display tags proving they would not cause short-term vision problems to users" (Reuters). Nintendo, in their Health and Safety Information and Usage Guidelines, state that "viewing of 3D images by children 6 and under may cause vision damage". The world's biggest electronics companies have also warned about the dangers of watching 3D television. For example, Sony has claimed that "some people may experience discomfort (such as eye strain, eye fatigue, or nausea) while watching 3D video images or playing stereoscopic 3D games on 3D televisions". Similar concerns can be found on websites belonging to LG, Samsung and Panasonic. Furthermore some of these companies recommend restricting use. Samsung highlights that "pregnant women, the elderly, sufferers of serious medical conditions, those who are sleep deprived or under the influence of alcohol should avoid utilising the units 3D functionality." Recently the French watchdog (ANES[1]) issued an internal request to assess the potential health risks related to the use of the 3D stereoscopic technologies. Moreover the agency has recommended that "children under the age of six should not be exposed to 3D technologies" and "children under the age of 13 should only use 3D technologies in moderation". One may ask whether warnings issued by these manufacturers and institutions are based on thorough scientific research (proven facts) or if they simply reflect an attempt to limit the possibility of users making compensation claims due to adverse health impacts from 3D technology.

Accessibility to 3D stereoscopic technology is still increasing, as 3D is a standard function of many new TV sets. Nevertheless, user engagement with 3D technology is constrained largely due to limited availability of high quality 3D content. The number of newly released 3D stereoscopic movies between 2010 to 2014 remains stable [Woods]. However when compared with the number of movies created in 2D it is negligible On the other hand, the enthusiasm for the 3D format is declining. Taking into account movies, which were presented on both 3D and 2D screen, the median 3D takings as a percentage of total takings fell from 71% in 2010 to 37% in 2013 (BFI 2014). It can be speculated that one of the reason for this decrease is discomfort experienced by viewers. It is understandable that people who have had a bad experience while watching 3D stereoscopic movie are more cautious in selection of movie format.

[1]ANSES - French Agency for Food, Environmental and Occupational Health & Safety

Several organisations have undertaken work in the standardisation of 3D technology for example: SMPTE[1], EBU[2], 3D@Home Consortium, ITU[3], DTG[4], ISO[5]. Regardless of this, it is worth highlighting that at the moment the level of standardisation is far from satisfactory. There is a lack of agreement on definitions for technical requirements for the creation of 3D stereoscopic content and there are no objective tests which can be used to assess the quality of 3D content and the quality of 3D enabled devices. What more to the best of author's knowledge, there is no guidance on safe exposure time for 3D viewing. Finally there are no formally agreed procedures to test discomfort experienced by people exposed to 3D stimuli.

Concerns about the adverse effects of 3D stereoscopic stimulation have given rise to a number of studies aiming to determine the effect of this stimulation on discomfort. Much of the research is limited in terms of the methods used to assess discomfort (e.g. lack of pre-sessional data, problems in interpretation of the questionnaires used), or because they do not assess individual differences between 3D and 2D conditions. The most serious limitation, however, to these studies is that only association and not causation, of the problem can be shown.

It is also important to highlight that 3D steroscopic technology is used not only in the entertainment industry. As this technology enables more accurate understanding and analysis of an object it is used also in medicine, biomedicine (diagnosis, pre-operative planning, training /teaching) (Van Beurden et al. 2009, Schreer et al. 2005), military activities (training and simulation in virtual environments) (Schreer et al. 2005), geology (BGS), architecture (Minoli 2011), communication (mobile devices, scientific visualization) (Minoli 2011). 3D stereoscopic technologies have also entered some classrooms enabling visualization in areas that are abstract to aid understanding (Bamford 2011, Sensavis 2015).

From day to day the spectrum of 3D applications is getting wider and wider. It is therefore important to determine the impact of 3D stereoscopic stimuli on the visual system and the effect of these stimuli on viewing comfort.

[1]Society of Motion Picture and Television Engineers
[2]European Broadcasting Union
[3]International Telecommunication Union
[4]Digital TV Group
[5]International Organisation for Standardisation

1.2 Research aims

The aim of this thesis is to investigate the effect of 3D stereoscopic stimulation on visual discomfort. The key questions explored in this work are whether participants experience more visual discomfort whilst watching 3D stereoscopic stimuli than whilst watching 2D stimuli, and if so, why. The research addresses this question through subjective measurements of visual discomfort before and after viewing both 3D and 2D stimulation. Specific hypothesises were made, based on characteristic of the stimuli presented, in terms of the expected effect on the eyes responses and on discomfort.

The research described in this thesis tested these hypotheses by

- objectively analysing stimuli content and evaluating its effect on subjective reported discomfort
- objectively measuring eye response (heterophoria, fusional vergence, accommodation) and subjective reported discomfort
- analysing participants' viewing positions and their effect on subjective reported discomfort
- analysing participants attributes e.g age, gender and exploring that impact on subjective reported discomfort

In order to do this, special binocular vision tests and stimuli were required, which were developed by the author. The tests were displayed on the 3D stereoscopic screen and watched by participants equipped with 3D stereoscopic glasses. This way of presenting the binocular vision test/stimulus allowed for the control of eye movements so that they matched these found during the watching of 3D stereoscopic movies.

1.3 Thesis structure

The thesis is organised in seven chapters. This first chapter is an introductory section which outlines the motivation for the research, the research aims and the structure of the thesis. The next chapter defines the key terms and reviews the literature related to the research topic. The core part of the thesis consists of the experimental work and is described in chapters three to six. Each of these chapters has the same structure, and containing the following sections: purpose of the research, introduction, methods, results and discussion. In the final chapter, the major findings are summarised and the main conclusions are highlighted. At the end of this chapter possible applications of the research are discussed

1.4 Research approach

The first part of this research was a general review of the current state of knowledge in the field of discomfort whilst viewing 3D stereoscopic stimuli. Based on this review the possible causes of discomfort were identified. Following on this the main terms and problems associated with this research were discussed in the literature review section. Taking into account the current research and the problems, which can intensify as a result of differences between the normal viewing condition and 3D conditions the following experimental chapters were defined:

- Heterophoria adaptation during the viewing of 3D stereoscopic stimuli.

In this chapter two hypotheses were tested. The first hypothesis was that the viewing of 3D stereoscopic stimuli, which are located geometrically beyond the screen on which the images are displayed, would induce exophoric heterophoria (phoria) changes (adaptation). The second hypothesis was that participants whose phoria changed as a consequence of adaptation during the viewing of the stereoscopic stimuli would experience less visual discomfort than those people whose phoria did not adapt.

- Vergence - accommodative mismatch and visual - vestibular mismatch during viewing of 3D stimuli.

In this chapter two hypotheses were tested. The first hypothesis was that a greater mismatch between stimuli to accommodation and to vergence would produce greater symptoms in visual discomfort of viewing in 3D conditions when compared to the discomfort of viewing in 2D conditions. The second hypothesis was that 3D stimuli produce a greater sense of vection increasing the conflict between the visual and vestibular systems and thus produce greater VIMS symptoms compared to 2D viewing conditions. In this chapter it was also asked whether headache is reported during 3D stereoscopic stimulation and whether the headache whilst exposed to 3D stereoscopic stimulation is more severe than headache whilst exposed to 2D stimulation. This was considered important to investigate as people who experience symptoms associated with visual discomfort and VIMS can also experience symptoms associated with headache (Wilson 1996, Lawson et al. 2002, Scheiman & Wick 2008, Howarth & Hodder 2008, Ujike et al. 2008, Kennedy et al. 2010).

- The impact of participants fusion capacity on discomfort whilst watching movies in 3D versus 2D condition.

In this chapter it was hypothesized that participants with limited fusion range would experience more visual discomfort than participants with a wide fusion range. The hypothesis was analyzed in terms of positive fusional reserve (PFR), negative fusional reserve (NFR) and total fusional reserve (FR=PFR+NFR).

- Accommodation discrepancy whilst viewing 3D stereoscopic stimuli.

This chapter aimed to examine the response of the accommodation system to the change in the 3D stimulus position and to determine whether any changes would account for the visual discomfort reported during the viewing of 3D stimuli.

1.5 Ethical approach

Three dimensional (3D) technology is commercially available and is a standard feature of many new TV sets. Currently there is a lack of agreement on definitions for technical requirements for the creation of 3D stereoscopic content and there is no restriction on the use of this technology. In all experiments presented within this thesis stimuli were displayed on commercially available screens. Therefore participation in any study described in this thesis would not be expected to cause more problems than might be present whilst watching 3D at home or at cinema. All participants gave their informed consent for participation. The test procedure and the conditions were explained to each participant. Following familiarization with testing procedures and laboratory equipment, participants signed an informed consent form. In the conducted studies only participants over 18 were included, this approach was chosen to exclude the difficulties of children giving informed consent. All participants were aware that:

- they had an opportunity to ask questions about their participations
- they were under no obligation to take part in the study
- they had the right withdraw from the study at any stage for any reason, and would not be required to explain their reason for withdrawal

The investigator was aware of the duty of care to participants. If any unexpected/unplanned situation occured (e.g. participant feeling unwell/ weak) invigilator was able to provide assistance (e.g. provide a place to rest, provide a glass of water, help to get home or to a medical doctor). All experiments were conducted in Environmental Ergonomics Research Center. After completing the experiment any personal data collected during a study (names, ages, gender etc.) were anonymously coded and kept securely, in accordance with the requirements of the Data Protection Act.

Chapter 2

Literature Review

Purpose: This chapter describes the main terms and background literature related to the field of study. First the evolution of 3D is summarised. Next, the current state of research in the field of discomfort whilst viewing 3D stereoscopic stimulation is reviewed. The problems arising during the analysis of discomfort are identified. Finally, the chapter summarises the limitations of previous studies.

2.1 The evolution of 3D stimuli

The concept of reproducing the three dimensional visual sensations experienced by humans in the natural environment is not novel. The very first device capable of creating 3D stimuli was invented by Sir Charles Wheatstone in 1833. His invention showed that depth perception is a result of binocular disparity. The device was named a stereoscope[1] to reflect its ability to represent solid figures (Wheatstone 1838). The stereoscope consisted of two mirrors at right angles and two vertical picture holders where slightly different figures were presented. In a later version each half of the instrument could be rotated to adjust the angle of convergence (this principle is still used in an amblyoscope[2])(Howard 2012). Subsequent modifications of Wheatstone's stereoscope by Sir David Brewster (Brewster stereoscope), Oliver Wendell Holmes (Holmes stereoscope) and others became very popular and fashionable in Europe and in the U.S.A. From the middle of the nineteenth century the stereo cards photographically documented the popular personalities and important events of the period (Lipton 1982, Zone 1996). In the later part of the century, with the advent of illustrated magazines (Howard 2012) and motion pictures (Fehn 2005) the public lost interest in stereoscopic media. Moreover the stereoscope had some drawbacks. The illustration could be viewed by only one person at a time. Often technical diligence was poor (badly constructed stereoscopes, carelessly photographed views or improperly mounted paper prints), which further decreased the level of the stereoscope's popularity (Lipton 1982).

The next phase of 3D technology was the presentation of 3D moving images. The first stereo moving picture device was patented in 1852 by the Parisian optician Jules Duboscq (Howard 2012). Several instruments for showing moving stereoscopic images were subsequently constructed. In the period after 1870, interest in stereoscopic moving images declined as modern cinematography was developed (Howard 2012). At the beginning of the twentieth century new technologies for presenting 3D stereoscopic movies debuted. One of these was the anaglyph technique, where two images projected through a red filter and a green

[1]stereoscope - from Greek conjoin of two words *stereo* and *skopion* "to see-solid".

[2]amblyoscope - a device used primely for the diagnosis and treatment of strabismus.

filter were superimposed on a screen. The audience wore glasses with red and green lenses which partially separated the images for each eye. Another method of presenting 3D images was the eclipsing shutter technique. The technique involves shutters placed in front of both right and left projection lenses and shutters used in the viewing device worn by the audience. When the right shutter was opened at the projector, the right was opened at the viewing device and vice versa. In this way two images were delivered to each eye separately. The main limitation of this system was that it was not possible to present the left and right images to the appropriate eye simultaneously.

The next notable achievement in terms of stereoscopy technology was the application of polarising filters, patented by Edwin H Land in 1928, which led to the development of the first full colour 3D (Zone 1996). In this technology two different polarising filters were mounted in front of two projector lenses and the audience wore polarised glasses to separate the two images. Thus the right image was delivered only to the right eye and the left image was delivered only to the left eye. It is worth noting that the polarised 3D system and shutter glasses approach mentioned earlier are the two major 3D techniques currently in use.

In 1952 the movie Bwana Devil (the first colour 3D movie) started an expansion of the 3D industry. Between 1952 and 1954, Hollywood produced over sixty-five 3D films. However, limited experience of stereoscopic techniques, inadequate quality control in the laboratories and badly operated projection systems in the cinemas meant that the technology failed to arouse the audience's enthusiasm. Furthermore, adverse symptoms such us eyestrain, and headaches quickly discouraged people from watching 3D movies (Lipton 1982, Fehn 2005). Since 2005 the renaissance of 3D technologies has been observed in cinemas. In 2010 3D TV was brought to a wider audience showing its maturity by broadcasting the World Cup Championship in 3D.

As shown above 3D stimulations have a long history. Despite technological improvements in the field of production and delivery, some individuals continue to report adverse effects when viewing 3D content. It is important to investigate this topic to identity the sources of these problems. At present, although the differences between the visual stimulus presented by 3D displays and that of the real world are known, the relative effects are not yet recognised (Howarth 2011).

2.2 Current state of research

Over the last decade a number of investigations into potential adverse effects associated with the viewing of 3D stimuli have been conducted. Regardless of this researchers have not reached conclusive findings. The following possible causes of discomfort are the most frequently reported: vergence-accommodation mismatch, visually induced motion sickness (VIMS), stereoscopic distortion. This section describes the main terms and experiments which have been used to investigate these issues. Problems associated with assessing discomfort are also discussed.

2.2.1 Visual discomfort

Visual discomfort experienced by some people whilst viewing 3D stereoscopic stimulation is mentioned in the literature as the important health issue (Lambooij et al. 2009). However, visual discomfort is not the only term that has been used to describe a set of symptoms associated with viewing of 3D stimuli. It can be found that visual discomfort is used interchangeably with visual fatigue or asthenopia. Visual fatigue can be defined as a feeling of weariness resulting from a visual task. It can have psychic, ocular or muscular origins. However, there does not seem to be an objective proof of a reduction in vision aptitude (e.g. visual acuity) accompanying visual fatigue (Millodot 2014). According to Howarth & Bullimore (2005) vision cannot be fatigued and when people claim to have visual fatigue it is not their vision that gets tired, but rather the person themselves. On the other hand the term asthenopia is used to describe any symptoms associated with the use of the eye (Millodot 2014). Sheedy et al. (2003) state that asthenopia can be caused or induced by: glare from lighting, anomalies of binocular vision, accommodative dysfunction, uncorrected refractive error, compromised quality of viewed image such as poor contrast or legibility, less than optimal gaze angle, flickering stimuli such as CRT computer displays and dry eye. Although the first work in terms of adverse eye symptoms sensation was conducted in 1916 (Watten 1994) the mechanism of it is still not clear (Watten 1994, Sheedy et al. 2003). In the current work to describe a set of symptoms associated with vision problems whilst viewing 3D stereoscopic stimulation, the term visual discomfort will be used. Visual discomfort in this thesis is assessed subjectively by using questionnaires before and after viewing both 3D and 2D stimulation.

2.2.2 Vergence-accommodation mismatch

One of the differences between normal viewing conditions and virtual 3D conditions is the distance between the stimulus to accommodation and the stimulus to vergence. In the natural viewing condition the stimulus to accommodation and stimulus to vergence are determined by the their distance to the eye. Figure 2.1 illustrates this relationship. The accommodation required in dioptres (D) is represented on the ordinate, and the vergence in prism dioptres (Δ) on the abscissa. The Donders' line represents the amount of vergence required for each value of accommodation for equality between the two. Accommodation and vergence distance are identical in natural viewing, and the responses are neurologically coupled. Accommodation change evokes a change in vergence (accommodative vergence) and vergence change evokes a change in accommodation (vergence accommodation)(Fincham & Walton 1957). If the range of accommodation is measured for various values of vergence and the range of vergence is measured for various values of accommodation the data define a zone of single clear binocular vision (ZSCBV). It is worth noting that the zone has a finite width which demonstrates a tolerable "freedom range" of vergence from accommodation (Hofstetter 1945). This indicates that single binocular vision is possible even if the stimulus to accommodation and stimulus to convergence are not coincident. The boundaries of the zone vary from one person to another, and take the form of two straight, non-parallel lines. In figure 2.1 the right-hand grey-dashed line represents the limit of convergence (eyes turning inwards), and the left-hand grey-dashed line represents the limit of divergence (eyes turning outwards). The convergence boundary of the zone is more slanted than the divergence boundary, especially for higher values of accommodation, as more proximal vergence[1] is introduced (Scheiman & Wick 2008). Several criteria have been proposed to

[1] proximal vergence - the component of vergence results from knowledge of nearness of the target (Hung & Ciuffreda 2002), in other words it is initiated by an awareness of a near object (Millodot 2014, Grosvenor & Grosvenor 2007). Proximal vergence occurs automatically when the observer attends to a particular stimulus. It is therefore not voluntary but it is evoked by a voluntary change of attention from one object to another (Howard 2012).

define the area over which not only single clear binocular vision is possible but also comfortable vision is achievable. The most popular are Sheard's criterion and Percival's criterion which are used clinically to determine comfortable optical correction.

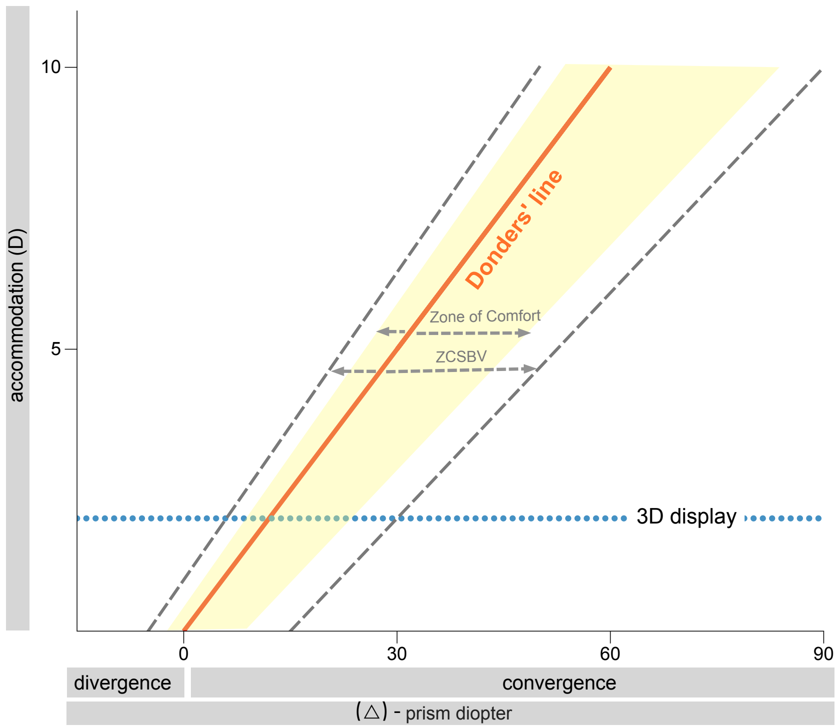


Figure 2.1: Zones of vision. The Donders line represents the accommodation and vergence demands of stimuli at different distances in the natural viewing condition. The dashed line indicates the Zone of Clear Single Binocular Vision (ZCSBV). The yellow shaded area represents the individual (hypothesised) Zone of Comfort within ZCSBV. The blue dotted line represents the accommodation and vergence demand of a 3D display at a distance of 50 cm from the viewe [based on Howarth (2011)].

A stereoscopic 3D display provides each eye with a separate image. Both images are displayed on a flat screen. The distance between the screen and eyes does not change while watching 3D stereoscopic stimuli which results in the stimulus to accommodation being fixed. However, parallax introduced between two images allows for an object to be perceived in front or behind the screen. Under such conditions the stimulus to vergence varies during stereoscopic stimulation. Consequently, unlike in the real word, the stimulus to accommodation and stimulus to vergence do not match. Figure 2.2 presents a schematic comparison of conditions where the stimuli to accommodation and vergence do match (a) and where they do not (b and c).

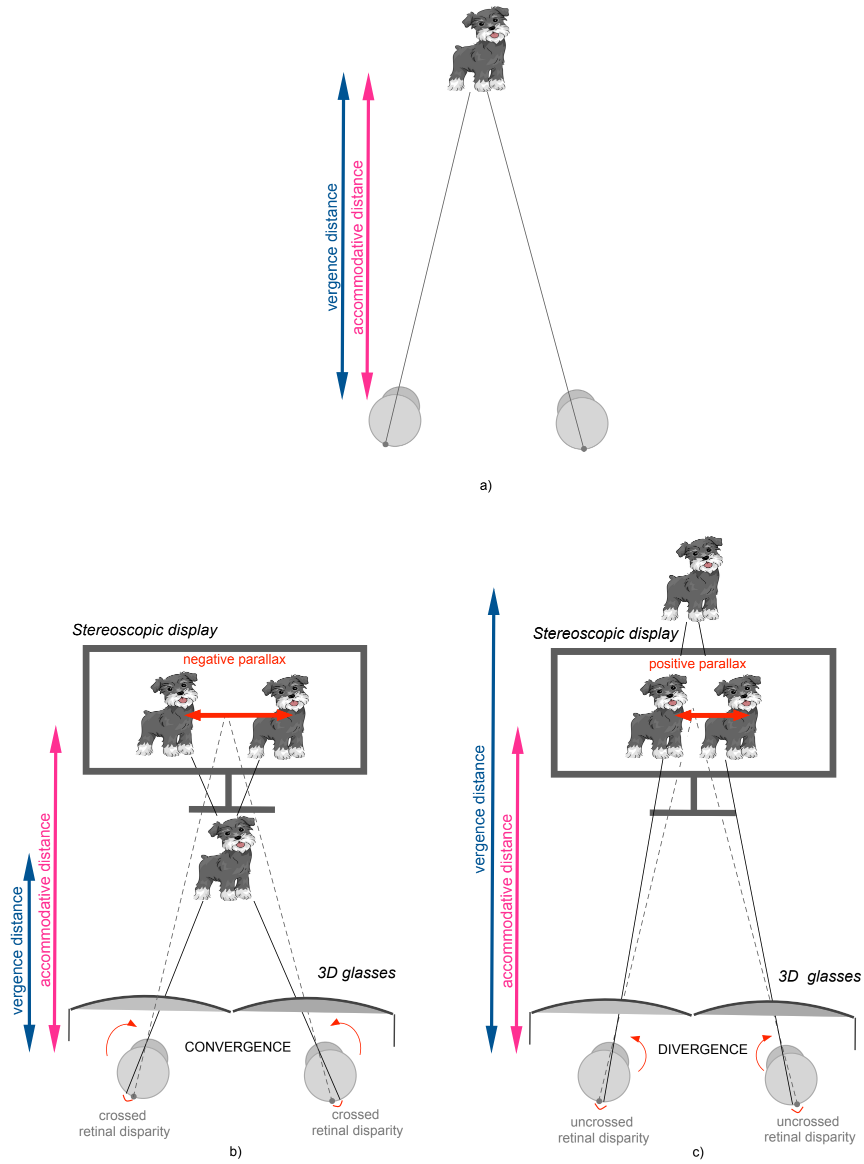


Figure 2.2: Vergence and accommodation distance with real stimulus (a) and stimulus presented on a 3D stereoscopic screen (b and c). In normal viewing, the vergence stimulus and accommodation stimulus are always at the same distance from the viewer's eyes and therefore stimulus to vergence and accommodation are equal. A 3D stereoscopic display produces a mismatch between stimulus to accommodation and stimulus to vergence. The accommodation distance is fixed, but vergence distance varies depending on the parallax used. If images are presented with negative parallax, stimulus to vergence appears in front of the screen (b), if images are presented with positive parallax, stimulus to vergence appears behind the screen. [Terminology: *parallax* - refers to the separation between left and right image presented on the 3D display; *negative parallax* - the image on the screen is shifted to the right for the left eye and to the left for the right eye; *positive parallax* - the image on the screen is shifted to the left for the left eye and to the right for the right eye].

In the literature many researchers assume that vergence-accommodation mismatch produces discomfort during the viewing of 3D stereoscopic stimuli (Inoue & Ohzu 1997, Ukai & Kato 2002, Hoffman et al. 2008, Yang & Sheedy 2011, Yang et al. 2012). However, empirical studies do not clearly support this hypothesis.

Yano et al. (2004) examined six participants who read text presented on a 3D stereoscopic display. During each experimental session the viewing distance was fixed at the same distance of 108 cm (stimulus to accommodation). The perceived position of stimulus varied from one experimental condition to another and was determined by one of seven different parallaxes (0°, ±0.82°, ±1.36°, ±1.90°). Subjective discomfort was assessed by a 5 point scale. It was found that on average severity of discomfort increased as positive (stimulus behind the screen) and negative parallax (stimulus in front of the screen) increased. It was also reported that some of the subjects did not experience visual discomfort while others strongly experienced visual discomfort, and this was particularly apparent for the maximum negative parallax. Based on the group data presented by Yano et al. (2004) vergence-accommodation theory appears to be supported. However, the differences in discomfort reported by participants might be related to differences in response to the presented stimulus or to the participants' capability to converge[1]. For example participants with a narrow fusional convergence had to put in more effort to fuse the stimulus than participants with a wide fusional convergence range. In this case participants with a narrow fusional range experienced more discomfort than participants with a wide fusional range[2]. Furthermore in this experiment symptoms were not assessed before the trial started. This approach does not show whether or not the discomfort was present from the outset, or had been caused by the stimuli.

Hoffman et al. (2008) investigated vergence-accommodation mismatch by using a volumetric stereoscopic display (figure 2.3) which allows control of vergence and accommodation stimuli independently.

[1]Capability to converge quantified by positive fusional convergence.

[2]As the variability between participants' capability to diverge is much smaller than the variability in participants capability to converge the difference in discomfort between participants were smaller when the image was presented with positive parallax than when the image was presented with negative parallax(based on study conducted in Chapter 4).

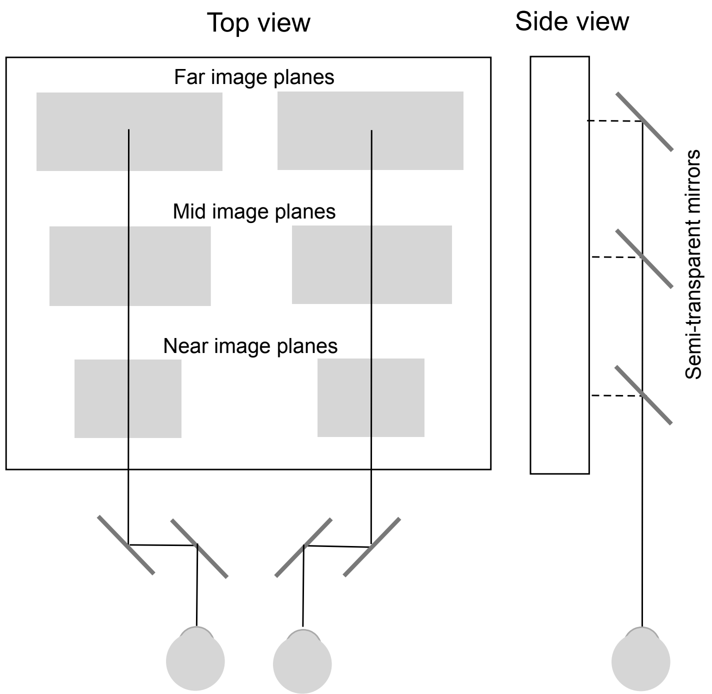


Figure 2.3: Volumetric stereoscopic display - optical instrument which can present 3D images for the left and the right eye without convergence and accommodation mismatch. It is however possible to introduce vergence-acccommodation mismatch by adding disparities between images. The set-up consists of: an LCD screen, 3 sets of 2 semi-transparent mirrors and 2 sets of 2 periscopic mirrors. Plane mirrors reflect images displayed on the screen towards the viewer. The viewers plane of focus is located at the distance of the plane mirrors. Periscopic mirrors allow for increased separation between the ocular axes and an adjustment of pupil distance [based on Hoffman et al. (2008)].

The advantage of this method is that it eliminates other differences between 2D and 3D displays such as cross-talk and vertical parallax (the literature related to these parameters is shown in subsection 2.2.4). This method does not require the wearing of 3D glasses (it has been reported that people complain about discomfort of wearing 3D glasses (Pölönen et al. 2009)). In the experiment eleven participants were exposed to a random dot stereogram in two sessions. During the first one the stimuli to accommodation and the stimuli to vergence were equal (2D condition) and in the second the stimuli to accommodation and the vergence were mismatched in 2 out of every 3 trials (3D condition). In this study it was found that significantly higher levels of discomfort were experienced by participants when a mismatch between stimuli to accommodation and stimuli to vergence existed. These results, however are still questionable because only post-test data were collected. Again, this methodological shortcoming prevents assessment of the effect of the 3D condition on viewers' discomfort over the session. Another limitation of this study is that only average data of discomfort are shown. The average data mask the "real" number of participants affected by the stimulus presented.

The effect of vergence-accommodation mismatch on visual discomfort was also analysed by Howarth & Underwood (2011). In their experiment sixteen subjects participated in four experimental conditions. Each experimental condition had a different magnitude of vergence-accommodation mismatch; in one of them there was no mismatch between stimulus to accommodation and stimulus to vergence (a control condition). The viewing distance (stimulus to accommodation) was 64.5 cm in all conditions. Visual discomfort was evaluated before and after each condition (duration 20 min.) with a six point scale. The collected data revealed that on average visual discomfort increased as the magnitude of vergence-accommodation mismatch increased. However, the individual data showed that participants experienced discomfort unequally: some of them did not experience visual discomfort even when the largest mismatch was produced. This indicates that visual discomfort arises as a consequence of the visual response to the stimulus, and not because of the stimulus itself[1]. In this case, the difference between the participants in response to the presented stimulus may reveal the reason for the discomfort.

[1]The problem with the accommodation-convergence conflict theory is that the conflict is present in the stimulus to the eyes, whereas it is the eyes response to the stimulus that will determine whether symptoms occur. There is obviously an association between the conflict and the symptom discrepancy but that does not prove causation, and evidence from optometry quite clearly indicates that, for the normal eye, small amounts of conflict should not cause symptoms Howarth (2011).

Yang & Sheedy (2011) and Yang et al. (2012) evaluated visual discomfort symptoms and VIMS symptoms (VIMS is described in a subsection below) before and after viewing of stimulus in a 2D and in a 3D condition. Twenty-one subjects participated in the earlier study. In the experiment two commercially available movies were presented, “Spy Kids” and “Lava Girl and Shark Boy” (duration 90 min., viewing distance of 200 cm from the screen). Each participant watched one movie in 2D in one session and the other movie in 3D in the other session. In the later study two hundred and three teenagers and adults were tested whilst viewing a computer animated comedy entitled “Cloudy with a chance of meatballs” (duration 90 min., viewing distance 338 cm or 481 cm away from the TV) in either a 2D or 3D condition. In both cases blurred vision, double vision and floating/drifting image (the last symptom only in Yang & Sheedy (2011)) were reported more frequently by the group where the 3D movie was watched than the group where the 2D movie was watched. Yang & Sheedy (2011) suggested that increases of those symptoms in the 3D condition compared with the 2D condition is related to greater variance in accommodation and vergence response while viewing the 3D movie than while viewing the 2D movie. In the study conducted by Yang et al. (2012) older viewers experienced greater visual symptoms in the 2D condition while younger participants reported greater visual symptoms in the 3D condition. It was suggested that double images observed during the viewing of 3D stereoscopic stimuli could be a result of an inappropriate/inadequate vergence response or cross-talk observed on the screen. As the ability to fuse stereoscopic images depends on the participant’s fusion range an inappropriate vergence (or in other words a small fusion range) may in fact produce this kind of problem. On the other hand, the problem with cross-talk which is perceived as a ghost, shadows or double contours can be minimised by controlling contrast of the image and its parallax. Previously, it was shown that the appearance of cross-talk increases with increase in contrast and parallax (Pastoor 1995). Moreover, cross-talk can be caused by device technical imperfections (e.g. if an active eyewear lens remains transparent for too long during each cycle) or incorrect head positioning (e.g. passive linear polarisation glasses, auto-stereoscopic screen). In this case an improvement in spectacle synchronisation or even appropriate instruction regarding head position should reduce the problem. In the experiment presbyopic participants reported less blurred and double vision than young (pre-presbyopic) participants. In relation to this observation it was pointed out that younger participants have more closely linked vergence-accommodation processes than presbyopic individuals and because of this pre-presbyopic people experience more vergence-and/or accommodation-related symptoms. The main limitation of these experiments is that individual differences in discomfort between 2D and 3D conditions was not analysed. The second weakness of these experiments is that there is no information about the stimuli used in the experiment other than the movie title and movie's running time. It is not known whether only positive, negative or both parallaxes were used in the movies. And so the size of vergence-accommodation conflict is not known.

The mismatch between the vergence and accommodation has been considered by many other researchers (Inoue & Ohzu 1997, Ukai & Kato 2002, Okada et al. 2006, Torii et al. 2008, Fukushima et al. 2009) in a context of accommodation discrepancy (accommodation overshoot). This issue is not analysed in this chapter but it is presented in detail in chapter 6.

2.2.3 Visually induced motion sickness

Another factor considered in the context of discomfort experienced during 2D and 3D stereoscopic stimulation is visual-vestibular conflict. Visual-vestibular conflict or sensory conflict may produce visually induced motion sickness (VIMS), which is a form of motion sickness produced when a stationary observer is exposed to moving visual images (Diels & Howarth 2009). When visual motion is unaccompanied by physical self-motion, the mismatch between the self-motion cues delivered by the visual system (i.e. vection) and the lack of coherent signals from the vestibular and somatosensory systems is considered as a primary causal factor of VIMS (Diels & Howarth 2013). Vection is defined as visually induced perception of self-motion (Tschermak 1931), and is believed to be a major factor explaining visually induced motion sickness characteristics (Bos et al. 2008). Under natural conditions vection is often felt by one who is sitting on a motionless train while watching another train moving nearby and in the widescreen cinema Howard (2012). In general, visual movement can be perceived as either object motion or self motion. When the environment appears to move, as in dynamic displays, we are more inclined to attribute the relative movement to ourselves instead of surroundings. On the other hand if we see individual objects or groups move with respect to us the perceived relative motion is due to object moving than our own movement (Diels 2008).

The sensory conflict theory is not the only theory, which tries to explain the origin of VIMS. Other theories, which have been put forward in reference to VIMS, are postural stability theory and eye movement theory. The postural stability theory states that motion sickness results from prolonged instability in the control of posture (Riccio & Stoffregen 1991). According to this theory poor postural control is not only a result of VIMS, but also precedes onset of VIMS (Stoffregen & Smart Jr 1998, Reed-Jones et al. 2008)). In term of the eye movement theory which was proposed by Ebenholtz (1992) optokinetic nystagmus (OKN) evoked by moving visual patterns can innervate the vagal nerve, and such innervations lead to VIMS. For the purpose of this thesis, the work presented will only consider motion sickness induced by conflicting inputs which is the most widely accepted theory of motion sickness.

People who experience VIMS suffer from symptoms such as: dizziness; nausea; headache; drowsiness; sweating; salivation, and in some cases, vomiting (Wilson 1996, Lawson et al. 2002, Howarth & Hodder 2008, Ujike et al. 2008, Bos et al. 2008, Kennedy et al. 2010, Häkkinen et al. 2006). These symptoms have been reported in many virtual environments (VE), such as fight and automobile simulators (Stoffregen et al. 2000, Lawson et al. 2002), moving-rooms (Stoffregen & Smart Jr 1998, Smart et al. 2002), head-mounted displays (HMD) (Howarth & Costello 1997, Hill & Howarth 2000, Patterson et al. 2006, Merhi et al. 2007, Sharples et al. 2008) or while viewing optic flow patterns (Diels & Howarth 2007, 2013). The same symptoms have also been observed outside the laboratory environment. In 2003 an incident of VIMS was reported at a junior high school in Japan. Thirty-six students out of two hundred and ninety four, who watched a 20 minutes movie displayed on a large screen were taken to the hospital because of VIMS symptoms. The movie shown was shot with a handheld video camera, and was characterised by various types of image motion and vibration. The incident described by Ujike et al. (2008) is a strong argument that the motion and vibration in visual content can cause adverse symptoms among people exposed to it.

With an increase of popularity of video game systems (e.g. X-box, PlayStation, PCs) many researchers have asked whether symptoms related to VIMS occur when commercially available games are used. Stoffregen et al. (2008), Dong et al. (2011), Chang et al. (2012) assessed the incidence and the severity of motion sickness during the playing of "off-the-shelf" console video games. The incidence of motion sickness in their experiments was assessed at the end of exposure to the stimuli. Each participant verbally stated their motion sickness status (yes/no). Based on this statement, participants were divided into "Sick" and "Well" groups. Symptom severity was measured using a Simulator Sickness Questionnaire (SSQ) before and after exposure to the stimuli. In these experiments the incidence of motion sickness varied between 42.3% and 61%. Interestingly, in studies conducted by Stoffregen et al. (2008), Dong et al. (2011), Chang et al. (2012)) the statistically significant differences in SSQ score (pre exposure - post exposure change) were found in a group who reported motion sickness ("Sick"group) as well as in a group who did not report motion sickness ("Well"group). This suggests that the total sickness score in the SSQ questionnaire should not be considered as an indicator of motion sickness because it also assesses symptoms which can be induced by different reasons (e.g. an increase of total sickness score can be the result of a general discomfort or eyestrain). In other words playing 2D computer game can give a rise to symptoms not necessarily related to motion sickness.

Anecdotal complaints of visual and nausea symptoms after the re-introduction of the 3D stereoscopic format to the cinema raised questions about potential adverse effects during the viewing of 3D stereoscopic stimuli. From an academic perspective, the reasons for reported adverse effects remains unresolved.

As discussed earlier symptoms related to VIMS have been reported when 2D stimuli were used. Ujike & Watanabe (2011) investigated whether 3D stereoscopic stimuli are more effective in inducing VIMS symptoms than 2D stimuli. In the experiment thirty four adults watched visual stimuli for ten minutes in either a 2D condition or 3D condition. The computer graphics simulated travel along the streets with various types of image motion. Before and after each session the SSQ was completed by participants. In addition, viewing comfort was assessed (on a five point category scale) each minute while viewers watched the visual stimulus. From the results of SSQ, calculations were made for three clusters (nausea, oculomotor, disorientation) and a total score. The results showed a greater increase in the 3D condition than the 2D condition, but statistically significant differences between 2D and 3D conditions were only found in the average score for nausea. However, it is not clear whether the symptoms score increased in this sub-group due to nausea or due to an increase score for different symptoms listed in this cluster. For example, discomfort caused by an uncomfortable chair or uncomfortable 3D glasses has an influence on the overall symptoms score in the nausea cluster (see table 2.1). Also, average values of comfort showed that discomfort increased more in the 3D condition than the 2D condition. In this case however it is not known whether the discomfort is related to vision, headache or motion sickness symptoms. The same visual stimulus used by Ujike & Watanabe (2011) was also used in an experiment conducted by Naqvi et al. (2013). In this study nineteen participants watched stimuli in a 2D condition and twenty participants watched stimuli in a 3D condition. The reported symptoms were higher for the 3D condition than for the 2D condition. Statistically significant differences between these two conditions were found in the average scores for nausea, dizziness and the total score. However, in this experiment similar problems occurred in term of sub-group results. These results could be influenced by symptoms unrelated to the cluster name. Furthermore in this case symptom measurement before the trial was not performed. Thus there is not a clear picture whether these symptoms were induced during the viewing of 3D stimuli or whether participants experienced symptoms prior to the onset of the experiment. In the experiments conducted by Ujike & Watanabe (2011) and by Naqvi et al. (2013) similar numbers of participants took part. However when the SSQ was completed only at the end of the session, more statistically significant differences were found than in an experiment where the SSQ were completed before and after the session (Ujike & Watanabe 2011). The differences between these two experiments show how important the choice of method of symptom assessment is (questionnaire completed only at the end of the session vs questionnaire completed before and after the session).

Table 2.1: SSQ symptoms and clusters. The SSQ questionnaire contains 16 symptoms (see left column). Symptoms are scored on a 4 point scale and then added within each cluster (N - Nausea, O - Oculomotor, D - Disorientation). The scores for each cluster are calculated from the sum of symptoms by conversion formulas provided in Kennedy et al. (1993). A total symptom score is calculated by summing the three clusters and applying conversion formula provided in Kennedy et al. (1993)

SSQ symptoms	Clusters		
	N	**O**	**D**
General discomfort	✗	✗	
Fatigue		✗	
Headache		✗	
Eyestrain		✗	
Difficulty focusing		✗	✗
Increased salivation	✗		
Sweating	✗		
Nausea	✗		✗
Difficulty concentrating	✗	✗	
Fullness of head			✗
Blurred vision		✗	✗
Dizzy (eyes open)			✗
Dizzy (eyes closed)			✗
Vertigo			✗
Stomach awareness	✗		
Burping	✗		

N - Nausea, O - Oculomotor, D - Disorientation
✗ - indicates which cluster each symptom belongs to

VIMS symptoms (e.g.dizziness, nausea) before and after viewing stimuli were assessed in the experiments conducted by Yang & Sheedy (2011) and Yang et al. (2012). In both cases symptoms related to motion sickness were reported more frequently in the 3D condition than in the 2D condition. Furthermore in the later experiment it was shown that the perception of the object moving and the perception of oneself moving through space was higher in the 3D condition than the 2D condition. Yang et al. (2012) also noted that women reported greater motion sickness symptoms than men. Findings presented by Yang & Sheedy (2011) and Yang et al. (2012) indicate that VIMS is an important factor in terms of further understanding discomfort experienced by participants whilst viewing 3D stimuli. However, as mentioned earlier these experiments did not present individual differences between VIMS reported in 2D and 3D conditions.

2.2.4 Stereoscopic image distortion

The image presented to each eye during 3D stereoscopic stimulation should ideally reproduce the stimulus provided in the real word. However, imperfections of the binocular image pair can occur. In the literature several types of stereoscopic distortion have been described, these include:

- keystone distortion - this is caused by convergence (toed-in)[1] camera configuration. In this case the camera image sensors are facing towards slightly different planes (IJsselsteijn et al. 2006). This generates an asymmetric image and results in vertical parallax. The magnitude of vertical parallax is greater at the corners of the image, decreasing convergence distance and decreasing focal length. This type of distortion can be avoided by using a parallel camera configuration (Woods et al. (1993)). Vertical parallax can also be induced if there is vertical misalignment between cameras.

- depth plane curvature - this is a side effect of toed-in camera configuration and is linked with keystone distortion. Images at the corner of the image appear further away from the viewer than images at the centre of the image.

- shear distortion - this occurs in a stereoscopic display that allows only one correct viewing position (IJsselsteijn et al. 2006) e.g. autostereoscopic display). Sideways movements of the viewer result in the object in front of the screen appearing to move in the same direction as the viewer; and the object behind the screen appearing to move in the opposite direction to the viewer. In this case the object distance can be wrongly perceived and a false motion impression can be induced.

- cross-talk - this is perceived as ghost, shadow or double contours. It can be caused by: imperfect image separation techniques by which the right-

[1]toed-in - a point of convergence is chosen by joint inward rotation of the left and right cameras

eye view leaks through to the left-eye view and vice versa; presentation (a problem with the display), device defect (e.g. active eyewear lens remains open too long during each cycle) or incorrect head positioning (e.g. in linear polarisation technique, auto-stereoscopic display). Pastoor (1995) showed that cross-talk increases with increasing contrast and parallax[1].

In a study conducted by Kooi & Toet (2004) twenty four participants viewed a stationary 3D stimulus which was subject to 35 different transformations. The modifications which were applied to the stimulus included: rotation, scaling and deformation operations (some of the stimuli were combinations of two types of modification). The stimuli were presented to each participant in three steps: step one - 3.5 s presentation of the original stimulus; step two - a short break; step three - 5 s presentation of manipulated stimulus. Following this task, participants were asked to compare the modified stimulus with the original stimulus using a 5 point scale. Kooi & Toet (2004) concluded that the distortions which affect viewing comfort the most are: cross-talk and blur. However, it has been questioned whether 5s (the stimulus exposure time used in their study) is long enough for discomfort to develop in response Howarth (2011).

Vertical parallax can also be induced when the viewers head is not upright (e.g. if a viewer whilst viewing a 3D movie rests their head on their partners shoulder). This issue was analysed by Kane et al. (2012) who hypothesised that the vertical vergence eye movements required to fuse stereoscopic images when the head is rolled cause visual discomfort. To test this hypothesis a head roll was simulated (i.e. the stimulus was rotated rather than moving viewers head, to allow better control). The experiment consisted of three subsections where the unrolled stimulus (0° of stimulus rotation) was compared with rolled stimuli (10°, 20°, 30° of stimulus rotation). Each stimulus was presented for one minute and after that participants completed a comparison questionnaire. The questionnaire included seven questions (e.g. which session was more uncomfortable for your eyes?), which were assessed by participants on a 9 point scale (where 5 indicated that the sessions were equally uncomfortable). Data analysis found that viewing 3D stereoscopic stimulation when the head was rolled (i.e. vertical parallax was

[1]parallax - distance between two matching parts of stereoscopic image pair

present) was more uncomfortable than when the head was upright (no vertical parallax). On average visual discomfort increased with the amount of stimulus roll and with the magnitude of on-screen horizontal disparity. The key problem with this experiment is that only average scores of discomfort are shown. The average data do not indicate how many participants experienced more discomfort when the modified stimulus was used. This way of presenting data masks the true number of participants affected by the modified stimulus. As the response to the presented stimulus (not the stimulus itself) is the cause of discomfort, individual ability to fuse vertically separated images will contribute to different levels of discomfort.

2.2.5 Limitations of existing research

The literature presented has shown that there is a general lack of consistency in methods for assessing discomfort. Different researchers have used different methods to assess the effect of watching 2D and 3D stimuli and some of the methods have been criticised for a number of reasons. Furthermore, in some experiments, artificial (laboratory - created) stimuli were used. In others, commercially available games and movies were presented to participants. Utilisation of a movie or game without any objective knowledge of its parameters (e.g. positive parallax, negative parallax, vertical parallax) makes it impossible to assess the actual impact of content - specific factors on the participant. Moreover, the lack of information about the movies' parameters makes comparison between the results of different experiments impossible (e.g. some movies may contain only positive parallax, while others may contain positive and negative parallax). The advantage of the laboratory created stimuli lies in the fact that all of the parameters are known and under the control of the experimenter. However, artificial stimuli do not reflect the whole spectrum of effects that are observed in commercially available games and movies. Also the level of engagement of participants is not the same as for commercially available games/movies.

To sum up the main methodological limitations of previous studies are presented below:

- In many experiments only post-session data were collected. This approach does not give a clear picture whether symptoms were induced during the viewing of 2D or 3D stimuli or whether the participant experienced symptoms at the onset of the experiment. This approach was criticised by Howarth (2011) and assessing symptoms in this way was recognised as a methodological error of Visual Display Unit (VDU) users in the past (Howarth & Istance 1985). However this problem is still observed in more recent studies (Yano et al. 2004, Hoffman et al. 2008).

- As all potential causes of 2D discomfort are also present during the watching of 3D stimuli, assessment of 3D discomfort should, in fact, take into account the difference between 2D and 3D discomfort. So far only the discomfort differences between groups have been analysed (e.g. group A - watched 3D stereoscopic stimuli, group B - watched 2D stereoscopic stimuli), but not individual differences between 2D and 3D discomfort (e.g. Ujike & Watanabe (2011), Yang et al. (2012). Even if the same participants watched 2D and 3D stereoscopic stimuli (e.g. Yang & Sheedy (2011)) individual differences in discomfort between these two conditions have not been taken into consideration.

It is important to analyse change of discomfort experienced in 2D and 3D conditions by each of participants. Comparison of a 2D and 3D group average discomfort will mask significant changes that can occur in the visual function of individual participants.

- Another drawback of group averaging is that this way of presenting data hides the actual number of participants affected by the stimulus. For example some participants could experience discomfort whilst others did not, but by averaging the data the appearance is that all did. At this point it should be highlighted that it is not the stimulus itself which produces discomfort, but the response to it. As the response to a presented stimulus may vary between participants the amount of reported discomfort is also likely to vary. This drawback can be simply eliminated by presenting distribution of the data (e.g. a histogram), which provides information on how differently different people were affected. However many researchers missed this information.

- In many studies (e.g. Yang & Sheedy (2011), Yang et al. (2012) participants were exposed to commercially available movies or games, however in these experiments there is no information about the size of horizontal parallax utilised in the movies and therefore no information about the size of vergence-accommodation mismatch. Furthermore, if the movie is not CGI (Computer-generated imagery) stimuli it is likely that vertical (unwanted) parallax is present.

  Some of the movies also contain a positive parallax which exceeds the viewer's inter-pupillary distance. The lack of information about the magnitude of parallaxes (horizontal and vertical) in the movies prevents this being excluded as a reason for discomfort whilst viewing 3D stereoscopic stimulation. It can be presumed that the effect of the magnitude of parallaxes used in the movies will not be equal for each participant as it will be dependant on viewer's capacity for divergence, convergence and to fuse vertically separated images.

- To asses the side effects of watching 2D and 3D movies the SSQ (Simulator Sickness Questionnaire) was widely used. However, several problems have been noted in terms of the use and interpretation of this questionnaire. For example Clemes (2004) commented that the cluster names in the SSQ may produce confusion and lead to incorrect assumptions that participants experience problems related to the name of the cluster. Similar observations were made in terms of total SSQ score. Chang et al. (2012) pointed out that the SSQ assesses many symptoms which can occur in the absence of motion sickness (e.g. headache, eyestrain, fatigue) which may produce an increase in total sickness scores when in fact participants do not experience motion sickness.

2.2.6 Improvement of current knowledge

As discussed above there are many limitations in previous studies. Because of these limitations, only an association and not causation of the problem can be shown. For a better understanding of the effect of 3D stereoscopic stimulation on visual response and visual discomfort, several hypotheses are tested in this thesis. Literature specific to each of the tested hypotheses is presented separately at the beginning of each chapter.

Chapter 3

Heterophoria adaptation during the viewing of 3D stereoscopic stimuli

Purpose: The current chapter aims to examine subjective and objective visual change as a result of playing a computer game under 2D condition versus 3D condition. The subjective indicator of visual change used here was a pre- and post- questionnaire, and the objective indicator of visual change was a change in horizontal phoria measured before and after playing the game.

In this experiment two hypotheses were tested. The first hypothesis was that the viewing of 3D stereoscopic stimuli, which are located geometrically beyond the screen on which the images are displayed, would induce exophoric heterophoria (phoria) changes (adaptation). The second hypothesis was that participants whose phoria changed as a consequence of adaptation during the viewing of the stereoscopic stimuli would experience less visual discomfort than those people whose phoria did not adapt.

3.1 Introduction

Most adults have two eyes, separated by between 50 and 75 mm (Dodgson 2004). A consequence of this separation is that each eye has its own view of an object, and slightly different images fall on the two retinas. In order for us to have a unified, single view of the world the neural signals from the two eyes are combined. In the normal eye, the image of a fixated object will fall on the two foveas, and since the foveas both have the same perceived direction the object will be seen as single. Objects located elsewhere will also be seen as single when the eyes move to fixate them, and thus single vision is achieved by both sensory and motor neural activity. Overall, stereoscopic vision is a result of disparity information delivered to the visual system from two viewing positions in a natural scene.

To produce a 3D effect on a flat screen the disparity information has to be induced artificially. To achieve this condition two cameras produce an image of the same scene from slightly different positions. If the cameras are set up (adjusted) properly, only horizontal (not vertical) parallax[1] occurs on the screen. Positive parallax causes the object to appear behind the screen, and negative parallax causes the object to appear in front of the screen. Unlike the real world, a 3D stereoscopic display produces a stimuli to accommodation provided by the image on the screen, and a stimuli to convergence provided by geometrical location of the image. (Rushton et al. 1994, Ukai & Howarth 2008, Hoffman et al. 2008, Lambooij et al. 2009, Howarth 2011, Yang et al. 2012). The same situation, namely a change in the relation between the accommodation stimulus and the vergence stimulus, occurs when prism or decentered lenses are worn in front of the eyes Ramsdale & Charman (1988). The image of an object which is viewed through a base-out prism will be located geometrically closer than the object itself, and to see it singly will require increased convergence. Similarly, base-in prisms will produce an image located further than the object, requiring decreased convergence. In both cases the stimulus to accommodation remains the same with or without the prism.

When the sensory information is removed, for example when one eye is covered, the eyes will take up a position of rest (heterophoria) (Maddox 1893).

[1]Parallax refers to the separation of the left and right images on the screen.

Heterophoria equals the difference between the positions of the eye when fusion is prevented and when it is not allowed. Clinically it can be classified by the direction of the deviation of the eye under cover such as esophoria (turing of the eye inward from the active position when fusion is broken), exophoria (turning of the eye outward from the active position when fusion is broken). Heterophoria is not present when the position of the visual axes in the absence of stimuli to fusion is the same as the position of the visual axes in the active position and this condition is know as orthophoria (Millodot 2014). Figure 3.1 illustrates position of the eye under cover (fusion - free position) in orthophoria (a), esophoria (b), exophoria (c).

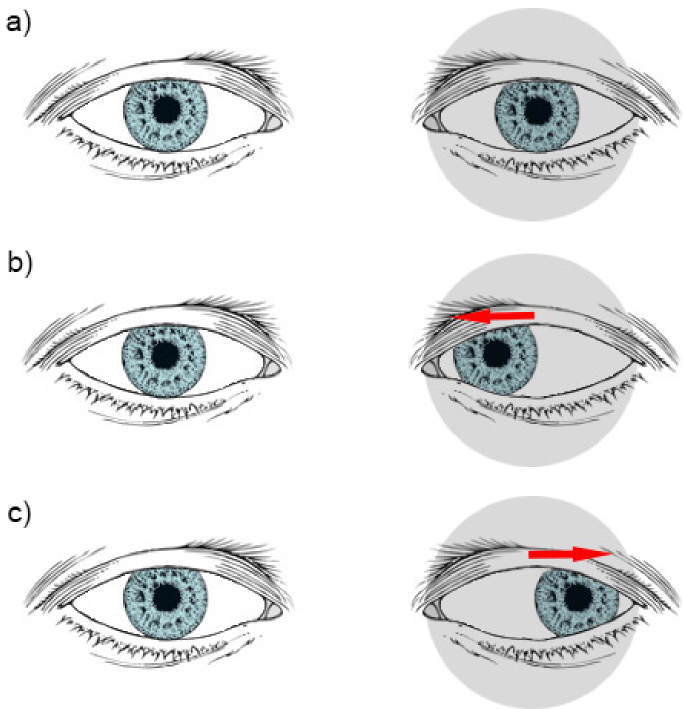


Figure 3.1: Classification of heterophoria deviation. Position of eye under cover in orthophoria, the left eye not moved (a), position of the eye under cover in esophoria, the left eye has deviated inward (b), position of the eye under cover in exophoria, the left eye has deviated outward (c).

The position of heterophoria is determined by a number of factors, both immediate and historical. The accommodation and vergence systems are neurologically linked (Maddox 1893, Fincham & Walton 1957) and so immediate changes in accommodation will alter the position of the eye under cover. When accommodation is steady, however, it is the past history of activity, which ultimately determines the position of the eye. This position can be altered over time, and this is commonly referred to as heterophoria (phoria) adaptation, prism adaptation, or vergence adaptation. The wearing of prisms will produce a change in heterophoria (Mitchell & Ellebrock 1955, Schor 1979, North et al. 1990, North & Henson 1992, Patel et al. 2003, Brautaset & Jennings 2005, 2006), as will the wearing of lenses (Schor 1979, North et al. 1985, Jiang et al. 2007, Sreenivasan et al. 2009), and sustained fixation on a physical target (Ehrlich 1987).

Several studies have shown that phoria adaptation can be reduced in subjects with vergence disorders. North & Henson (1992) compared the ability to adapt to prism - induced phorias in three groups of subjects: those with normal binocular vision, those with abnormal binocular vision and/or asthenopia (selected from the University of Wales' Orthoptic Clinic) and with subjects who received orthoptic treatment (attending the Orthoptic Department of the Bristol Eye Hospital). The normal binocular vision subjects presented a capability to adapt to near and distant prism-induced phorias. The majority of participants with abnormal binocular vision demonstrated reduced heterophora adaptation or no adaptation. Ability to adapt to prism-induced heterophoria improved for the group where subjects received orthoptic treatment (the orthoptic treatment took 8 weeks). Brautaset & Jennings (2005) showed that people with CI (convergence insufficiency[1]) have reduced and less complete adaptation to prisms. In their next experiment (Brautaset & Jennings 2006) showed that CI patients improve their ability to (perform) prism adaptation after oculomotor training (the home based orthoptic treatment lasted 12 weeks). Nilsson & Brautaset (2011) measured heterophoria adaptation to prisms at 40 cm and 6 m. They showed that subjects diagnosed with CE (convergence excess[2]) have reduced ability to adapt to prisms at both near and far fixation. Changes in adaptation were also found

[1] CI - a reduced ability to converge on near objects. Usually associated with a high exophoria at near and a relatively orthophoric condition at distance. It results in complaints of ocular fatigue, astenopia, headache, blur and occasional diplopia, which are observed with near work.

[2] CE - A high esophoria at near, associated with a relatively orthophoric condition at distance. It gives the same symptoms as CI.

after orthoptic treatment by Thiagarajan et al. (2010) (the orthophtic treatment lasted 2 weeks).

Winn et al. (1991) compared adaptation to induced heterophoria between presbyopic and prepresbyopic subjects. They found that older subjects had a significantly reduced adaptation to prisms compared with the younger group. However, these results were not confirmed by studies conducted by Rosenfield et al. (1995) who noted no significant correlation between heterophoria adaptation and age. Rosenfield (1997) explained that the difference between the results of these two studies may be caused by the differences in the age range of the subjects tested (Winn et al. (1994) tested participants up to 85 years of age, whereas Rosenfield et al. (1995) tested participants up to 65 years of age), and by the difference in methodology of studies (Rosenfield et al. (1995) used higher vergence demand than the earlier study.In terms of visual discomfort and phoria adaptation Howarth (1996) found that when viewing a screen for 15 min through low power prisms (< 4 prism dioptres) subjects showed prism adaptation without an accompanying change in discomfort, but when higher powered prisms (6 prism diopters) were employed some subjects reported an increase in discomfort. This is consistent with the expectation based on the Zone of Clear Single Binocular Vision (ZCSBV) (Howarth 2011).

The first question we asked in this study is whether the viewing of stereoscopic 3D images produces phoria adaptation in the same way as is seen when objects are viewed through a prism. The second question we asked relates to the link between adaptation and discomfort. It is reasonable to assume that vergence adaptation is an integral part of the normal visual system (Patel et al. 2003, Winn et al. 1994) and that people who are less adaptable could experience more binocular difficulties. With that in mind, we considered the possibility that heterophoria adaptation is a mechanism which serves to maintain clear binocular vision without excessive visual discomfort. We expected, therefore, that subjects in our experiment whose phorias did change as a consequence of adaptation during the viewing of the stereoscopic stimulus would experience less visual discomfort than people whose heterophoria did not adapt. To examine these issues we evaluated changes in comfort as well as adaptation over twenty minute periods, during which participants played a 3D stereoscopic computer game.

3.2 Methods

3.2.1 Procedure

Participants played a computer game on two occasions. On one the game was presented stereoscopically in 3D, and on the other it was in 2D. This latter condition acted as a control. Each condition was employed on different days, with half of the participants experiencing the 2D condition first, and the other half the 3D condition first. In each case the game was played for 20 min. Subjective symptoms and heterophoria were assessed both before and after the playing of the game, to allow for the evaluation of any changes.

3.2.2 Participants

Twenty people, all of whom were either staff or students at Loughborough University participated in the experiment. The only criterion to take a part in the study was stereoscopy vision, on which 3D stereoscopic technology depends. Participants were aged between 19 and 45 (mean age: 26.9 $\pm$ 7.2 years) and all had normal, or corrected to normal, vision. They all also had normal binocular vision, enabling them to fuse the two images produced by the game. All participants were fully informed of the procedure, and of their right to withdraw, in accordance with the study approval granted by the Loughborough University Ethical Committee and the tenets of Helsinki.

3.2.3 Stimulus

The game chosen was entitled Ziro (by Kokakiki; www.kokakiki.com) which was displayed on an Acer GD245HQ computer screen using an NVIDIA GeForce GTX580 graphics card (www.nvidia.com). In this game dice are moved around a board. Two conditions were employed, one with a normal 3D stereoscopic view, and the other (control) with a 2D view.

This game was selected for two reasons. First, the game has only positive parallax (uncrossed retinal disparity) and geometrically all portions of the image are either in the plane of the screen or behind it. Second, the game does not produce the sensation of vection so it is unlikely to produce visually-induced motion sickness (VIMS) which has been suggested as one of the causes of complaints by people watching 3D stereoscopic films (Howarth 2011, Yang & Sheedy 2011).

In the 3D condition the parallax between images was fixed at 48 mm. The depth of the dice (which were all on the same plane) was 150 cm behind the screen representing a depth of 9.6 prism dioptres beyond the plane of the screen for a testing distance of 50 cm. To produce the stereoscopic sensation of depth, images for the right and left eyes were alternated on the screen at a refresh rate of 120 Hz. This display was viewed through active shutter glasses (www.nvidia.com). The lenses in these glasses darken and lighten alternately in synchrony with the computer screen, providing a separate image for each eye at a refresh rate of 60 Hz (Figure 3.2).

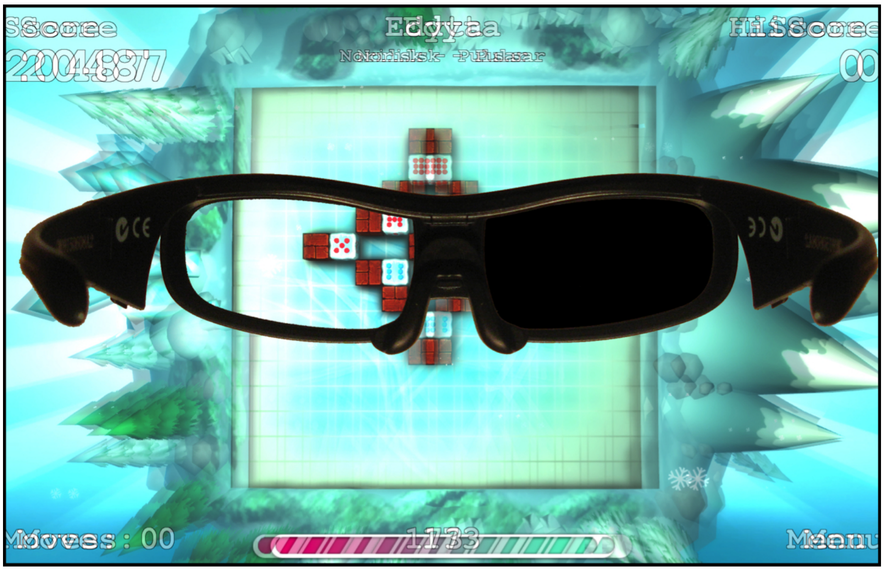


Figure 3.2: Shutter glasses working principle: to the naked eye the screen is showing two overlapping images, but these are actually alternating rapidly and the synchronous lightening and darkening of the lenses allows each eye to see the image designed for it.

3.2.4 Heterophoria measurement

Horizontal near heterophoria was measured using a modified Thorington technique (Rainey et al. 1998, Escalante & Rosenfield 2006) at a distance of 50 cm, which was the distance used when playing the game. Previous studies have shown that the modified Thorington technique provides good repeatability (Rainey et al. 1998, Escalante & Rosenfield 2006). The magnitude of the phoria was quantified using a tangent scale which consisted of a horizontal row of numbers, each of which is 10 mm apart (i.e. equivalent to 2Δ at a distance of 50 cm), separated by dots to produce a 1Δ scale. Each of the numbers was approximately 5 mm high. The amount of deviation was measured in prism diopter [Δ] (see figure 3.3).

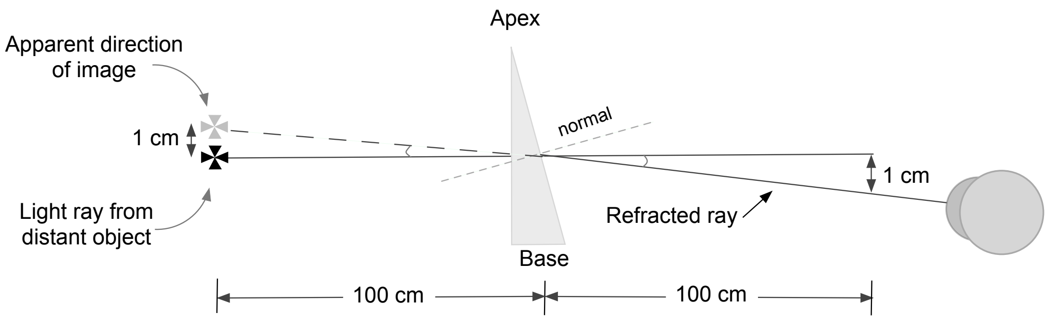


Figure 3.3: Diagram demonstrating definition of prism dioptre. One prism dioptre shifts the light by 1.0 cm in a distance of 100 cm from prism. To refixate the shifted image, the eye must rotate 0.57°

During measurement a red Maddox rod[1] was introduced in front of the right eye, and a white light positioned below the screen then produced the appearance of a vertical red line. The left eye saw the scale, and the participant was instructed to report where the line crossed the scale (see figure 3.4).

[1] A Maddox rod consists of a series of glass or plastic rods mounted in a trial lens ring. Each rod acts as a strong convex cylindrical lens and these convert the image of a spot of light into a line of light perpendicular to the axis of the rod.

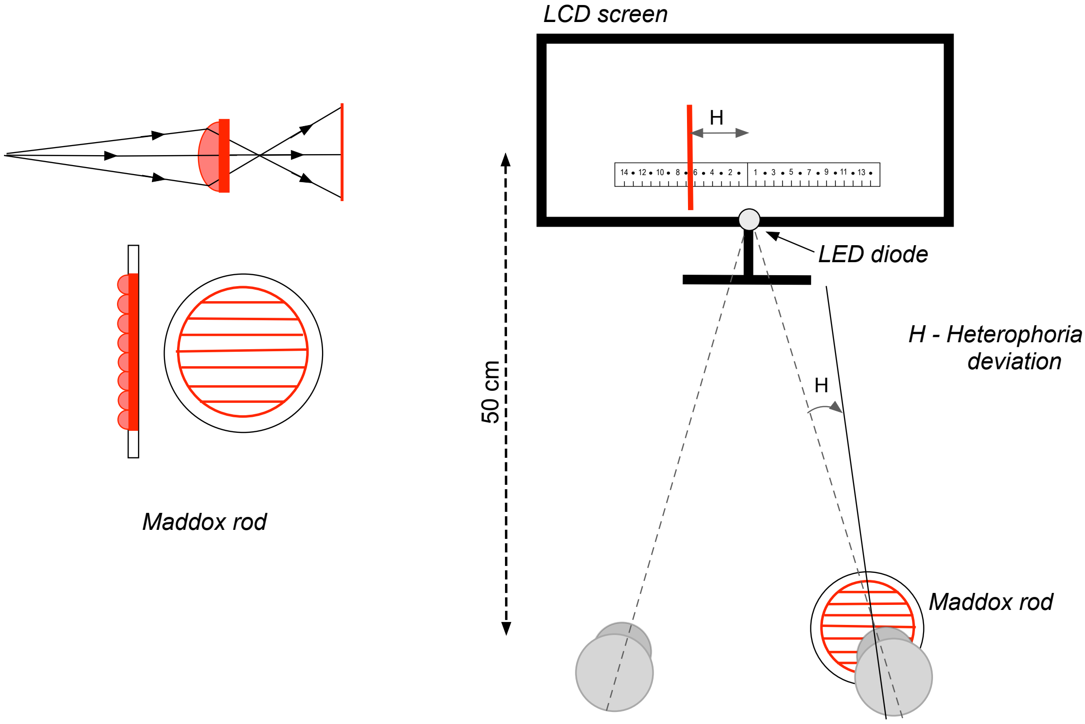


Figure 3.4: Schematic drawing of the apparatus.

Two precautions were employed during this process. First, to avoid confusion, the numbers on the exophoric side of the scale were even, whilst those on the esophoric side were odd. Second, to avoid learning effect bias during heterophoria measurements the two different scales shown in (figure 3.6) were presented to participants (a) before and (b) after the trial. The second of these (b) had six added to each value shown in (a). This precaution was taken to ensure that the responses were not influenced by memory of the value provided earlier, and the true value was obtained subsequently by simply subtracting six from the number reported. A chin rest and brow bar were employed to keep the participants head in the correct position.

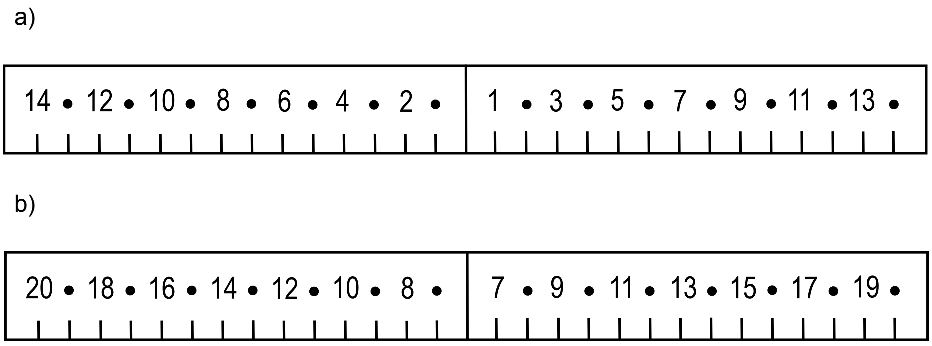


Figure 3.5: Heterophoria measurement scales. To avoid the participants being influenced by their previous result, the scale which was used second (b) had 6 added to each value of (a) (and 6 was subsequently subtracted during the data analysis).

Interpretation of appearance of a red line when the eyes are dissociated by the use of a Maddox rod are schematically summarised in figure 3.6.

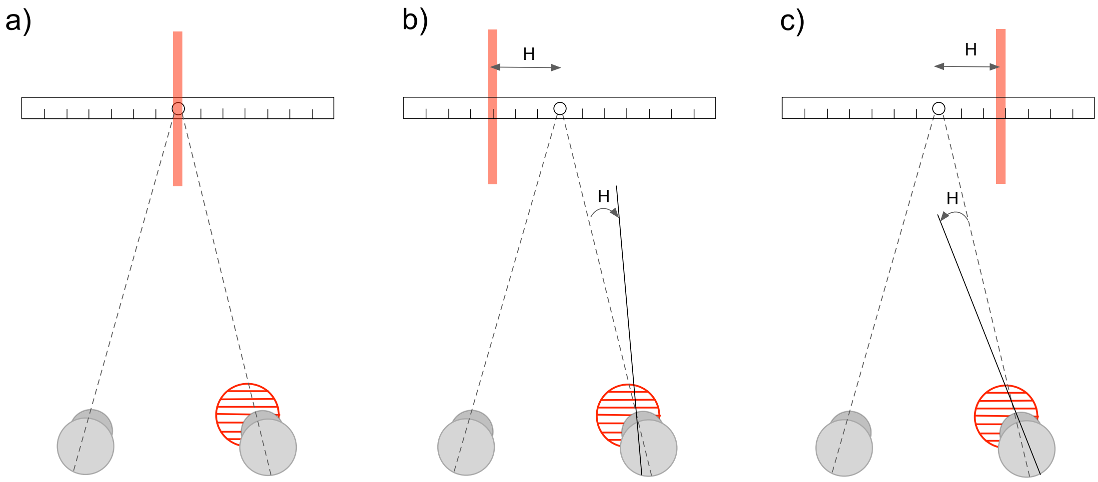


Figure 3.6: A Maddox rod in testing position for horizontal heterophoria a) - the line passes through the spotlight; the patient has no heterophoria, b) - the line is to the left of the spotlight; the participant has an exophoria, c) - the line is to the right of the spotlight; the participant has an esophoria.

3.2.5 Symptom measurement

To evaluate visual discomfort a questionnaire based on a design by Howarth & Istance (1985) was used (see table 3.1). with zero representing absence of the symptom. During analysis the first eight questions were considered as priming questions, which allowed the person to integrate the symptoms themselves and to then produce a single number which provided an overall rating of their general visual discomfort (Q:9). This approach has been found to be more sensitive than analysing the responses to individual questions (Howarth et al.).

Table 3.1: Symptom Questionnaire

		N	**SL**		**M**		**S**	
1	Do your eyes feel tired ?	0	1	2	3	4	5	6
2	Are your eyes sore or aching ?	0	1	2	3	4	5	6
3	Do your eyes feel irritated ?	0	1	2	3	4	5	6
4	Are your eyes watering or runny ?	0	1	2	3	4	5	6
5	Do your eyes feel dry ?	0	1	2	3	4	5	6
6	Do your eyes feel hot or burning ?	0	1	2	3	4	5	6
7	Does your vision feel blurred ?	0	1	2	3	4	5	6
8	Do you have double vision ?	0	1	2	3	4	5	6
9	Do you have any feeling of general visual discomfort ?	0	1	2	3	4	5	6

N - none, SL - slight, M - moderate, S - severe.

3.2.6 Data analysis

All data were analysed using SPSS Statistica 19 (www.ibm.com / SPSS Statistics). A Shapiro - Wilks test was used to evaluate the normality of the heterophoria changes, and as none were found to be outside the required limits the use of Students t - test for dependent variables was appropriate. The discomfort data were treated non - parametrically, using a Wilcoxon signed rank test and the relationship between each heterophoria change and discomfort change was tested using Spearmans correlation test.

Table 3.2: Test of normality

Heterophoria	Shapiro Wilk test (p)
2D heterophoria pre	0.105
2D heterophoria post	0.064
2D heterophoria difference	0.081
3D heterophoria pre	0.052
3D heterophoria post	0.303
3D heterophoria difference	0.483

if: $p < 0.05$ distribution is abnormal, $p > 0.05$ distribution is normal.

3.3 Results

3.3.1 Heterophoria

Following the viewing of the 2D stimuli, heterophoria changes were observed in both an eso (five subjects) and an exo (eight subjects) direction, whilst the remaining seven participants showed no change. The mean heterophorias were in the exo direction, 3.70 (S.E. = 0.83) and 4.20 (S.E. = 1.04) in pre and post stimuli, respectively (figure 3.7). The small exophoric shift over the trial for the group as a whole was not statistically significant ($p = 0.16$, df = 19; t - test).

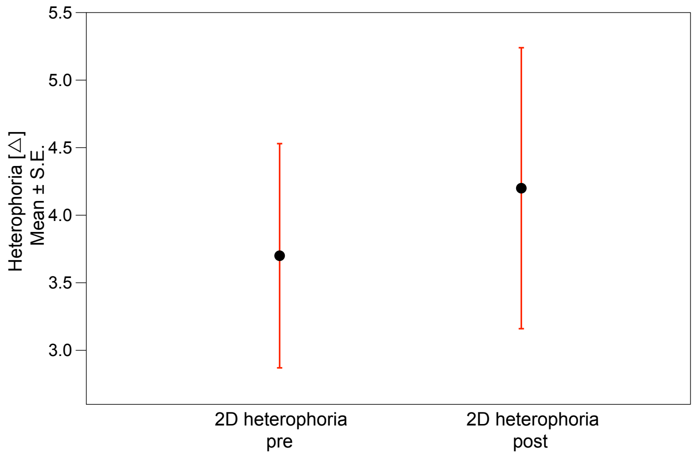


Figure 3.7: Mean heterophoria before and after 2D stimuli. Error bars indicate ± 1 S.E.

Following the viewing of the 3D stimuli, heterophoria changes were again observed in both an eso (four subjects) and an exo (13 subjects) direction, whilst the remaining three participants showed no change. The mean heterophorias were in the exo direction, 4.55 (S.E. = 0.77) and 6.05 (S.E. = 0.83) in pre and post stimuli, respectively, and the change seen over these trials was statistically significant ($p = 0.007$, df = 19; t - test) (figure 3.8).

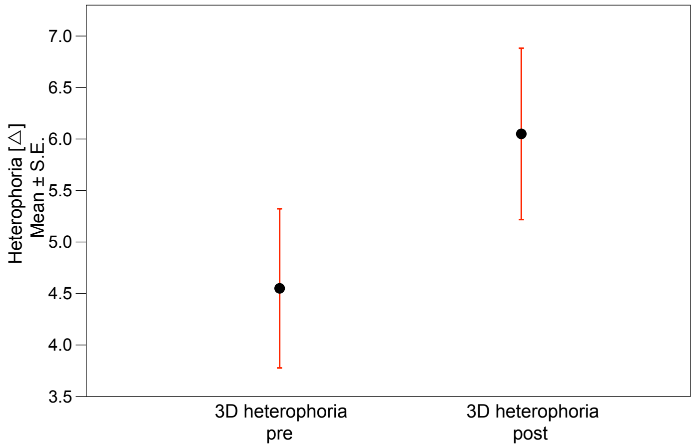


Figure 3.8: Mean heterophoria before and after 3D stimuli. Error bars indicate ± 1 S.E.

Figure 3.9 shows the change in heterophoria for 2D conditions (left), and 3D conditions (middle), and the difference between them (right). The increased exophoric change in the 3D condition, in comparison with the 2D condition, was statistically significant ($p = 0.035$, $df = 19$; t - test).

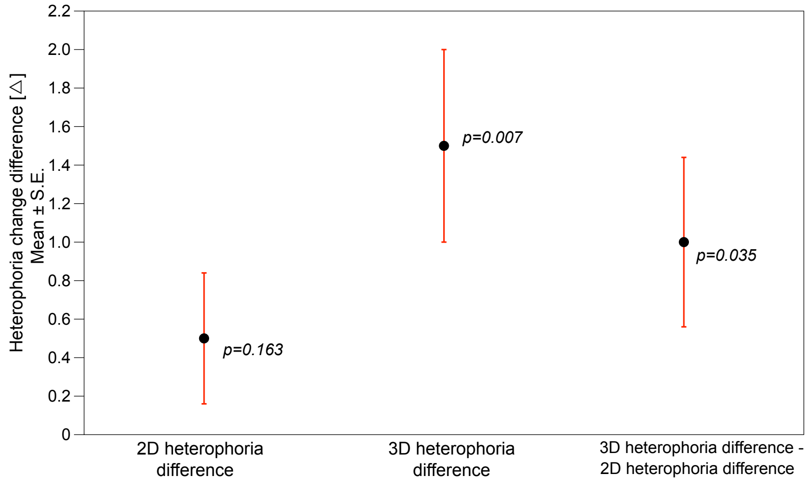


Figure 3.9: Mean change in heterophoria for 2D conditions (left), and 3D conditions (middle), and the difference between them (right). Error bars indicate ± 1 S.E.

3.3.2 Discomfort

Following the playing of the game in the 2D condition, half of the participants (10 people) reported no difference in general visual discomfort from that reported before playing it. However, four people reported a slight (1 scale point) increase in general visual discomfort, four reported a moderate ($>$ 1 scale point) increase in general visual discomfort (figure 3.10). Interestingly two participants reported decrease in visual discomfort. This can be explained by random variation in the data. An alternative explanation for these findings is that TV is watched for pleasure and relaxation. For example we had a student who came to participate in experiment before an exam as he wanted relax before it. Overall the values of the discomfort medians were 0.0 (IQR = 1.0) and 1.0 (IQR = 2.0) in pre and post stimuli, respectively. This increase was significant (p = 0.032, df = 11; Wilcoxon).

There was no significant correlation between heterophoria change and discomfort change (r_s = - 0.14, p = 0.56; Spearmans correlation test). These results are presented in the top panel of figure 3.11, which shows scatter plots of change in heterophoria and change in discomfort. Eight of the participants reported the same level of general visual discomfort before and after playing the game in 3D stereoscopic mode. Seven people reported a slight (1 scale point) increase in general visual discomfort, five reported a moderate ($>$ 1 scale point) increase in general visual discomfort and

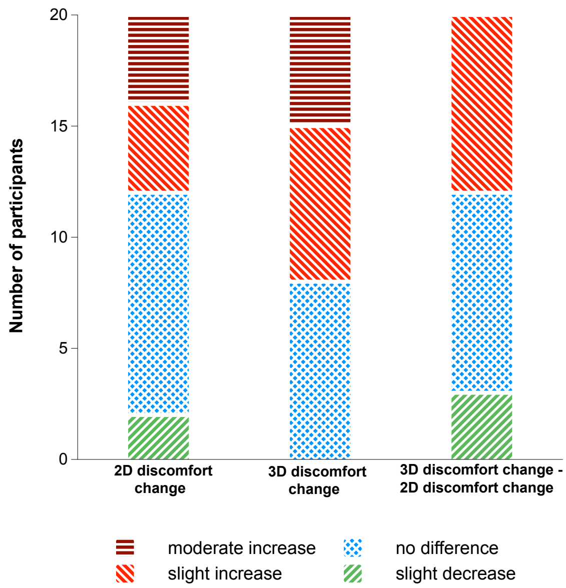


Figure 3.10: Changes in general visual discomfort for 2D condition (left), 3D condition (middle), and the difference between them (right).

no - one reported a decrease (figure 3.10). The values of the discomfort medians were 0.0 (IQR = 1.0) and 2.00 (IQR = 2.0) in pre and post stimuli, respectively. This overall increase was significant (p = 0.002; df = 12; Wilcoxon). There was no significant correlation between heterophoria change and discomfort change (r_s = - 0.04, p = 0.85; Spearmans correlation test). These results are shown in the middle panel of figure 3.11.

Any causal factors of discomfort unrelated to the stereoscopic aspects of the 3D displays should be present in both the 2D and 3D sessions. Consequently any difference between the amounts of discomfort reported in the two conditions will be either because of the disparity present, or else through random variation. Of the 20 participants, eight showed a greater amount of discomfort in the 3D condition and twelve did not, three of whom showed a lesser amount (figure 3.10). The increased discomfort change in the 3D condition in comparison with the 2D condition was statistically significant (p = 0.031, df = 10; Wilcoxon). There was no significant correlation between heterophoria change and discomfort change (r_s = 0.03, p = 0.90; Spearmans correlation test), as seen in the bottom panel of (figure 3.11).

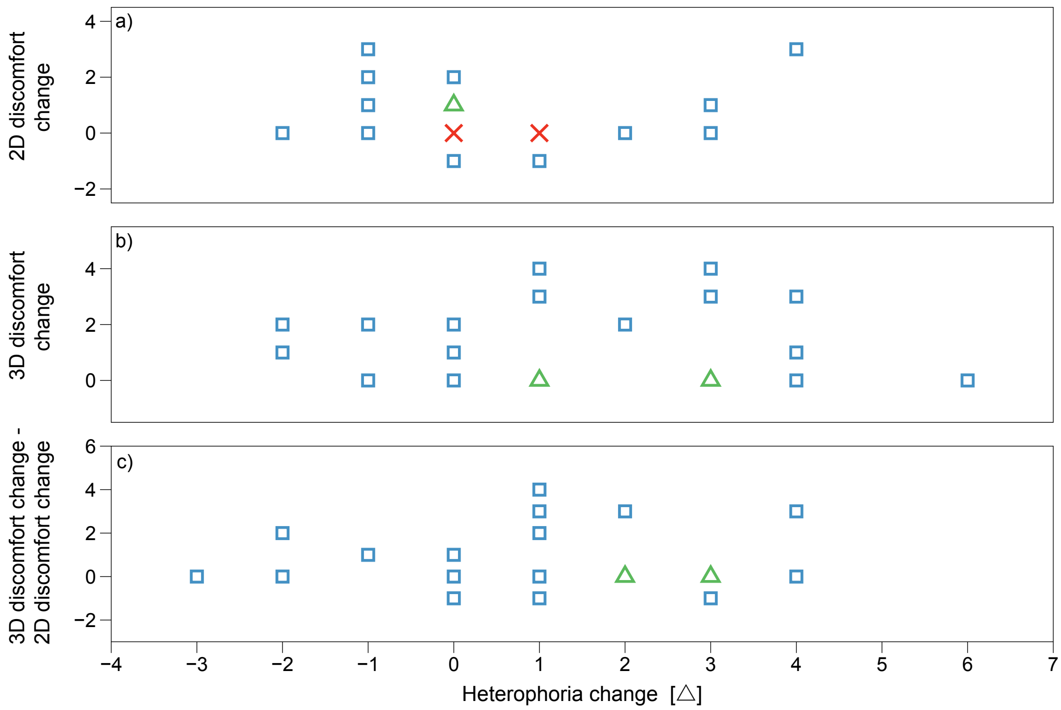


Figure 3.11: Visual discomfort and heterophorias. 2D condition (top) 3D stereoscopic condition (middle) and the difference between these (bottom). Symbols: square - one participant, triangle - two participants, cross - three participants.

3.3.3 Discomfort and heterophoria

If we group participants according to the difference in discomfort change between the two conditions (figure 3.12) we can dichotomise them as those who did (Group 1) and those who did not (Group 2) perceive a greater change in discomfort in the 3D stereoscopic condition than in the 2D condition. If we then examine the difference between the groups in a number of aspects of their heterophoria, we find no significant difference between the groups (table 3.3).

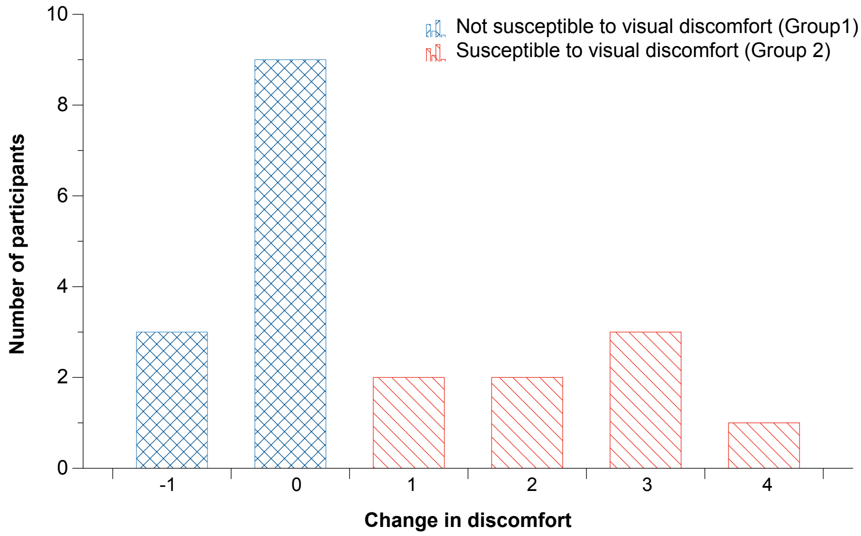


Figure 3.12: The number of participants showing each amount of difference in change in discomfort between the 2D and 3D conditions.

Table 3.3: Category classification for visual discomfort score change. The degree of freedom for each category is 18

	Susceptible to visual discomfort		Not susceptible to visual discomfort		Independent t-test
	Mean	S.E	Mean	S.E	p sig.(2-tailed)
Heterophoria 3D change - 2D change	0.75	0.65	1.17	0.61	0.66
Initial heterophoria 2D	4.88	1.55	2.92	0.90	0.26
Initial heterophoria 3D	5.13	1.67	4.17	0.71	0.61
Final heterophoria 2D	5.38	1.78	3.42	1.26	0.37
Final heterophoria 3D	6.38	1.59	5.83	0.95	0.76
Change in heterophoria 2D	0.50	0.60	0.50	0.44	1.00
Change in heterophoria 3D	1.25	0.75	1.67	0.68	0.69

3.4 Discussion

We have tested the hypothesis that the viewing of a stereoscopic 3D image located geometrically 9.6 prism dioptres further away than the screen on which the images are displayed will induce (exophoric) heterophoria adaptation, and found this to be the case. In order to maximise our chances of detecting heterophoria adaptation, we chose to have our participants play a computer game in which all disparities present were uncrossed, and of the same magnitude. The image we used was placed at a fixed distance behind the screen, producing a stimulus to the visual system similar to that which would be seen were the screen to be viewed through base-out prisms (which would be expected to produce prism adaptation of the heterophoria). In the conducted experiment four out of twenty participants experienced esophoria adaptation after viewing a 3D stereoscopic image. It is most likely this reflects noise in the data therefore this observation is considered as not significant. If we take the entire group into account the effect is significant in the exophoric direction (as expected).

In considering this result in the context of the eyes' response to 3D stereoscopic films and television, we must not forget that there is usually a subtle difference between the alteration to the normal visual world produced by prisms and by other types of stereoscopic displays. The prismatic change is of a fixed magnitude for prism wear, but the disparities present in the display can be of different sizes (and may even be in different directions) at different times during the viewing of film and television programmes. To ensure that factors other than the disparity did not contaminate our results, we compared the change found under the 3D stereoscopic conditions with those found in the 2D control condition. Although we might have expected a slightly larger amount of heterophoria adaptation in the control condition than was measured, in all likelihood some adaptation occurred before the initial measurement of the heterophoria took place because the participants were sat in front of the screen whilst the experiment, and the game, were explained to them.

In the conducted experiment the increase of visual discomfort was significant in 2D condition ($p = 0.032$) and in 3D condition ($p = 0.002$). Interestingly in the 2D condition 10% of participants reported decrease in visual discomfort. This observation can be explained by random variation in the data. An alternative explanation for these findings is that TV is watched for pleasure and relaxation. For example we had a student who came to participate in experiment before an exam, as he wanted relax before it. This decrease in discomfort however is not considered as significant as it was observed only in 2 participants and was only slight (1 scale point). Furthermore it should be highlighted that not everyone experienced more visual discomfort during the viewing of the 3D stimulus than during the viewing of 2D stimulus, and for those who did it is not at all clear that the discrepancy between the stimulus to accommodation and the stimulus to convergence was in any way a causal factor. Nine of the twenty participants reported the same level of visual discomfort in the 2D and 3D conditions, three reported less discomfort in the 3D condition, and eight reported more. The results are consistent with the hypothesis that for most people playing this type of game the difference in the stimuli to accommodation and to convergence should be within tolerance limits (Lambooij et al. 2011, Howarth 2011) but that some individuals with weak binocular vision systems could show symptoms. This distinction is lost if averaged data for a group of subjects are examined (Hoffman et al. 2008, Shibata et al. 2011). To explore the difference between those participants who experienced more discomfort when viewing the game stereoscopically, and those who did not, we dichotomised the results on that basis. No significant difference was measured between these groups in terms of their initial heterophoria, final heterophoria, or change in heterophoria. There was clear variability in the magnitude of the heterophoria adaptation between individuals during the watching of the 3D stimuli, but no causative link between the heterophoria change and the visual discomfort change was apparent.

Although our results are clear, we recognise that the picture seen may change under different experimental conditions. It is quite possible that a longer viewing time, such as the 1-2 hours people spend watching a film, could have produced more symptoms. On the other hand, it is possible that adaptation may improve matters. A further limitation, in terms of the generality and applicability of our results to a real-world context, is that we only employed uncrossed disparity and this is not necessarily what would be found in a 3D stereoscopic film or television programme. Nevertheless, the adaptation we have found under our conditions is consistent with previous work showing heterophoria adaptation when other stimuli were employed.

Chapter 4

Vergence-accommodative mismatch and visual-vestibular mismatch during viewing of 3D stimuli

Purpose: The aim of the current chapter was to compare the difference in severity of symptoms reported by participants when viewing commercially available movies in 3D versus 2D conditions.

In this experiment two hypotheses were tested. The first hypothesis was that a greater mismatch between stimuli to accommodation and to vergence would produce greater symptoms in visual discomfort of viewing in 3D conditions when compared to the discomfort of viewing in 2D conditions. The second hypothesis was that 3D stimuli produce a greater sense of vection increasing the conflict between the visual and vestibular systems and thus produce greater VIMS symptoms compared to 2D viewing conditions.

Both hypotheses were tested in terms of movie content (the size of parallax in the presented movies), seating position (2m and 4m from the screen), gender and participants' age (participants below 40 years of age and participants aged 40 and over).

In addition, the analysis of the magnitude of vergence-accommodation mismatch was conducted for the movies presented in the experiment.

4.1 Introduction

3D stereoscopic technology provides an additional dimension to the viewing of visual content. This allows greater immersion in the content, which intensifies the viewer's experience. Additional information associated with image depth is derived from stereoscopic techniques and utilises binocular disparity as (depth) cue. This occurs when there is a parallax between images. Parallax can be either negative, when the stimulus is presented in front of the screen or positive, when the stimulus is presented behind the screen (see figure 2.2). The presence of parallax in the content produces a vergence-accommodation mismatch in the stimulus, which has been suggested as a reason for discomfort during the viewing of 3D stereoscopic stimuli (Hoffman et al. 2008, Yang et al. 2012, Inoue & Ohzu 1997, Ukai & Kato 2002). In addition, moving images in 3D technology are created and displayed to achieve motion and action while viewers remain stationary. Exposure to this kind of stimuli signals sensations from the visual system which do not match those from the vestibular system. The conflict between these signals has been suggested as an additional reason for people complaining about discomfort while watching 3D stereoscopic stimuli (Howarth 2011, Yang et al. 2012).

As described above, two possible reasons for discomfort whilst viewing 3D stereoscopic stimuli are considered here. So far a number of studies have analysed these problems, however there were methodological limitations in these. The limitations were discussed in the literature review sections (see subsection 2.2.5). In this study, to exclude these limitations, each participant was exposed to 2D stimuli as well as 3D stimuli. The difference in discomfort of viewing 3D stimuli and 2D stimuli reported by each individual participant was assessed instead of the difference between groups of participants. Based on mean and maximum parallax used in the movies an analysis of the accommodation - vergence mismatch in terms of seating position was conducted. The parallax of each movie was calculated by CS MSU Graphics & Media Lab (Lomonosov Moscow State University, Russia) team. Afterwards these data were analysed in terms of accommodation - vergence conflict.

In the present experiment the following hypotheses are tested:

- On the basis of the vergence-accommodation mismatch theory it is expected that greater mismatch between stimuli to accommodation and stimuli to vergence will produce greater symptoms of visual discomfort during the viewing of 3D stimuli. This hypothesis was tested in two ways. Firstly, based on the mean vergence-accommodation mismatch in presented movies (see figures 4.4 and 4.5), and secondly by comparing visual discomfort at different viewing distances.

  For the first case it was expected that the group who watched the movie with the smallest vergence-accommodation mismatch would experience less visual discomfort than the group who watched the movie with the largest vergence-accommodation mismatch.

  For the second case it was expected that participants, who watched the movie with a closer seating position would experience more visual discomfort than participants sitting farther away. Figures 4.4 and 4.5, where the magnitude of vergence-accommodation mismatch decreases with increasing viewing distances, suggest such a hypothesis to be valid.

  Furthermore, as people age, the amplitude of accommodation decreases (Donders & Moore 1864) resulting in presbyopia[1]. Because of this, older people decouple the accommodation-vergence response in their everyday lives. It is therefore presumed that changing vergence without changing accommodation is a natural viewing condition for presbyopic participants in contrast to pre-presbyopic participants. In this case, while viewing 3D stereoscopic stimuli, the mismatch between stimulus to accommodation and stimulus to vergence is the same despite the participants age, but the response to the presented stimuli differs.

  Consequently, is expected that older participants (40 years old and above) will experience less visual discomfort than younger participants whilst viewing 3D stereoscopic stimuli. Furthermore, the absence of accommodation

[1]The onset of presbyopia occurs when the amplitude of accommodation decreases to 5.00D or less, and this level is reached approximately at the age of 40. After that the accommodation amplitude continues to decrease to 0.00 D around the age of 75 (Donders & Moore 1864).

responses in the presbyopic group eliminates other potential reasons of visual discomfort related to the accommodation response (e.g. accommodation overshoot or accommodation undershoot).

- In terms of visual-vestibular conflict theory it is expected that 3D stimuli would increase the sensation of self-motion while the participant remains physically stationary. This would then increase the sensory conflict, and thus it is expected that more VIMS will be experienced in the 3D condition than in the 2D condition.

  Furthermore, it is expected that greater VIMS symptoms will be experienced by participants at the closer seating position as a larger part of the visual field is stimulated, compared with those at the farther seating position, where a relatively small part of the visual field is being stimulated. This hypothesis is partly also based on the fact that peripheral motion gives a greater sense of self-motion (vection) than central motion (Bos et al. 2008). Furthermore, this hypothesis is consistent with previous observations, where the size of the screen influenced the amount of VIMS (Howarth & Harvey 2007).

- On average, females have smaller inter-pupillary distance (62.3±3.6 [SD]) than males (64.7±3.6 [SD]) Dodgson (2004). It can be predicted that this 3.7% difference in inter-pupillary distance might have an impact on perceived position of the observed object. In terms of vergence-accommodation mismatch the size of the mismatch will be larger for females than for males (figure 4.1). So, more discomfort can possibly be expected for females than males. In terms of VIMS and gender some previous studies have reported females to be more susceptible than males to VIMS (Clemes & Howarth 2005, Yang et al. 2012), but others have not found any significant differences (Cheung & Hofer 2003, Woodman & Griffin 1997).

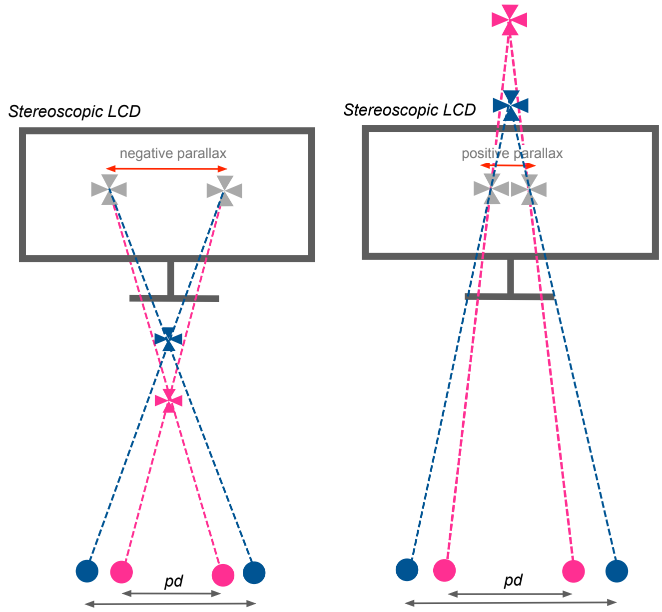


Figure 4.1: On average females have smaller inter-pupillary distance (pd) than males (blue eyes). As the virtual position of the objects increases (farther from the screen) with decreasing inter-pupillary distance, it can be expected that the accommodation-vergence mismatch will be larger in terms of females than males.

In this chapter it was also asked whether headache is reported during 3D stereoscopic stimulation and whether the headache whilst exposed to 3D stereoscopic stimulation is more severe than headache whilst exposed to 2D stimulation.

Furthermore, in the conducted study, the question was asked whether the same factors contribute to visual discomfort, headache and VIMS whilst watching 3D stereoscopic stimuli. This was mainly motivated by the fact that symptoms caused by e.g. vergence-accommodation mismatch or binocular vision problems are likely to be associated with visual discomfort and headache Scheiman & Wick (2008)(not necessary with VIMS). Therefore a correlation between visual discomfort change and VIMS would be expected. On the other hand it is expected that symptoms caused by vection are likely to correlate with VIMS symptoms and headache Wilson (1996), Lawson et al. (2002), Howarth & Hodder (2008), Ujike et al. (2008), Kennedy et al. (2010)but not necessarily with visual discomfort. Furthermore, it is apparent from the literature that eye problems only very rarely produce VIMS type symptoms. Therefore correlation between visual discomfort change and VIMS change would not be expected. To test this, the relationship between the different symptoms is analysed. In each case, the difference in symptom change between the 2D and 3D conditions is used in the analysis.

In the experiment three commercially available movies were presented to participants. A description of stimuli details relevant to the specific hypotheses tested are presented in subsection 3.2.3.

4.2 Methods

4.2.1 Procedure

Three variables were examined using a balanced experimental design in which participants were recruited to view one of three commercially available movies (Grand Canyon Adventure [2008], Avatar [2009] or Pirates of the Caribbean: On Stranger Tides [2011]). Each movie was watched in two sessions with a 15 minute break.

- Variable (1) 2D vs 3D: participants were divided in two groups: one watched the first part of the movie in 2D and the second part in 3D, the other watched them in reverse order.
- Variable (2) viewing distance: Participants were seated either 2m (31 of visual angle) or 4m (16 of visual angle) from the screen, changing position during the break in the movie.
- Variable (3) age: the complete sample was divided into two groups on the basis of age (participants aged below or above 40 years old).

In order to evaluate differences between the conditions, symptoms of visual discomfort, headache and VIMS were assessed by questionnaire before and after the viewing of the movie on both sessions.

During the current experiment participants wore 3D glasses regardless of the conditions (2D or 3D). In the 2D condition the 3D mode of the glasses was switched off. This approach minimises the differences between the two viewing conditions. The discomfort related to the 3D glasses (weight or additional set of correction glasses) has the same effect on discomfort reported by participants in the 2D and 3D condition.

4.2.2 Participants

Ninety six people (48 female, 48 male) were recruited to participate in the experiment. They were aged between 21 and 70 (average age: 37 ± 13.8 years). The only criteria to take part in the present study was stereoscopy vision, this was tested using a 3D stereoscopic TV. During the study participants wore their own optical correction as needed. All subjects signed a consent form voluntarily after a full explanation of the experiment.

In the experiment 3% (n=3) of potential participants were unable to see the 3D effect because they lacked binocular vision, on which 3D technology depends, and so they did not participate in the study.

4.2.3 Stimulus

One of three commercially available movies: Grand Canyon Adventure [2008], Avatar [2009] or Pirates of the Caribbean: On Stranger Tides [2011] was shown to each participant on a Panasonic Viera VT20, 50" plasma screen, using a "BlueRay" disc player. The movie was watched through active shutter glasses synchronised to the 3D TV with an infrared signal. To produce the stereoscopic sensation of depth, images for the right and left eyes were alternated on the screen at a refresh rate of 120 Hz. Figure 4.2 presents the mean horizontal parallax of each movie. The largest mean negative parallax was observed in the Grand Canyon Adventure movie and the largest positive parallax was observed in the Avatar movie. Figure 4.3 presents the mean vertical (unwanted) parallax[1], which is the largest for the Grand Canyon Adventure movie.

Table 4.1: Overview of movies used in the experiment.

Movie	Year	Running time	Genre
Grand Canyon Adventure	2008	44 min.	documentary \adventure
Avatar	2009	162 min.	science fiction \fantasy \adventure \action
Pirates of the Caribbean: On Stranger Tides	2011	137 min.	fantasy \adventure \action

[1] vertical parallax - is generated by misalignment of the cameras, imperfectness of the lenses, zoom discrepancy, photographic mismatches in focus.

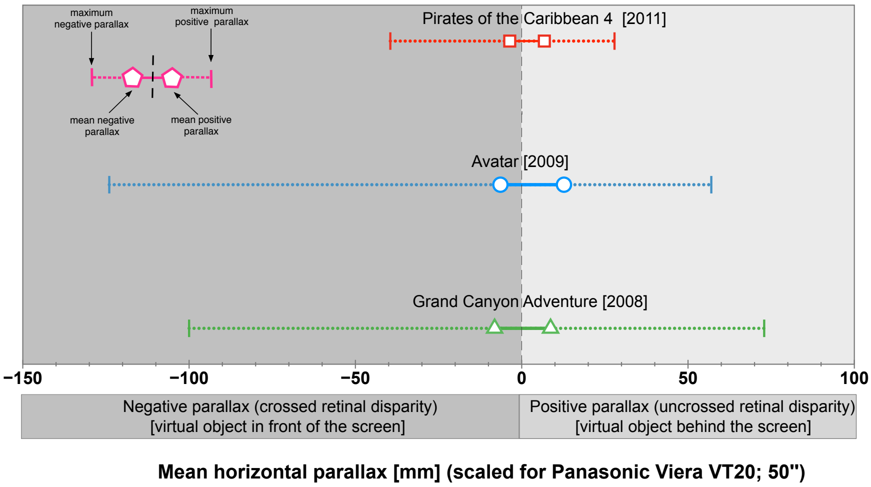


Figure 4.2: Mean and maximum horizontal parallax in the following movies: Grand Canyon Adventure [2008], Avatar [2009], Pirates of the Caribbean: On Stranger Tides [2011]. Based on data delivered by CS MSU Graphics & Media Lab team (Lomonosov Moscow State University, Russia).

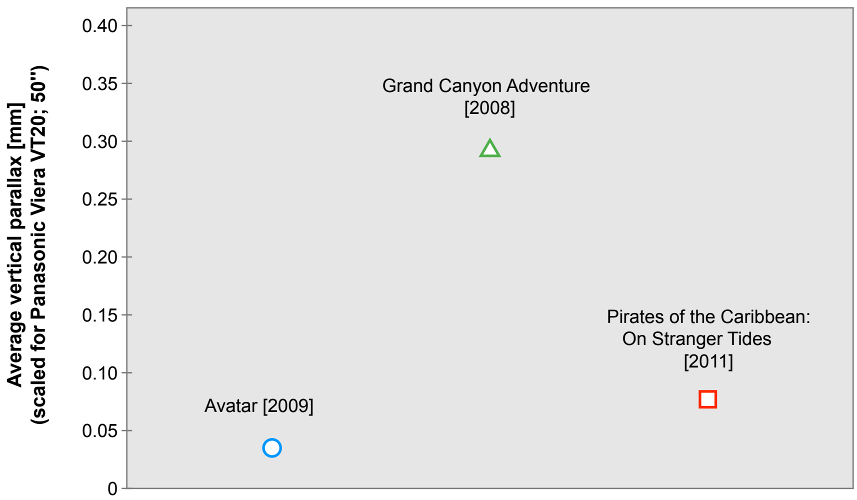
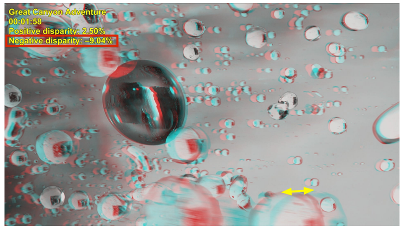
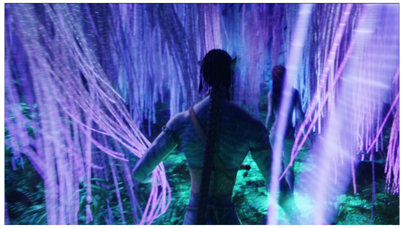
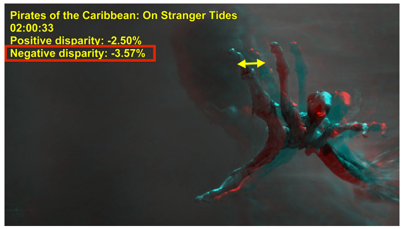


Figure 4.3: Mean vertical parallax in the following movies: Grand Canyon Adventure [2008], Avatar [2009], Pirates of the Caribbean: On Stranger Tides [2011]. Based on data delivered by CS MSU Graphics & Media Lab team (Lomonosov Moscow State University, Russia).

In most 3D stereoscopic movies and games the separation of the left and right images on the display screen (parallax) is not fixed but rather varies over the time. The increase or decrease of the horizontal parallax in the movie/game changes the perceived position of the stimuli and so changes the value of vergence-accommodation mismatch. On our request the CS MSU Graphics & Media Lab team selected the movie frames with high horizontal parallax in the movies used during the current experiment. Table 4.2 presents examples of the frames with high negative parallax (perceived image in front of the screen) and table 4.3 presents an example of the frames with high positive parallax (perceived image behind the screen). In tables 4.2 and 4.3 the middle column presents the anaglyph frames, where the distance in between the red and blue objects (yellow arrow) indicates the parallax. The right column in each table (see tables 4.2 and 4.3) shows 2D visualisation of anaglyph frames. As presented in tables 4.2 and 4.3 it is important to highlight that in one single frame of the movie some objects are presented in front of the screen and others behind the screen. This observation shows that parallax in a movie varies not only in time, but also varies within a single frame.

These data (see figure 4.2) are used to analyse the magnitude of vergence-accommodation mismatch in the movies presented during the current experiment. The results of this analysis are further used to test the vergence-accommodation mismatch theory.

Table 4.2: High negative parallax observed in movies.

<table>
<tr><th>Movie</th><th colspan="2">Negative parallax</th></tr>
<tr><td>Grand Canyon Adventure</td><td>
</td><td></td></tr>
<tr><td>Avatar</td><td>
</td><td></td></tr>
<tr><td>Pirates of the Caribbean:
On Stranger Tides</td><td>
</td><td></td></tr>
</table>

The left hand column shows the anaglyphs of a frame with high negative parallax taken from each movie. The distance between the red and blue objects (the yellow arrow) indicates parallax. The right hand column shows 2D visualisation corresponding anaglyph frame. In the top left corner of each anaglyph frame details about the magnitude of parallax are shown [metric value = % of frame width].

Table 4.3: High positive parallax observed in the movies

Movie	Positive parallax	
Grand Canyon Adventure		
Avatar		
Pirates of the Caribbean: On Stranger Tides		

The left hand column shows the anaglyphs of a frame with high positive parallax taken from each movie. The distance between the red and blue objects (the yellow arrow) indicates parallax. The right hand column shows 2D visualisation corresponding anaglyph frame. In the top left corner each of each anaglyph frame details about the magnitude of parallax are shown [metric value = % of frame width].

4.2.4 Symptom measurement

As was presented in the introduction, different approaches have been taken in the past to assess the effect of 2D and 3D stimulation on viewing comfort. In the present experiment the symptom changes during each movie session was assessed in accordance with the method proposed by Howarth & Istance (1985). In this method individual symptoms prime the participants to answer an overall question, which delivers a single number to represent their condition. In terms of assessing the subjective change during the session, the approach of analysing an overall question has been found to be more sensitive than analysing the responses to individual questions (Howarth et al. n.d.).

The questionnaire used in the present experiment consists of three groups of symptoms: group A - contains the symptoms related to visual discomfort (based on Howarth & Istance (1985)), group B - contains the symptoms related to headache and group C - contains the symptoms related to VIMS (based on topical symptoms related to VIMS, see chapter 2.2.3). The questionnaire was constructed in such a way that each participant could at first rate a number of symptoms, and then give the overall rating of their visual discomfort, headache and VIMS. The structure of this questionnaire is shown in table 4.4.

It is important to highlight that people who experience symptoms associated with visual discomfort (group A) and VIMS (group C) can also experience symptoms associated with headache (group B). To the best of the author's knowledge, people who experience symptoms associated with vection (the feeling of self-motion which gives rise to VIMS) do not suffer from visual discomfort from the same cause. The symptoms associated with visual discomfort relate to eye problems (have ocular origin). It is only in very rare circumstances the eye problems may produce some symptoms associated with VIMS (e.g. vertical heterophoria[1] or divergence insufficiency[2]).

The questions were assessed on a seven point rating scale, where zero represents an absence of symptoms and seven represents severe symptoms. The

[1] association but not necessary causation between vertical heterophoria and motion sickness was reported by Jackson & Bedell (2012).

[2] based on Scheiman & Wick (2008) divergence insufficiency is a very uncommon condition, but causes significant symptoms

questionnaire was completed before and after the 2D and 3D sessions.

Because all causes of 2D discomfort are also present during 3D stimuli, the primary measure of interest was not the symptoms change over the 2D session (2D post exposure score - 2D pre exposure score) session or the 3D session (3D post exposure score - 3D pre exposure score), but rather the difference between the changes in these two sessions.

Table 4.4: Symptom Questionnaire

	N	SL		M		S	
Group A							
Tired eyes	0	1	2	3	4	5	6
Sore or aching eyes	0	1	2	3	4	5	6
Irritated eyes	0	1	2	3	4	5	6
Dry eyes	0	1	2	3	4	5	6
Hot or burning	0	1	2	3	4	5	6
Blurred vision	0	1	2	3	4	5	6
Difficulty focussing	0	1	2	3	4	5	6
Overall how much visual discomfort are you experiencing ?	0	1	2	3	4	5	6
Group B							
Headache at the sides of head	0	1	2	3	4	5	6
Headache at the front of head	0	1	2	3	4	5	6
Headache at the back of head	0	1	2	3	4	5	6
Fullness of head	0	1	2	3	4	5	6
Heaviness of head	0	1	2	3	4	5	6
Overall how much headache are you experiencing?	0	1	2	3	4	5	6
Group C							
Nausea	0	1	2	3	4	5	6
Dizziness	0	1	2	3	4	5	6
Drowsiness	0	1	2	3	4	5	6
Sweating	0	1	2	3	4	5	6
Salivation	0	1	2	3	4	5	6
Overall how much sickness are you experiencing ?	0	1	2	3	4	5	6

N - none, SL - slight, M - moderate, S - severe

4.3 Results

The results section is organised as follows. First the vergence-accommodation mismatch, in terms of movie shown and seating position is analyzed (section 4.3.1). Next, the results of the difference in discomfort between stimuli presented in the 2D condition and 3D condition is demonstrated (sections 4.3.2 - 4.3.3).

4.3.1 Analysis of vergence-accommodation mismatch

The aim of the current section was to analyse the magnitude of the vergence-accommodation mismatch produced by horizontal parallax in the movies used in the experiment. Based on the horizontal parallax presented in figure 4.2 a calculation of vergence-accommodation mismatch was conducted. The virtual position of the image was calculated from the formula established from the figure presented in appendix A . Accommodation and vergence stimuli are expressed in dioptres [D] (dioptre $= \frac{1}{d}$, where d is the distance between the stimuli and eyes in metre). Vergence-accommodation mismatch was calculated as the difference between the stimulus to vergence and the stimulus to accommodation in dioptres [D].

Negative values express vergence-accommodation mismatch for images perceived in front of the screen, positive values express vergence-accommodation mismatch for images perceived behind the screen. Figure 4.4 presents the average size of the vergence-accommodation mismatch and figure 4.5 presents the size of vergence-accommodation mismatch for high parallax in the movies presented during the experiment. The size of vergence-accommodation mismatch in figures 4.4 and 4.5 has been calculated in terms of the viewing position for each movie separately and was scaled for Panasonic Viera VT20;50". In the present experiment the distance between viewers and TV screen was either 2m or 4m (grey area in figures 4.4 and 4.5), which are not untypical viewing distances within the home environment. The others viewing distances presented in figures 4.4 and 4.5 indicate the mismatch which would be predicted at other viewing distances.

As shown in figures 4.4 and 4.5, the average size of vergence-accommodation conflict with both negative parallax (top row) and positive parallax (bottom row) decreased as viewing distance increased in a non-linear manner. The largest av-

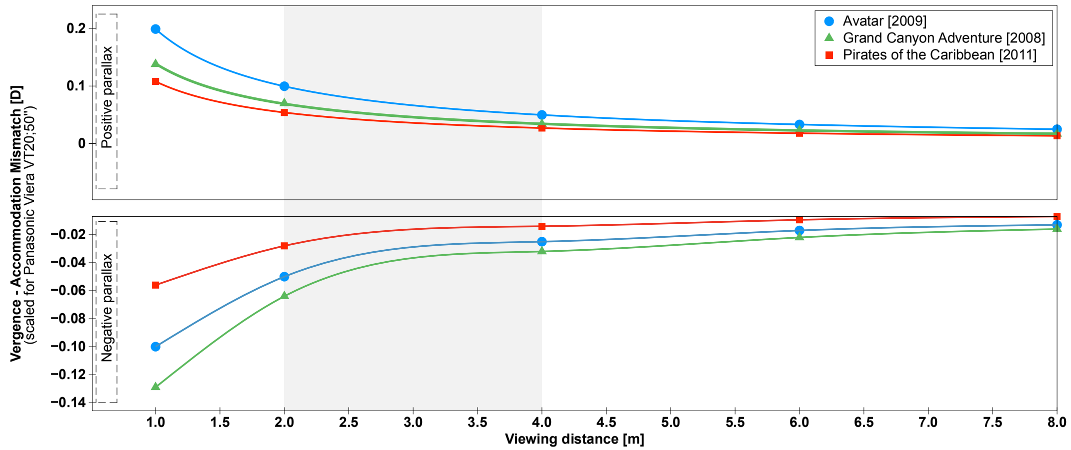


Figure 4.4: The average size of the vergence-accommodation mismatch (grey area - the distance between viewers an TV screen used in the current experiment).

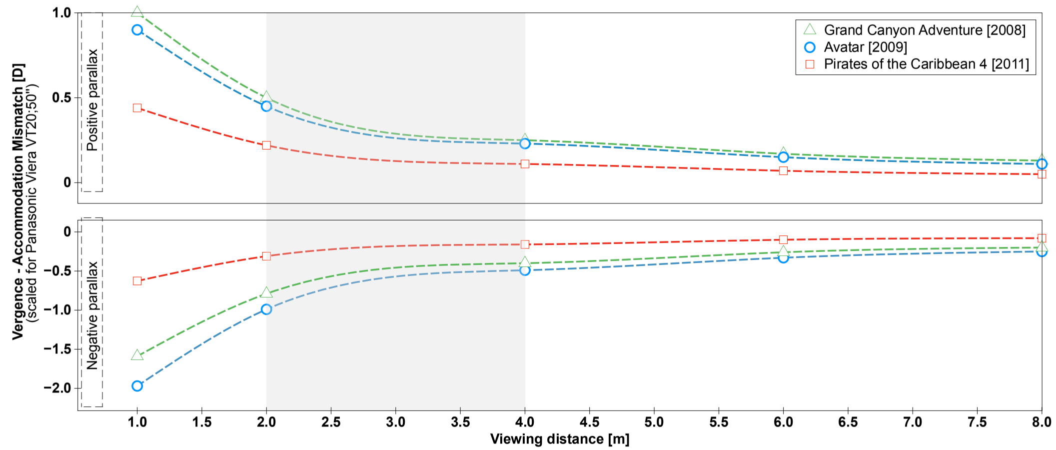


Figure 4.5: The size of the vergence-accommodation mismatch in frames with high parallax (grey area - the distance between viewers an TV screen used in the current experiment).

erage vergence-accommodation mismatch with negative parallax was observed in the movie entitled Grand Canyon Adventure [2008] and with positive parallax was observed in the movie entitled Avatar [2009]. The smallest average vergence-accommodation mismatch with negative as well as with positive parallax was observed in the movie Pirates of the Caribbean [2011]. The average size of vergence-accommodation mismatch was < 0.1 D (at the closer seating position (2m from screen)) when the image was perceived in front of the screen as well as when the image was perceived behind the screen.

Based on frames with high parallax the smallest accommodation-vergence mismatch was observed in the movie Pirates of the Caribbean [2011], for negative as well as positive parallax. For negative parallax the largest vergence-accommodation mismatch was observed in the movie Avatar [2009]. For positive parallax the largest vergence-accommodation mismatch was observed in the movie Grand Canyon Adventure [2011]. The analysis of vergence-accommodation mismatch based on a frame with high negative and positive parallax showed that the mismatch in both cases did not exceed 1D at the closer seating position (2m from screen).

As presented in figure 4.4 and 4.5 for all investigated movies vergence-accommodation mismatch was observed when the image was perceived in front of the screen as well as when it was presented behind the screen.

Based on the analysis it was expected that:

- less visual discomfort would be experienced in the group who watched the movie Pirates of the Caribbean [2011] (the smallest mismatch between stimulus to accommodation and stimulus to vergence in the positive as well as the negative parallax) than in the two other groups, where the movies Avatar [2009] and Grand Canyon Adventure [2008] were presented.
- participants seated closer to the screen (larger vergence-accommodatiom mismatch) would experience more visual discomfort than participants seated farther away (smaller vergence-accommodatiom mismatch).

4.3.2 Influence of movie type on discomfort

To check whether movie content affects comfort whilst viewing 3D and 2D stimuli, the results were pooled across distances for all three movies. The balance of the experiment design allows conditions to be pooled. Figures 4.6 - 4.8 show the differences between 3D and 2D conditions in terms of visual discomfort, headache and VIMS for each movie.

General visual discomfort

The largest number of participants (41%) who reported a greater amount of vision discomfort change (VD post - VD pre) in the 3D condition in comparison to the visual discomfort change (VD post - VD pre) in the 2D condition was observed for the movie Grand Canyon Adventure. For movies Avatar, and Pirates of the Caribbean, a greater amount of visual discomfort change in the 3D condition was reported by 22% and 28% of participants, respectively. For each of the movies more than 50% of participants reported the same change of visual discomfort in the 2D and 3D conditions.

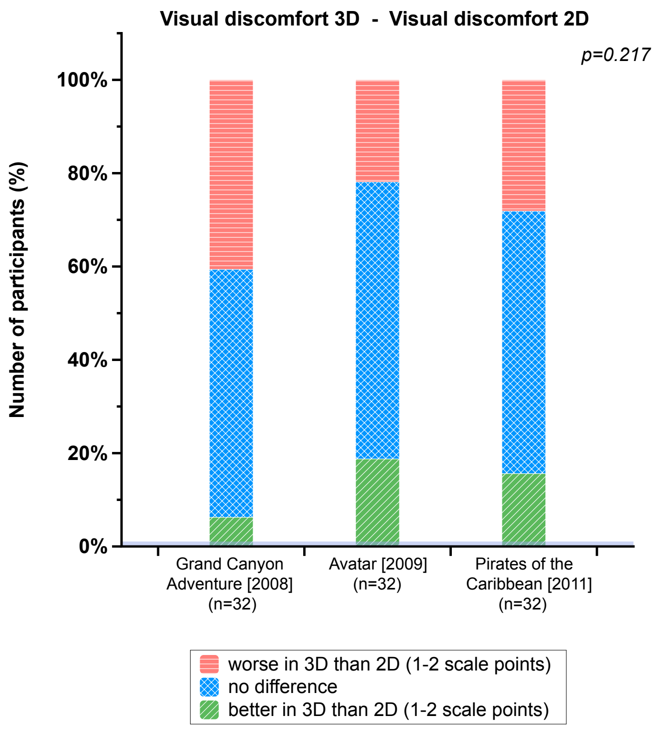


Figure 4.6: The differences in visual discomfort between the 3D condition and the 2D condition in term of the movie presented.

Some participants reported a lesser amount of visual discomfort change in the 3D condition compared to the 2D condition. This was reported by 6% to 18% of participants depending on the movie presented. The comparison showed that differences in visual discomfort were not statistically significant between the movies (p=0.217; Kruskal-Wallis Test).

Headache

Results for headache change between the 3D and 2D conditions were very similar in terms of movie presented as shown in figure 4.7. A greater amount of headache change (H post - H pre) in the 3D condition than the 2D condition was reported by 22% of participants in case of movie Avatar, by 28% of participants in case of movie Grand Canyon Adventure, and by 22% of the participants in case of movie Pirates of the Caribbean. The same change of headache in the 3D condition as well as in the 2D condition was reported by 59% to 69% of participants. A lesser amount of headache change in the 3D condition compared with the 2D condition was reported by 9% to 13% of participants depending on the movie presented. Comparison showed that the differences reported in headache were not statistically significant between the movies (p=0.932; Kruskal-Wallis Test).

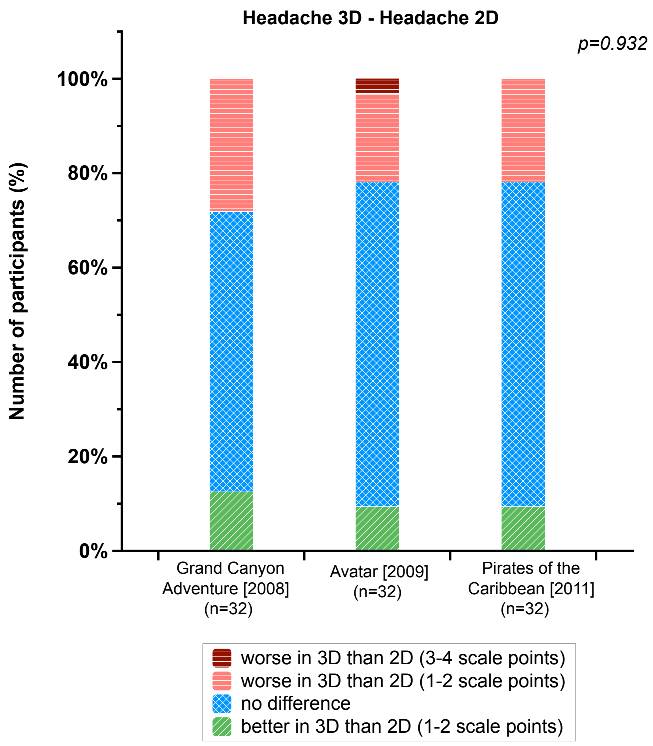


Figure 4.7: The differences in headache between the 3D condition and the 2D condition in term of the movie presented.

VIMS

The results of VIMS change between the 3D and 2D condition in terms of presented movie are shown in figure 4.8. A greater amount of VIMS change (VIMS post - VIMS pre)in the 3D condition than the 2D condition was reported by 16% of participants for the movie Grand Canyon Adventure, by 22% of participants for the movie Avatar and by 12% of participants for the movie Pirates of the Caribbean. The same level of VIMS change for the 2D and the 3D condition was reported by 75% to 88% of participants. A lesser amount of VIMS change in the 3D condition than the 2D condition of was reported by 0% to 3% depending on the movie presented. Differences in VIMS were not statistically significant between the movies (p=0.829; Kruskal-Wallis Test).

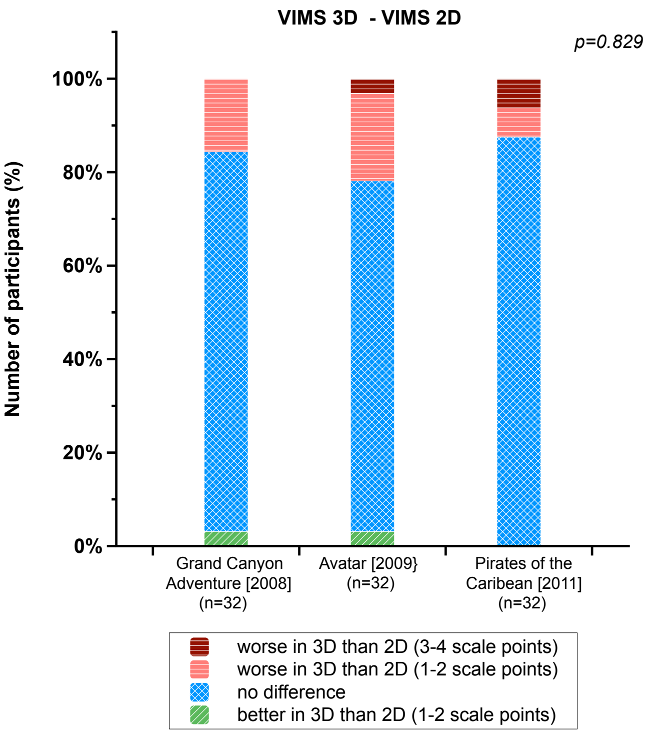


Figure 4.8: The differences in VIMS between the 3D condition and the 2D condition in term of the movie presented.

The analysis of the data in terms of movie watched show that differences in visual discomfort, headache and VIMS were not statistically significantly different between the movies. Consequently, the data from the three movies were pooled and presented in the following subsections (4.3.6 - 4.3.5).

4.3.3 The influence of viewing distance on discomfort

In the following subsection the effect of viewing distance on discomfort is analysed. In this study two viewing positions were investigated: 2m (closer seating position) and 4m (farther seating position) from the screen. Half of participants (n=48) watched a movie at a closer seating position and the other half (n=48) watched a movie at a farther seating position in either the 2D condition or the 3D condition. Figures 4.9 - 4.11 compare the differences in discomfort reported by the two groups of participants (group 1: participants who watched 3D in a closer seating position and 2D in a farther seating position, group 2: participants who watched 3D in a farther seating position and 2D in a closer seating position).

General visual discomfort

In the group who watched 3D at a closer seating position and 2D at a farther seating position 15% of participants reported a lesser amount of visual discomfort in the 3D condition than in the 2D condition. 56% of participants reported no difference between visual discomfort in the 3D condition and the 2D condition and 29% of participants reported a greater amount of visual discomfort in the 3D condition than 2D condition (see the right bar in figure 4.9).

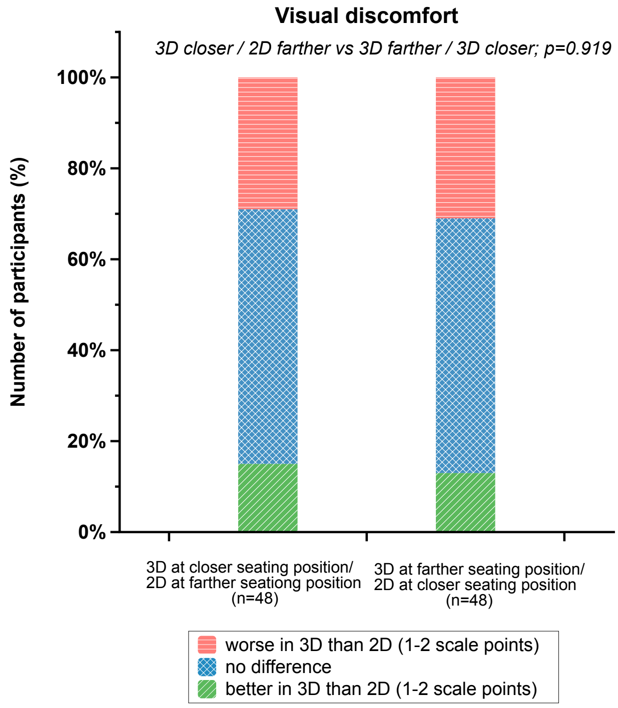


Figure 4.9: The effect of seating position on visual discomfort.

In the group who watched 3D at a farther seating position and 2D at a closer seating position 13% of participants reported a lesser amount of visual discomfort in the 3D condition, than in the 2D condition. 56%

of participants reported no difference between visual discomfort reported in the 3D condition and the 2D condition and 31% of participants reported a greater amount of visual discomfort in the 3D condition than the 2D condition (see the right bar in figure 4.9).

The difference between the two seating position groups was not statistically significant (p=0.919; Mann-Whitney test).

Headache

In terms of headache, in the group who watched 3D at a closer seating position and 2D at a farther seating position 10% of participants reported a lesser amount of headache in the 3D condition than in the 2D condition. The same level of headache was experienced for the 2D and 3D condition by 67% of participants and an increase in headache for the 3D condition compared with the 2D condition was reported by 23% of participants (see the left bar in figure 4.10).

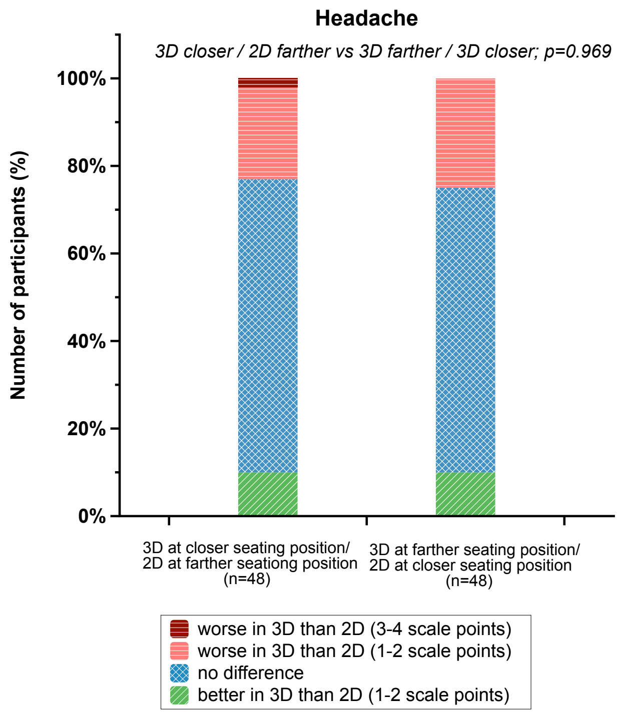


Figure 4.10: The effect of seating position on headache.

In the group who watched 3D at a farther seating position and 2D at a closer seating position 10% of participants reported a lesser amount of headache in the 3D condition than in the 2D condition. The same level of headache was experienced for the 2D and 3D condition by 65% of participants and an increase in headache for the 3D condition compared with the 2D condition was reported by 25% of participants (see the right bar in figure 4.10).

The difference between the two seating position groups was not statistically significant (p=0.969; Mann-Whitney test).

VIMS

In the case of VIMS in the group who watched 3D from the closer seating position and 2D from the farther seating position 75% of participants reported no difference between visual discomfort in the 3D condition and the 2D condition. 25% of participants reported a greater amount of visual discomfort in the 3D condition than in the 2D condition (see the left bar in figure 4.11).

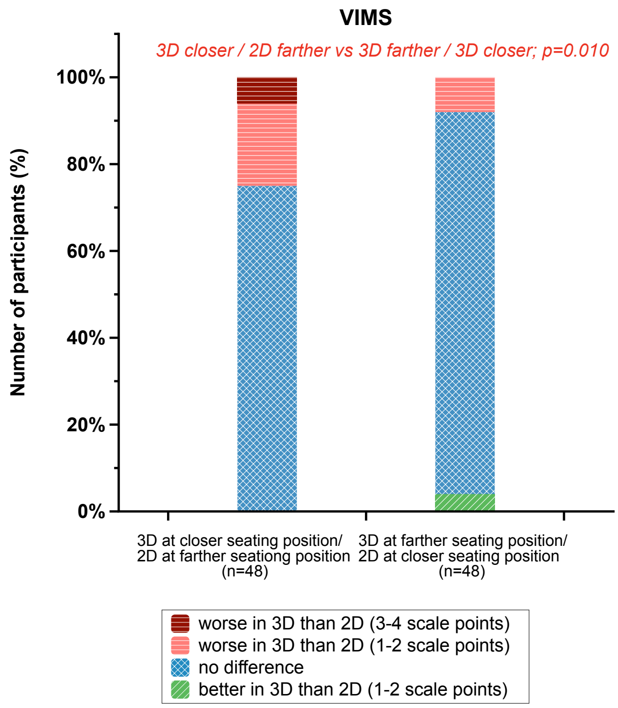


Figure 4.11: The effect of seating position on VIMS.

In the group who watched 3D from the farther seating position and 2D from the closer seating position 4% of participants reported a lesser amount of visual discomfort in the 3D condition than in the 2D condition. 88% of participants reported no difference between visual discomfort in the 3D condition and the 2D condition and 8% of participants reported a greater amount of visual discomfort in the 3D condition than the 2D condition (see the right bar in figure 4.11). The difference between the two seating position groups was statistically significant (p=0.010; Mann-Whitney test).

4.3.4 The effect of gender on discomfort

In the following section the effect of gender on discomfort was analysed. The average age for female participants was 39 ± 13 years and for males was 39 ± 14 years. 25% of females and 42% of males watched the movie Grand Canyon Adventure, 35% of females and 31% of males watched the movie Avatar, and 40% of females and 27% of males watched the movie Pirates of the Caribbean. The analysis of symptoms reported by females and males was conducted in terms of visual discomfort (see figure 4.12), headache (see figure 4.13) and VIMS (see figure 4.14).

General visual discomfort

When comparison was made between the change in symptoms which were reported when watching a 2D movie (symptoms before compared with symptoms after) and the change reported when watching the 3D movie 27% of females and 33% of males reported a greater change in symptoms for the 3D condition than the 2D condition. For 58% of females and 54% of males symptom change was the same in the 2D and 3D conditions. A greater change in symptoms for the 2D condition than the 3D condition was reported by 15% of female and 13% of male participants (see figure 4.12). No statistically significant differences between females and males were found (p=0.42; Mann-Whitney test).

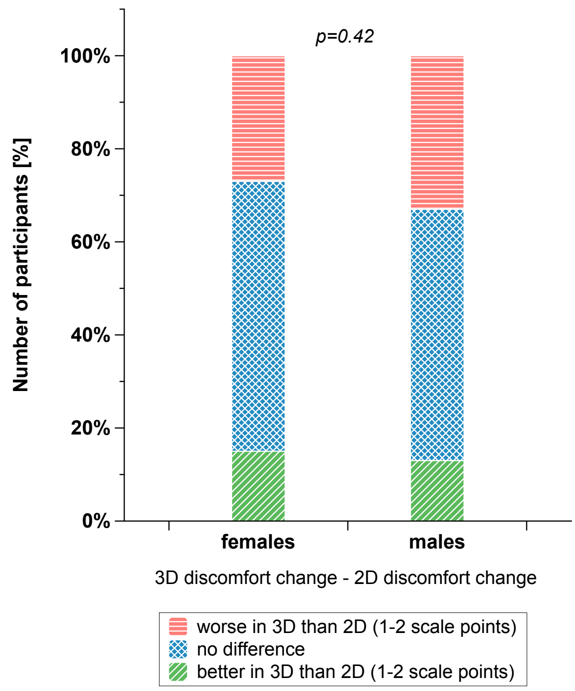


Figure 4.12: The effect of gender on visual discomfort.

Headache

When comparing the change between the two sessions (headache in the 2D condition against headache in the 3D condition) a greater change of symptoms for 3D compared to 2D was reported by 25% of females and 23% of males. No change in the level of symptoms was reported by 63% of females and 69% of males. A greater change in symptoms for the 2D condition than the 3D condition was reported by 12% of females and 8% of males (see figure 4.13). No statistically significant differences between females and males were found (p=0.88; Mann-Whitney test).

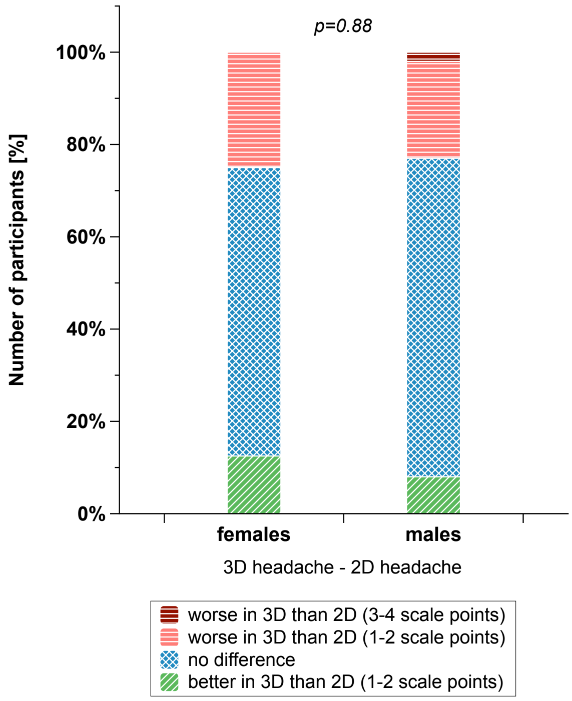


Figure 4.13: The effect of gender on headache.

VIMS

When comparison was made between the change in symptoms which was reported when watching a 2D movie (symptoms before compared with symptoms after) and the change reported when watching a 3D movie 17% of females and 17% of males reported a greater change in symptoms for the 3D condition than 2D condition. No change in level of symptoms was reported by 81% of both females and males and a decrease in symptoms was reported by 2% of both females and males (see figure 4.14). No statistically significant differences between females and males were found (p=0.98; Mann-Whitney test).

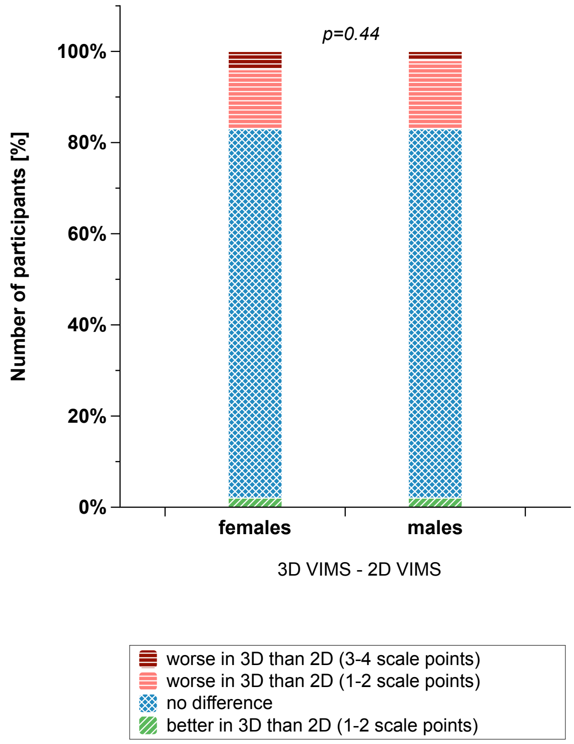


Figure 4.14: The effect of gender on VIMS.

4.3.5 Does age have an influence on discomfort ?

In the following subsection the effect of age on discomfort was analysed. Participants were divided into two groups on the basis of age (group 1: participants below 40 years of age, group 2: participants aged 40 and over). The groups were equal in terms of number of participants, with 48 in each. In each age group one third of participants watched each movie: Avatar (n=16), Grand Canyon Adventure (n=16) and Pirates of the Caribbean (n=16). The comparison between age groups was conducted in terms of visual discomfort(see figure 4.15), headache (see figure 4.17) and VIMS (see figure 4.18).

General visual discomfort

When considering 2D and 3D conditions, 44% of participants in the group less than 40 years old and 17% of participants in the group 40 years old and older reported greater change in visual discomfort for the 3D condition than the 2D condition. For 43% of younger participants (< 40 yrs) and for 68% of older participants (≥ 40 yrs) symptoms change was the same for the 2D and 3D condition. A lesser amount of visual discomfort in the 3D condition than the 2D condition was reported by 13% (< 40 yrs) and by 15% (≥ 40 yrs). These results are presented in figure 4.15. The difference between the two groups (< 40 yrs and ≥ 40 yrs) was statistically significant (p=0.020; Mann-Whitney test). There was a significant

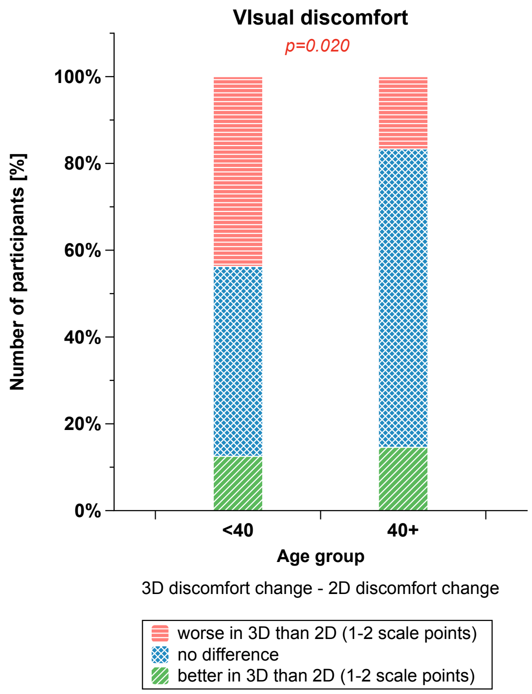


Figure 4.15: The effect of gender on visual discomfort.

correlation between participant age and difference in the level of visual discomfort between the 3D and 2D condition (r_s = - 0.223, p = 0.029; Spearmans correlation test),(see figure 4.16).

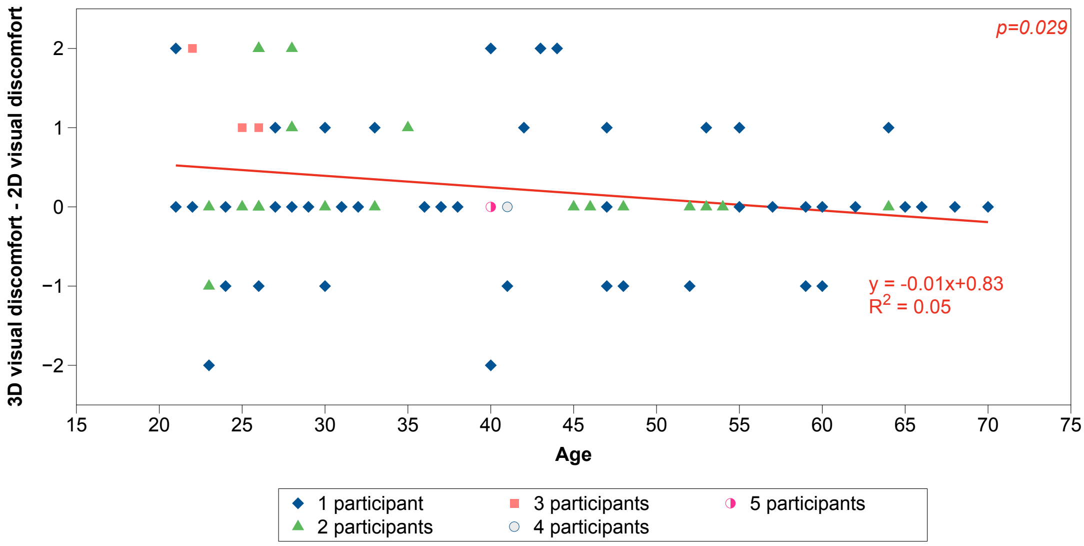


Figure 4.16: Relationship between visual discomfort difference reported by participants across two sessions (3D-2D) and participants' age.

Headache

When considering the change in headache over the two sessions, 33% of participants in the group less than 40 years old and 15% of participants in the group 40 years old and older reported greater change in visual discomfort for the 3D condition than the 2D condition. For 58% of younger participants ($<$ 40 yrs) and for 73% of older participants ($\geq$ 40 yrs) symptom change was the same for the 2D and 3D condition. A lesser amount of visual discomfort in the 3D condition than in the 2D condition was reported by 8% ($<$ 40 yrs) and by 12% ($\geq$ 40 yrs).

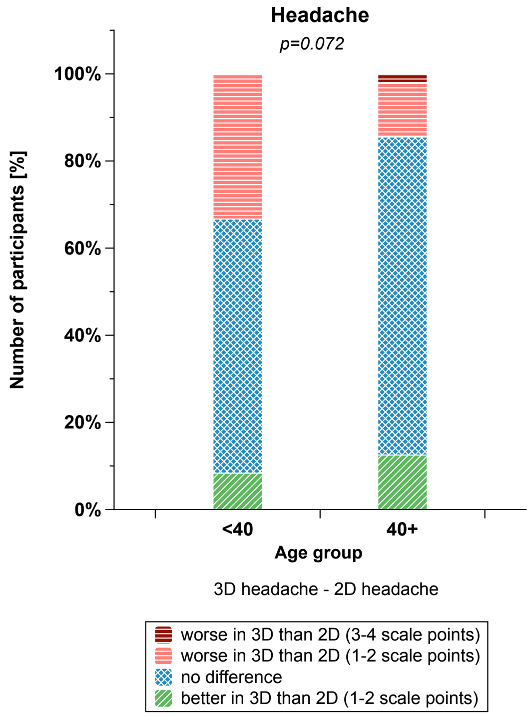


Figure 4.17: The effect of gender on headache.

These results are presented in figure 4.17. The difference between the two groups ($<$ 40 yrs and $\geq$ 40 yrs) was not statistically significant (p=0.072; Mann-Whitney test). There was no significant correlation between participant age and difference in the level of headache between the 3D and 2D conditions (r_s = - 0.199, p = 0.052; Spearmans correlation test),(see figure 4.19).

VIMS

When comparing symptom change over the 2D and 3D sessions, 25% of the participants in the group less than 40 years old and 8% of participants in the group 40 years old and older reported a greater change in VIMS after the 3D session than after the 2D session. For 73% of the younger participant group and for 90% of the older participant group symptoms change was the same for the 2D and 3D condition. A lesser amount of VIMS in the 3D condition than the 2D condition was reported by 2% in both age groups. These results are presented in figure 4.18. The difference between the two groups (< 40 yrs and ≥ 40 yrs) was not statistically significant (p=0.06; Mann-Whitney test). There was no significant correlation between participant age and difference in the level of VIMS between the 3D and 2D condition (r_s = - 0.122, p = 0.236; Spearmans correlation test),(see figure 4.20).

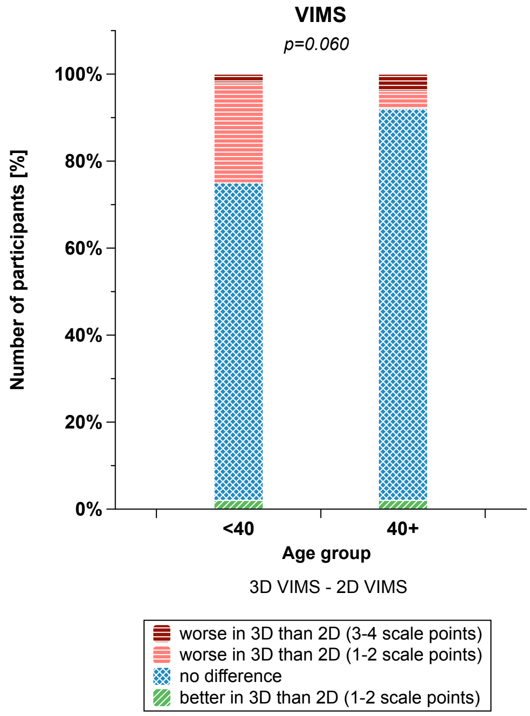


Figure 4.18: The effect of gender on VIMS.

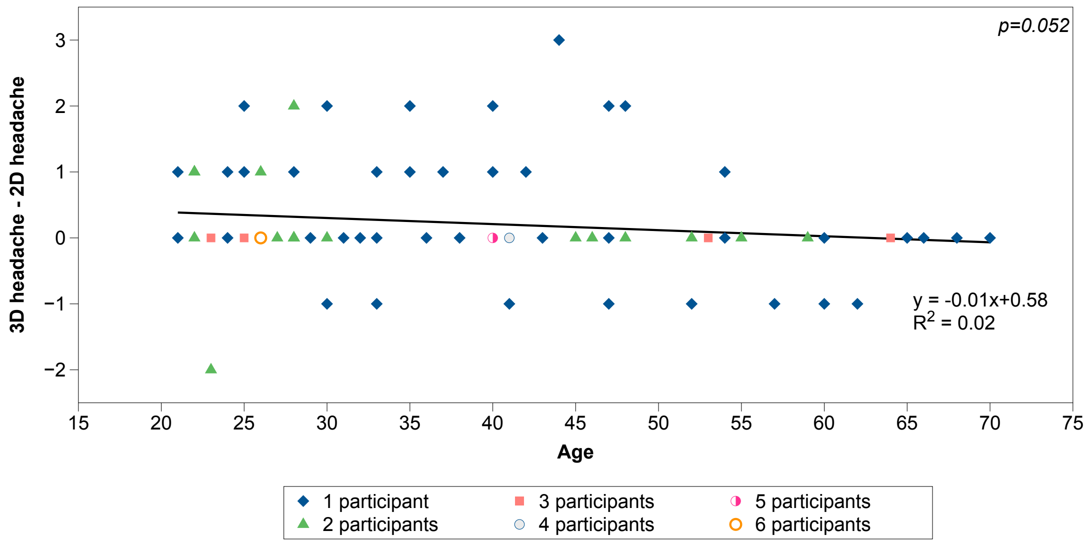


Figure 4.19: Relationship between headache difference reported by participants across two session (3D-2D) and participants age.

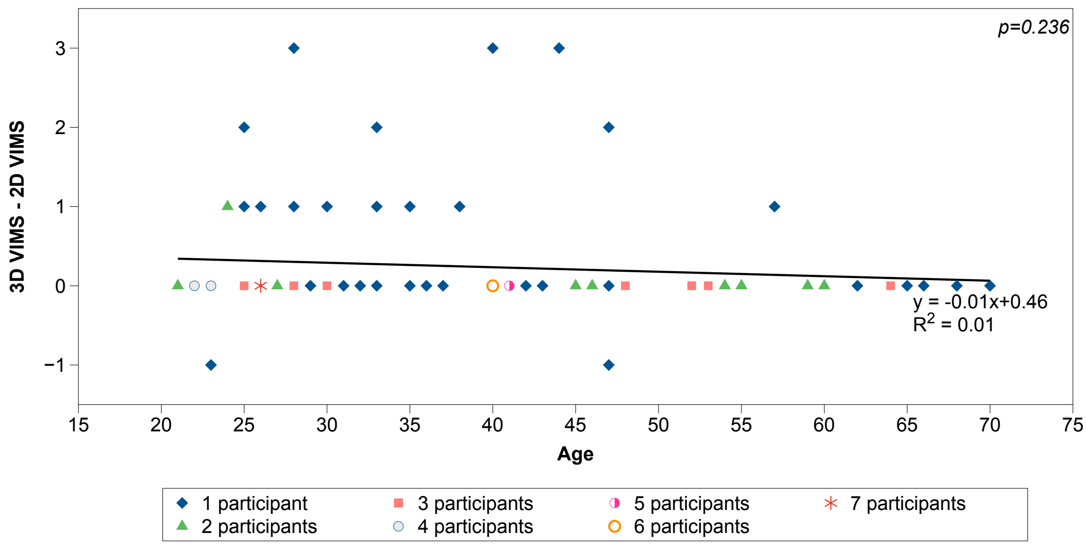


Figure 4.20: Relationship between VIMS difference reported by participants across two sessions (3D-2D) and participants' age.

4.3.6 Changes in severity of symptoms reported for the 2D condition, the 3D condition, and the differences between them

In the current subsection changes in discomfort for the 2D condition, 3D condition and the differences between them are reported. The comparison for each condition was conducted in terms of visual discomfort (see figure 4.21), headache (see figure 4.22) and VIMS (see figure 4.23).

General visual discomfort

After watching a movie in the 2D condition, 73% of participants reported no difference in general visual discomfort from that reported before watching the movie. However, 20% of participants reported a slight increase, and 7% reported a slight decrease in general visual discomfort (see figure 4.21; the left column). This overall increase was significant (p=0.019; Wilcoxon).

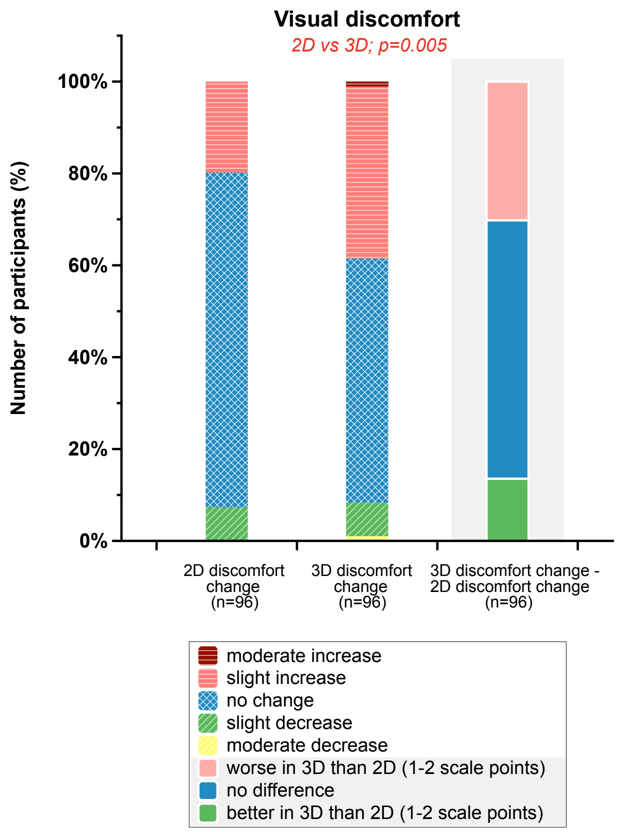


Figure 4.21: Changes in general visual discomfort for 2D condition (left), 3D condition (middle), and the difference between them (right).

After viewing a movie in the 3D condition, 53% of participants reported the same level of general visual discomfort as before the movie. An increase in general visual discomfort was reported by 39% of participant, and a decrease was reported by 8% of participants (see figure 4.21; the middle column). This overall increase was significant (p=0.001; Wilcoxon).

When comparing discomfort change between the two sessions, it was found that 56% of participants showed the same change of visual discomfort in the 3D condition as in the 2D condition. A greater amount of visual discomfort was reported by 30% of participants and a lesser amount of visual discomfort was reported by 14% of the participants for the 3D condition (see figure 4.21; the right column). The increase in discomfort for the 3D condition in comparison to the increase in discomfort for the 2D condition was statistically significant (p=0.005; Wilcoxon).

Headache

In terms of headache, after viewing a movie in the 2D condition no change in symptoms between pre- and post- viewing was reported by 79% of the participants. An increase of headache was reported by 14% of the participants and a slight decrease in headache was reported by 7% of participants (see figure 4.22; the left column). This overall increase was not statistically significant (p=0.180; Wilcoxon).

After watching a movie in the 3D condition, 65% of the participants did not report any difference in headache between pre- and post- viewing. However, 29% of participants reported a slight increase, and

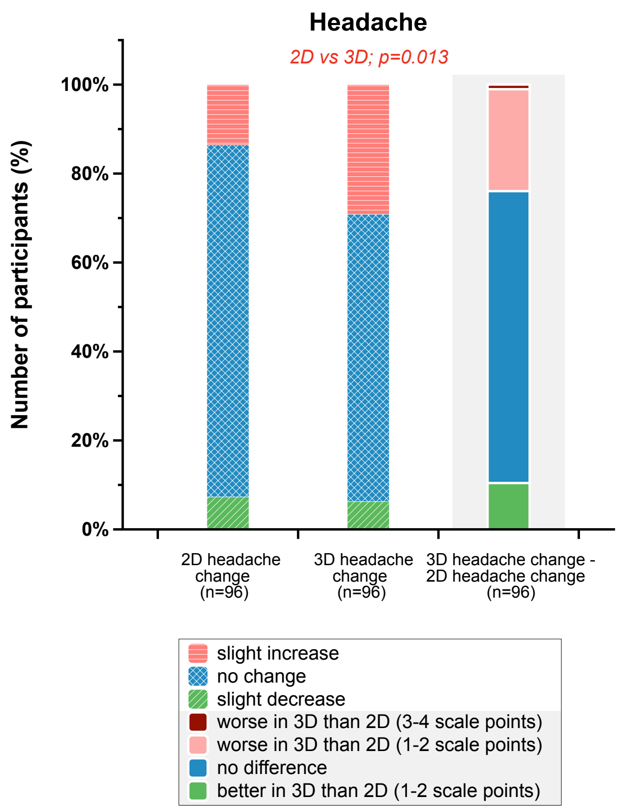


Figure 4.22: Changes in headache for 2D condition (left), 3D condition (middle), and the difference between them (right).

6% of participants reported a slight decrease in headache (see figure 4.22; the middle column). This overall increase was significant (p=0.001; Wilcoxon).

When comparing change between the two sessions, 66% of the participants reported the same amount of headache in both conditions 3D and 2D. A greater amount of headache was reported by 24% participants, and a lesser amount of headache was reported by 10% of participants for the 3D condition (see figure 4.22; the right column). The change between the two conditions was statistically significant (p=0.013; Wilcoxon).

VIMS

In terms of VIMS symptoms, 92% of participants reported no change in symptoms level after watching the movie in 2D compared to symptom level before, 2% of participants reported an increase in symptoms and 6% of participants reported a decrease in symptoms (see figure 4.23; the left column). The difference between pre- and post- viewing was not statistically significant (p=0.132; Wilcoxon).

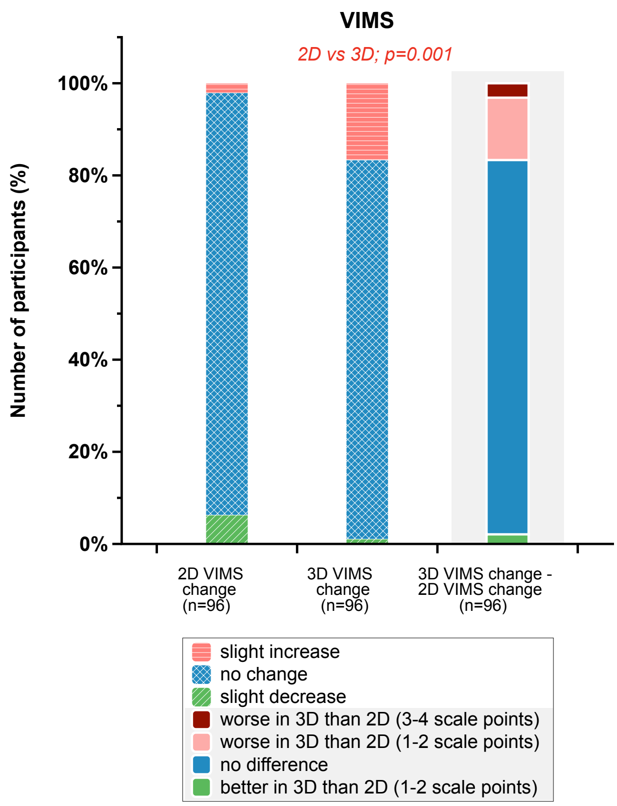


Figure 4.23: Changes in VIMS for 2D condition (left), 3D condition (middle), and the difference between them (right).

After viewing the movie in the 3D condition, 82% of the participants showed the same level of VIMS as they reported before the movie, 17% of the participants showed an increase and 1% of the participants reported a decrease of VIMS compared with that reported before watching the movie (see figure 4.23; the middle column). The difference between pre- and post- viewing was statistically significant (p=0.001; Wilcoxon).

The same level of VIMS was experienced for the 2D and 3D conditions by 81% of participants, an increase in VIMS for the 3D condition was reported by 17% of participants, and a decrease was reported by 2% (see figure 4.23; the right column). The change between the two conditions was statistically significant (p=0.001; Wilcoxon).

Relationship between changes in different symptoms

Figure 4.24 shows the relationships between different symptoms in terms of 3D symptoms change - 2D symptoms change. The left panel shows visual discomfort difference (3D change - 2D change) against headache difference (3D change - 2D change). A statistically significant positive correlation between these two discomfort symptom groups was observed (r_s = 0.32, p = 0.002; Spearmans correlation test). The middle panel compares visual discomfort difference (3D change - 2D change) with VIMS difference (3D change - 2D change). No statistically significant correlation between these two symptom groups was observed (r_s = 0.14, p = 0.175; Spearmans correlation test). The right panel shows VIMS difference (3D change - 2D change) against headache difference (3D change - 2D change). A statistically significant positive correlation between these two discomfort symptom groups was observed (r_s = 0.35, p = 0.001; Spearmans correlation test).

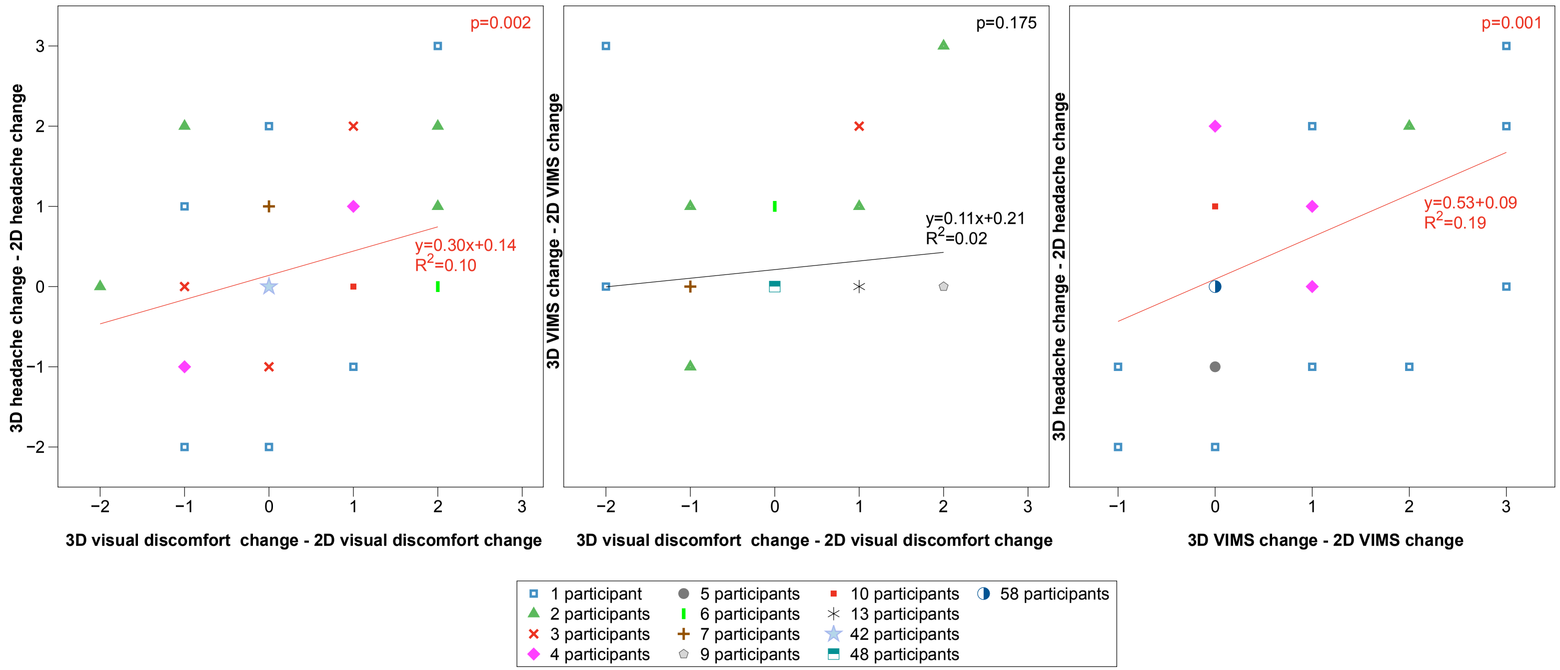


Figure 4.24: Relationship between symptoms reported by participants (3D symptom change - 2D symptom change). The left panel shows visual discomfort difference (3D-2D) against headache difference (3D-2D), the middle panel shows visual discomfort difference (3D-2D) against VIMS difference (3D-2D) and the right panel shows VIMS difference (3D-2D) against headache difference (3D-2D).

4.4 Discussion

The experimental section of the present chapter was split into two parts. In the first, analysis of the magnitude of vergence-accommodation mismatch was conducted. In the second part the difference in severity of symptoms reported by participants watching a movie in a 3D condition versus a 2D condition was analysed.

The dominant theory in the literature, regarding the reason for discomfort whilst watching 3D stereoscopic movies, is accommodation-vergence mismatch theory. Because of this it is important to analyse the magnitude of vergence-accommodation mismatch present in movies available to the public. To the best of our knowledge, no studies have provided information about the magnitude of vergence-accommodation conflict. In the current experiment three "off the shelf" movies were presented to participants (Grand Canyon Adventure [2008], Avatar [2009] and Pirates of the Caribbean: On Stranger Tides [2011]). Based on horizontal parallax, the magnitude of vergence mismatch was calculated for each of the investigated movies, and the following observations were made:

- In the movies presented in this study the mismatch between stimuli to accommodation and stimuli to vergence was present with both negative (image in front of the screen) and positive parallax (image behind the screen). The magnitude of vergence-accommodation mismatch varied between the movies. However, the average vergence-accommodation mismatch did not exceed 0.1D (negative and positive parallax) at the closer seating position (2m from screen). In terms of the magnitude of vergence-accommodation mismatch, for frames with high parallax, there were no films in which the magnitude of vergence-accommodation mismatch exceeded 1D (negative and positive parallax) at the closer seating position (2m from screen).

- The magnitude of vergence-accommodation mismatch decreases as the viewing distance increases. Based on this observation (in terms of vergenceaccommodation mismatch theory) it can be expected that participants with a closer seating position would report more visual discomfort than participants sitting further away during the viewing of 3D stimuli.

In the present study accommodation-vergence mismatch theory and visual-vestibular conflict theory were examined. Therefore, the experiment was constructed in such a way, that different conditions (i.e. viewing distances, the average magnitude of vergence-accommodation mismatch), or different participant groups (i.e. participants below 40 years of age, participants aged 40 and over) were compared to find evidence to support or disprove these hypotheses.

On the basis of the accommodation-vergence mismatch theory it was expected that a greater mismatch between a stimulus to accommodation and a stimulus to vergence would produce greater symptoms in visual discomfort whilst viewing in the 3D condition.

In the experiment there were two ways in which this expectation was tested, and in neither case was the outcome as predicted on the basis of theory. The first way of analysing this hypothesis was to compare visual discomfort difference between the 3D and 2D condition reported by three groups of participants. Each group watched different movie, and so were exposed to a different amount of mismatch between stimulus to vergence and stimulus to accommodation.

The comparison in terms of vergence-accommodation mismatch between the movies showed that the smallest mismatch in the positive parallax as well as negative parallax was observed in the movie Pirates of the Caribbean [2011] (see figures 4.4 and 4.5). Based on this comparison it was expected that less visual discomfort would be experienced by the group who watched this movie than the two other groups where the movies Avatar [2009] and Grand Canyon Adventure [2008] were presented. As shown in figure 4.6 there were no statistically significant differences in visual discomfort between the 3D condition and 2D condition in relation to the watched movie. In the group who watched Pirates of the Caribbean [2011] fewer people reported an increase in visual discomfort in the 3D condition compared to the 2D condition than for those who watched Grand Canyon Adventure [2008]. However, in the group who watched the movie Avatar [2009], slightly fewer people reported an increase of symptoms in the 3D condition over the 2D condition when compared with Pirates of the Caribbean [2011]. This observation indicates that differences in vergence-accommodation mismatch between the movies (an across movie comparison) can not be considered as an indicator of visual discomfort reported by participants.

The second way of examinating this hypothesis was to compare visual discomfort difference between the 3D and 2D conditions reported by participants at different viewing distances. As shown in figures 4.4 - 4.5 the mismatch between the stimulus to accommodation and stimulus to vergence decreases as viewing distance increases, and hence it was expected that participants seated closer to the screen would experience more visual discomfort than participants seated further away. Despite different exposure to vergence-accommodation mismatch at different viewing distances no statistically significant differences in visual discomfort were reported by participants (see figure 4.9 - 4.11).

Based on these observations it can be concluded that during the viewing of the commercially available movies (where the distance between the participant and the screen is 2m or more) a decrease in mismatch between the stimuli to accommodation and the stimuli to vergence does not affect visual comfort during the watching of 3D stereoscopic stimuli.

In the experiment three different movies were presented to the participants. The largest number of participants who reported a greater visual discomfort in the 3D condition compared to the 2D condition was observed for the movie "Grand Canyon Adventure" [2008]. This observation could be attributed to the vertical (unwanted) parallax which was larger in this movie. This speculation is consistent with the data presented by Kooi & Toet (2004), Woods et al. (1993). The alternative explanation relates to the extreme positive parallax, which in this movie slightly exceeded the average human inter-pupillary distance. The adverse effect of positive parallax on discomfort cannot be supported by the average positive parallax value, which was smaller in this movie than in "Avatar". However, it should be noted that by averaging parallax values, some information on parallax variability is lost. Additional measures of parallax dynamic properties (e.g. rate of change) might provide more detailed information on the characteristics of stimulation. This factor was not investigated in this thesis, due to resource limitations, and may be a valid subject for future work.

In our experiment more younger viewers (21 to 39 years old) then older viewers (40 years old and older) reported a greater change in visual discomfort for the 3D condition than the 2D condition. A statistically significant difference in visual discomfort between these two groups was found (p=0.02). However it has to be noted that the increase of visual discomfort in the 3D condition compared to the 2D condition did not extend beyond 2 scale points in both age groups. It is known that the amplitude of accommodation declines with age, therefore older people have a decoupled accommodation vergence response in everyday life. As a consequence changing vergence without changing accommodation could be easier or more efficient for presbyopic, than for prepresbyopic people. An alternative explanation of these findings may be related to the accommodation response. In the literature (Inoue & Ohzu 1997, Ukai & Kato 2002, Okada et al. 2006, Torii et al. 2008, Fukushima et al. 2009) it can be found that some people experience accommodation overshoot whilst viewing 3D stereoscopic stimuli. The effect of accommodation overshoot on visual discomfort during the viewing of 3D stereoscopic stimuli will be analysed in chapter 6. However, presbyopic people have a reduced ability to accommodate, and so it is unlikely that this issue will have an impact on their comfort in contrast to pre-presbyopic participants. Therefore it can be assumed, that the visual system's response to the stimulus, rather than the stimulus itself is a reason for discomfort whilst watching a 3D stereoscopic stimulus.

In terms of visual-vestibular mismatch theory it was expected that 3D stimuli would produce a greater sense of vection, increasing the sensory conflict and thus producing greater VIMS. In our experiment participants did indeed report an increase in motion sickness symptoms in the 3D condition compared to the 2D condition (see figure 4.23). Furthermore, participants with a closer seating position reported more VIMS symptoms than participants seated further away whilst viewing 3D stimuli. This observation is consistent with a study conducted by Howarth & Harvey (2007). In the current experiment and in the experiment conducted by Howarth & Harvey (2007), a larger part of the visual field was stimulated and more VIMS was reported. Based on these observations it can be concluded that the amount of visual field stimulated during 3D presentation affect VIMS, and so viewing distance, is an important factor in terms of viewing comfort.

In this study the production of headache by the viewing of 3D stereoscopic stimuli on headache was assessed. When comparing the change between two sessions a statistically significant increase of headache in the 3D condition compared with the 2D condition was observed. Moreover, the difference in headache symptoms (3D-2D) reported by participants correlated with the difference in visual discomfort (3D-2D) and VIMS symptoms difference (3D-2D) (figure 4.24). This suggests that headache whilst viewing in 3D might be caused by the same factors which lead to visual discomfort and VIMS. On the other hand, no statistically significant correlation was found between visual discomforts difference (3D-2D) and VIMS difference (3D-2D). This suggests that the factors causing visual discomfort might be different from those which lead to VIMS.

The results were also analysed in terms of gender. Because females have on average a smaller inter-pupillary distance, it was expected that they would experience larger vergence-accommodation mismatch and so more visual discomfort than males. Furthermore, as the virtual image would be positioned slightly farther from the screen in such a case, females may experience greater immersion in the presented content when compared to males. As presented in the figures 4.12 - 4.14 no statistically significant differences between these two groups were found in terms of visual discomfort, headache or VIMS. These observations however are not consistent with data presented by Yang et al. (2012) who found a gender effect for visual discomfort and VIMS. However,Yang et al. (2012) pointed out that there is no known gender difference in visual abilities, and they were therefore unable to explain these differences.

In summary, the present study has shown:

- no statistically significant difference in visual discomfort change between 3D stereoscopic movies with different magnitude of vergence-accommodation mismatch
- no statistically significant difference between visual discomfort (3D visual discomfort - 2D visual discomfort) experienced when viewing movie at different distances
- statistically significant difference between VIMS (3D VIMS - 2D VIMS) experienced when viewing 3D stereoscopic movie at different distances
- a clear age effect on visual discomfort (3D visual discomfort - 2D visual discomfort)

- no influence of gender on viewing comfort was observed
- a correlation between visual discomfort and headache, and between VIMS and headache, but not between VIMS and visual discomfort
- greater discomfort in the 3D condition compared with the 2D condition (reported by 30% of participants in terms of visual discomfort, by 24% of participants in terms of headache and by 17% of participants in terms of VIMS).

Overall, the experiment has shown multiple causative factors of discomfort during the viewing of 3D stimuli. It has to be noted that not all participants are equally susceptible to these factors.

Chapter 5

The impact of participants' fusion capacity on discomfort whilst watching movies in 3D versus 2D condition

Purpose: The study presented in this chapter aims to examine participants' fusion[1] capacity measured by their fusional reserve and to determine whether this component has an impact on discomfort reported during watching movies in 3D versus 2D conditions.

In the previous chapter the severity of symptoms reported by participants while viewing commercially available movies in 2D and 3D conditions was analysed. This chapter follows on this analysis but in relation to participants' fusion range. As horizontal parallax presented on the 3D stereoscopic screen evokes fusional vergence it can be expected that difficulty in fusion may lead to visual discomfort. Furthermore, the parallax in the 3D stereoscopic movie may exceed the limit of a viewer's fusion range, especially when a strong effect in the 3D movie is intended. It was hypothesised that participants with limited fusion range would experience more visual discomfort than participants with a wide fusion range. The

[1]Fusion - refers to vergence movement made by the eyes in response to retinal disparity and resulting in images being located on corresponding retinal points (motor fusion). This process allows the images in each retina to be synchronised into a single percept (sensory fusion).

hypothesis was analysed in terms of positive fusional reserve (PFR), negative fusional reserve (NFR) and total fusional reserve (FR=PFR+NFR). Additionally, the impact of individual fusional range on headache and VIMS was analysed.

5.1 Introduction

A 3D stereoscopic stimulus (e.g. movie, game, etc.) is made of two images of the same scene captured from two horizontally offset viewpoints. As a consequence our eyes receive two slightly different images which may stimulate disparate (non-corresponding) retinal points. The distance from the fovea for of each these non-corresponding retinal points is defined as retinal disparity[1]. When retinal disparity is detected by the visual system, fusional vergence provides inward eye movement (convergence) or outward eye movement (divergence). These movements eliminate the disparity, as the images of the fixated points fall on the foveas.

If the stimulus on the screen is displayed with negative parallax[2] the images fall temporal to the fovea and the binocular disparities are classified as crossed. This condition gives rise to the perception that the image is nearer than the screen and fixation on the stimulus produces convergent eye movement. On the other hand, if the stimulus on a 3D stereoscopic screen is displayed with positive parallax[3] the images fall nasal to the fovea and the binocular disparities are classified as uncrossed. This condition gives rise to a perception of the image being farther than the screen and fixation on the stimulus is produced by divergent eye movement. These two conditions are presented in figures 5.1.

[1] retinal disparity occurs when the object is located in front of, or behind the fixation point

[2] negative parallax - the image on the screen is shifted to the right for the left eye and to the left for the right eye

[3] positive parallax - the image on the screen is shifted to the left for the left eye and to the right for the right eye

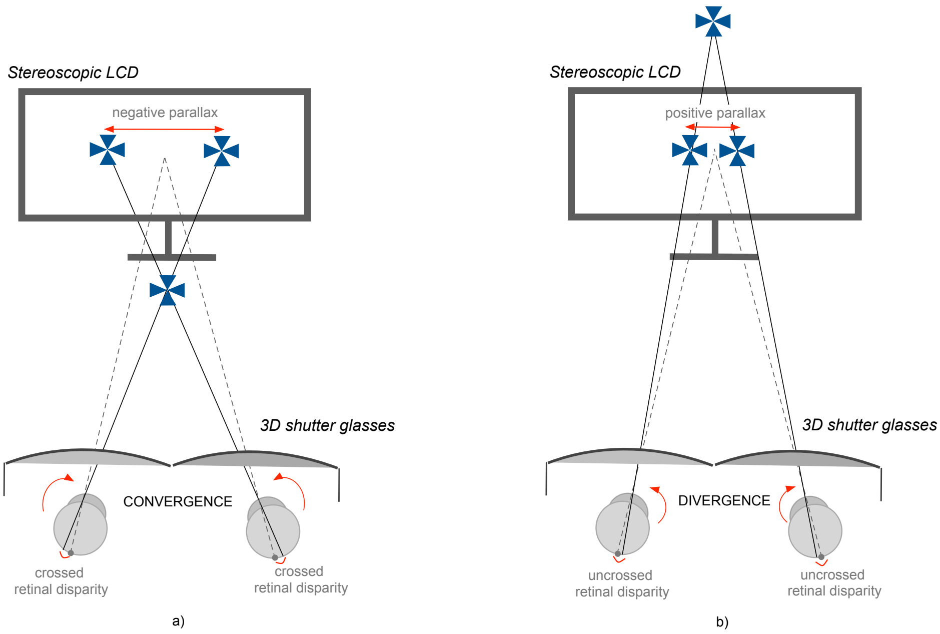


Figure 5.1: Fusional vergence eye movement when the two images are displayed on a 3D steroscopic screen with a) negative parallax b) positive parallax.

A clear perception of single stereoscopic depth can be only achieved for a limited range of binocular retinal disparities. Too large a parallax on the 3D stereoscopic screen would exceed this range and image fusion will then fail. In consequence an image which should be seen as single appears as double. This condition is know as diplopia. The disparity range within which single vision can be obtained is defined as Panum's fusional area (PFA). The angular subtense of this area is not constant over the retina and can be affected by many factors e.g: spatial frequency content of the stimulus[1] eccentricity[2] size of the stimulus[3]. Dissimilar images falling in Panum's fusional area do not fuse but exhibit binocular rivalry, in which we see two images in alternation.

[1]PFA is greater for blurred (low spatial frequency) targets than for sharp (high spatial frequency targets (Schor et al. 1984).

[2]PFA increases with retinal eccentricity of fusional stimuli i.e. with increasing horizontal distance from the fovea (Hampton & Kertesz 1983).

[3]PFA increases as size of stimulus increase to include peripheral retinal regions (Ogle 1950, Kertesz 1981).

Fusional vergence has been measured since 1948 (Rowe 2010, Fray 2013). Based on data collected over more than half of a century it is however still difficult to determine the "normal" fusional vergence value. This issue arises from the fact that metrological techniques (particularly stimulus and viewing distances) affect this binocular parameter in different ways. According to Scobee (1952) "no single value is either normal or abnormal in studies of muscle balance, but each measurement must be considered in relation to the entire examination". So far, there is no "golden" method of assessing fusional vergence. In clinical practice fusional vergence is usually measured with a Risley prism (rotary) or prism bar (Evans et al. 2007, Elliott 2013). It can also be measured with the use of vectograms or computer generated anaglyphic random dot stereograms (Feldman et al. 1989). Several researchers have shown that fusional reserves increase when measured in near fixation compared to those obtained in a distant fixation (Rowe 2010, Antona et al. 2008, Fray 2013, Von Noorden & Campos 2002). Furthermore, the size of a presented stimulus also has an impact on the fusional reserve range. In a study conducted by Feldman et al. (1993) the effect of stimulus size and the level of detail on fusional vergence was analysed. It was found in this study that positive fusional vergence and negative fusional vergence increase with the width and length of stimulus which was an unfilled square. However this was not observed when only the width of stimulus increased. No effect was seen when the square was filled with details, and the maximum fusional range was independent of the details pattern size and complexity. Feldman et al. (1993) concluded that the main factor which determines fusional vergence is the amount of retinal area contained within the boundary edges, rather than the area of direct retinal stimulation or the amount of detail a stimulus has. More recently Rowe (2010) also found larger fusional vergence values when a larger target was used. This was particularly observed for positive fusional vergence and for near distance. It is also suggested that targets which stimulate the peripheral retinal area (large targets) are more effective in terms of binocular vision (fusion) therapy (Kertesz 1982, Feldman et al. 1993). Fray (2013) showed that encouragement[1] during the measurement of fusional vergence has an impact on achieved results in

[1] Encouragement in terms of fusion reserve measurement relates to exhorting participants to keep two separate lines as a single line for as long as possible.

the case of positive fusional range (PFR) but not negative fusional range (NFR). Sheedy (1983) pointed out that at a constant accommodation level a difference of 10 Δ from one fusional vergence range measurement to another is not unusual unless rigorous controls are applied. Even a low dose of alcohol reduces positive and negative fusional reserve (Watten & Lie 1996).

As discussed, fusional vergence is a highly variable parameter of binocular vision. In the context of 3D stereoscopic stimulation it can be expected that a specific combination of the stimulus and viewing distance may increase viewers' effort to fuse images presented on a 3D stereoscopic screen. The purpose of the present study, however is not to show this, but rather to identify whether the person's fusional capability, as measured by their fusional reserves (the limits of their ability to converge and diverge their eyes) has an association with discomfort experienced whilst watching 3D stereoscopic stimulation. Furthermore, the parallax in 3D stereoscopic movies may exceed the limit of a viewer's fusion reserve especially when a strong 3D effect in the movie scene is intended. The closer one is to one's limits the more likely it is that stress or discomfort will occur. A hypothesis can be proposed that viewers with limited fusion vergence have to put more effort to fuse images on a 3D stereoscopic screen than viewers with a wider fusion range. If this is the case then participants with a wider fusion range will experience less visual discomfort than those with a narrower fusion range. Symptoms associated with fusional vergence problems are detailed in table 5.1. Furthermore abnormality of vergence eye movement (e.g. convergence insufficiency decreased positive fusional vergence) can be associated with dizziness presumably because of blurred or double vision when looking at a nearby object (Furman et al. 2010).

Table 5.1: Symptoms associated with clinical problems of convergence insufficiency, divergence insufficiency and fusional vergence disfunction.

convergence insufficiency	divergence insufficiency	fusional vergence dysfunction
eyestrain headache blurred vision double vision sleepiness difficulty concentrating on reading material loss of comprehension over time a pulling sensation around the eye movement of the print	double vision headache eyestrain nausea dizziness train and car sickness blurred vision difficulty focussing from far to near sensitivity to light	eyestrain headache inability to attend and concentrate problems with reading comprehension excessive tearing blurred vision

Scheiman & Wick (2008)

It can be seen (table 5.1) that some of these symptoms are those reported during the viewing of 3D stimuli. From clinical evidence it is known that fusional vergence is an important indicator of binocular vision status (Elliott 2013). Because of this it is expected that a limitation in fusional vergence may intensify adverse visual symptoms whilst watching 3D stereoscopic stimuli.

The expectation that the viewer's fusional vergence has an influence on discomfort whilst watching 3D stereoscopic stimuli is also consistent with what is know about the zone of clear, comfortable, single binocular vision (ZCSBV)(Hofstetter 1945) (see figure 2.1).

5.2 Methods

5.2.1 Procedure

At the beginning of the experiment fusional vergence was measured. After that participants watched one of three "off-the shelf" movies (Grand Canyon Adventure [2008], Avatar [2009] or Pirates of the Caribbean: On Stranger Tides [2011]). Each movie was presented in two sessions with a 15 minute break. Participants were divided into two groups. The first group watched the initial part of the movie in 2D and the final part in 3D. Participants from the second group did the opposite. They watched the initial part in 3D and the final part in 2D. People participating in the study from each group were seated either 2m or 4m from the screen, swapping position during the break in the movie. In this way four sets of participants were created to ensure that the experiment was balanced. Subjective symptoms were assessed before and after watching each half the movie.

5.2.2 Participants

In this experiment the same individuals participated as in the study presented in chapter 4. Ninety nine people were recruited to participate in the experiment, of which three were excluded. The reason for the exclusion of participants from the experiment was their lack of binocular vision on which the 3D technology depends. People who participated in the full-length study (n=96) were aged between 21 and 70 (average age: 37 ± 13.8 years), 50% of them were female. The participants were ethnically diverse. During the study participants wore their habitual optical correction as needed. All subjects signed a consent form after a full explanation of the experiment.

Whilst watching the movies, the participants wore 3D glasses regardless of present conditions (3D and 2D). In the 2D condition the 3D mode was switched off. In previous studies, it was reported that some participants complained about the poor quality of the glasses (their weight, their use with another set of correction glasses) (Pölönen et al. 2009). Hence, this approach was used to minimise the difference between conditions where 3D glasses are required and conditions where 3D glasses were not needed.

5.2.3 Stimulus

One of three commercially available movies: Grand Canyon Adventure [2008], Avatar [2009] or Pirates of the Caribbean: On Stranger Tides [2011] was presented to the participants. All details in terms of equipment used (screen, blue-ray player and glasses type) to show the movies were as presented in section 4.2.3. All specific aspects of the movies (horizontal parallax, vertical parallax, running time) were also presented in section 4.2.3.

5.2.4 Fusion reserve measurements

Fusional reserve was assessed by the test developed by in our laboratory (see appendix B). The test consists of two yellow vertical columns displayed against a green background on the 3D stereoscopic screen (Acer GD245HQ) at a distance of 1 m. These colours were chosen following pilot investigation to limit the impact of cross-talk. The angular size subtense of each vertical column was 0.14° in width and 9° in height. The test was created with the use of Image J software.

The fusional range examination was conducted with the use of 3D glasses, which allowed us to provide two distinct (separate) images for each eye on the same screen. The refresh rate for each eye was 60 Hz. As presented in figure 5.3a during the measurement of PFR the yellow column on the screen was shifted to the right for the left eye and to the left for the right eye. In the case of NFR measurement the yellow column on the screen was shifted to the left for the left eye and to the right for the right eye (see figure 5.3b). During testing the distance between two columns increased as required from the participant's convergent or divergent eye movement to maintain bifoveal fixation. The amount of fusional vergence was measured in prism dioptres [Δ], see figure 3.3). For example, if the distance between two vertical columns was 13 cm it was equivalent of 13 Δ at the testing distance of 1 metre. The vergence demand increased slowly and smoothly at pace of 1 Δ per second and incremental steps of 0.5 Δ. The maximum testing range was 50 Δ.

A chin rest and brow bar were employed to keep the participants head in the correct position. Participants were instructed to keep the target single as long as possible and to report when the target became doubled. Two separate vertical columns visible by the participant on the screen indicated that the fusion was broken and no longer possible. The point at which diplopia was first reported was noted as the maximal fusional range.

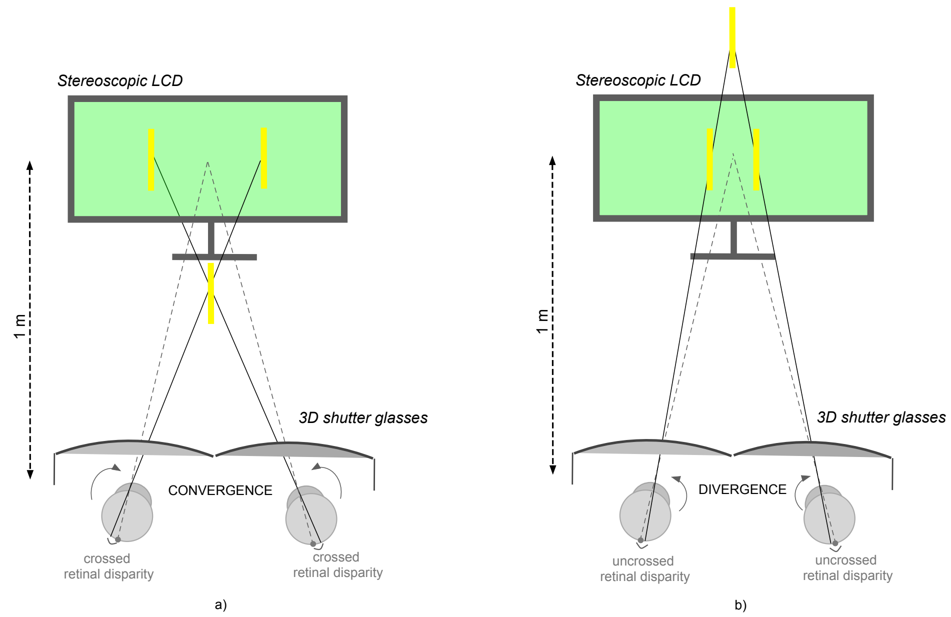


Figure 5.2: The working principle of the fusion reserve test. The two lines on the screen are seen by the separate eyes, and the single geometric image is located nearer or farther, than the screen. a) PFR test requires the patient to converge to maintain bifoveal fixation, b) NFR test requires the patient to diverge to maintain bifoveal fixation.

5.2.5 Symptom measurement

Discomfort symptoms were measured as described in section 4.2.4. As in chapter 4 and chapter 5 the same individuals participated. Changes in the severity of symptoms reported for the 2D condition and 3D condition were presented in the previous chapter.

5.2.6 Data analysis

All data were analysed using SPSS Statistica 19 (www.ibm.com / SPSS Statistics). The discomfort data were tested non-parametrically using a Wilcoxon signed rank test. The relationship between fusional range (PFR, NFR, PFR+NFR) and discomfort (visual discomfort, headache, visual induced motion sickness) was tested using Spearmans correlation test. A Shapiro-Wilks test was used to evaluate the normality of the fusional reserve (see table 5.2). The differences in visual discomfort between groups: susceptible and not susceptible to discomfort in relation to PFR and FR (PFR + NFR) were examined with the use of an independent t-test (data normally distributed). In the case of NFR the Mann-Whitney test as the nonparametric equivalent of the independent t-test was used.

Table 5.2: Test of normality

Fusional reserve	Shapiro - Wilk test (p)
PFR	0.117
NFR	0.001
RR=PFR+NFR	0.334

if: $p < 0.05$ distribution is abnormal,
$p > 0.05$ distribution is normal.

5.3 Results

The main aim of this section was to investigate whether the persons' fusional range has an impact on visual discomfort whilst watching 3D stereoscopic stimulation. Additionally, an analysis of the impact of an individual fusional range on headache and VIMS whilst watching 3D stereoscopic stimulation was conducted.

Figure 5.3 shows the mean values for fusional vergence. In terms of positive fusional vergence the mean value was 24.8 [Δ] (S.D.=11.2). In terms of negative fusional vergence the mean value was 6.3 [Δ] (S.D.=2.4). If we look at the PFR and the NFR together, the total fusional vergence was 31.2 [Δ] (S.D.= 12.0).

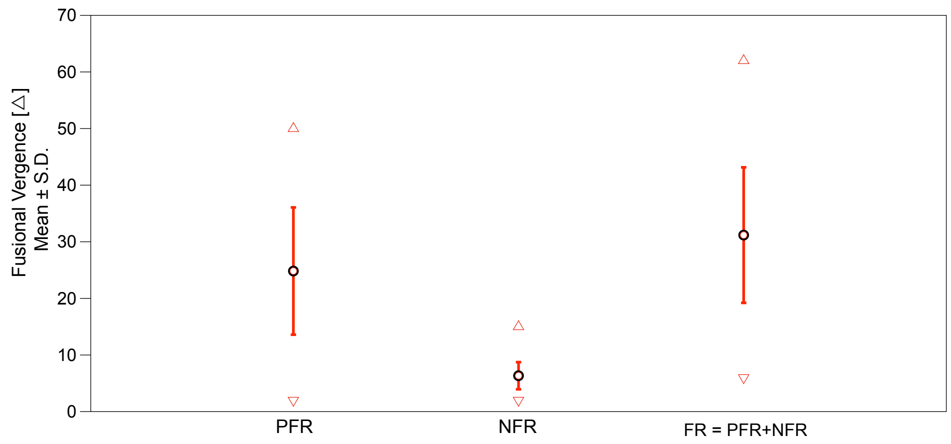


Figure 5.3: Mean fusional vergence. Errors bars indicate S.D, triangles represents the maximum (△) and minimum (▽) values.

5.3.1 Correlation between discomfort and fusional vergence

The aim of the current section is to analyse the correlation between the discomfort change reported by participants in the 2D condition, the 3D condition, the difference in discomfort between among two session and PFR, NFR, FR (PFR + NFR).

Figure 5.4 presents the relation between the change in visual discomfort reported in the 2D condition (2D post − 2D pre) and PFR (a), NFR (b) and FR (c). In the case of maximal convergent eye movement (figure 5.4a) there was no significant correlation between the change in visual discomfort reported in the 2D condition and PFR (r_s = 0.034, p = 0.744; Spearmans correlation test). In terms of maximal divergent eye movement (figure 5.4b) there was no significant correlation between the change in visual discomfort reported in the 2D condition and NFR (r_s = 0.130, p = 0.208; Spearmans correlation test). If we look at the maximal convergent and divergent eye movement all together (figure 5.4c) there was also no significant correlation between the change in visual discomfort reported in the 2D condition and FR (PFR + NFR) (r_s = 0.064, p = 0.536; Spearmans correlation test).

Figure 5.5 presents the relation between the change in visual discomfort reported in the 3D condition (3D post − 3D pre) and PFR (a), NFR (b) and FR (c). In the case of maximal convergent eye movement (figure 5.5a) there was no significant correlation between the change in visual discomfort reported in the 3D condition and PFR (r_s = - 0.190, p = 0.063; Spearmans correlation test). In terms of the maximal divergent eye movement (figure 5.5b) there was no significant correlation between the change in visual discomfort reported in the 3D condition and NFR (r_s = 0.011, p = 0.918; Spearmans correlation test). If we look at the maximal convergent and divergent eye movement all together (figure 5.5c) there was also no significant correlation between the change in visual discomfort reported in 3D condition and FR (PFR + NFR) (r_s = - 0.175, p = 0.089; Spearmans correlation test).

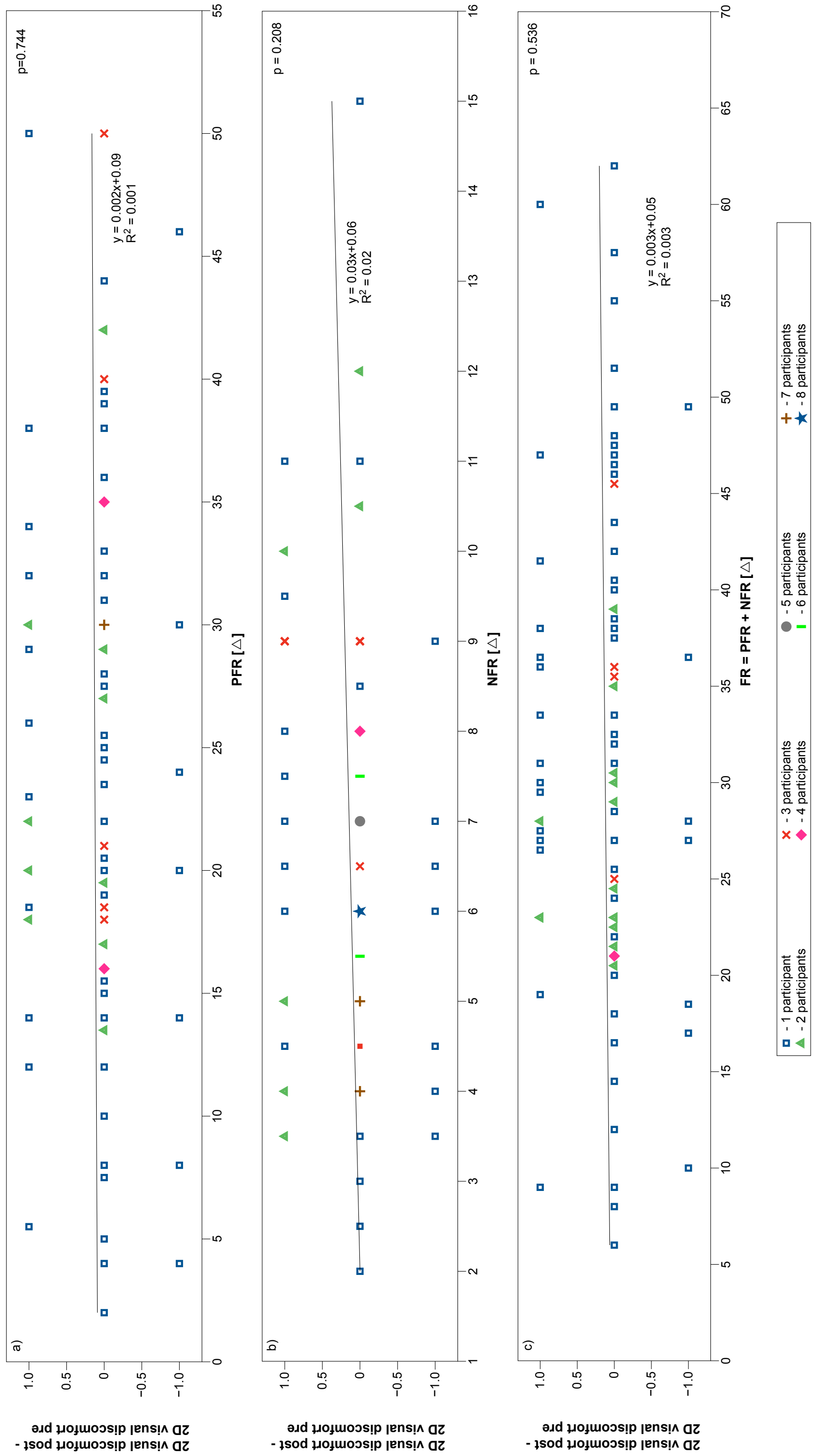


Figure 5.4: Change in visual discomfort reported in 2D condition (2D post − 2D pre) and: a) positive fusional reserve, b) negative fusional reserve, c) total fusional reserve.

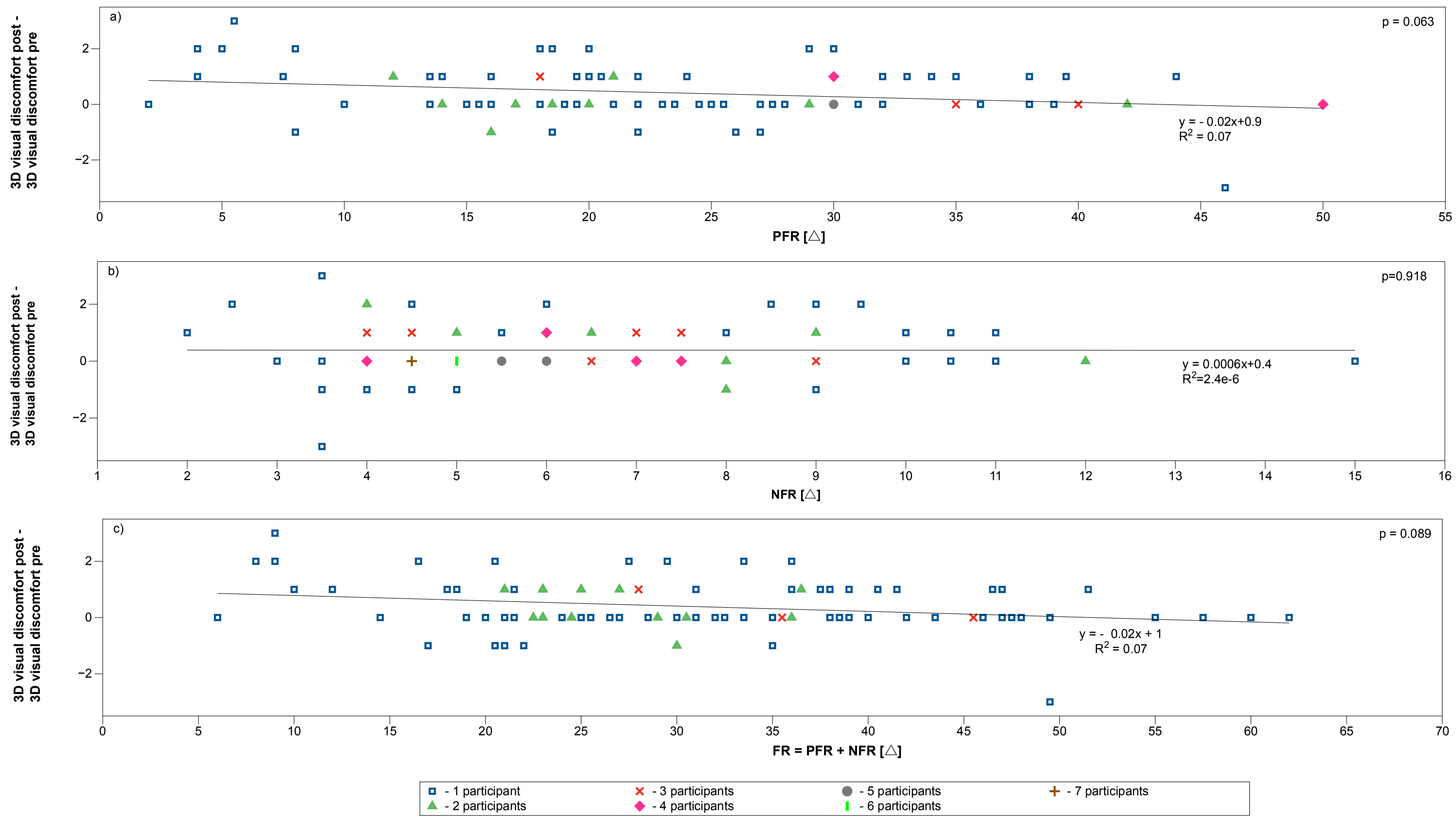


Figure 5.5: Change in visual discomfort reported in 3D condition (3D post − 3D pre) and: a) positive fusional reserve, b) negative fusional reserve, c) total fusional reserve.

Figure 5.6 shows the relation between the visual discomfort difference among two sessions (3D discomfort change - 2D discomfort change) and PFR (a), NFR (b) and FR (c). The increase of discomfort for the 3D condition in comparison to the increase of discomfort for the 2D condition was statistically significant ((p=0.005; Wilcoxon), see figure 4.21; the right column). In case of the maximal convergent eye movement (figure 5.6a) there was a significant negative correlation between visual discomfort and the PFR (r_s = - 0.215, p = 0.035; Spearmans correlation test). In terms of the maximal divergent eye movement (figure 5.6b) there was no significant correlation between visual discomfort and NFR (r_s = - 0.058, p = 0.577; Spearmans correlation test). If we look at the maximal convergent and divergent eye movement all together (figure 5.6c) there was a significant negative correlation between visual discomfort and FR (PFR + NFR) (r_s = - 0.216, p = 0.035; Spearmans correlation test).

With regard to headaches and VIMS symptoms there was no statistically significant correlation between these and PRF, NFR or FR in any of the viewing conditions. These results are presented in table 5.3.

Table 5.3: Correlation between discomfort and fusional range examined by Spearman's rank correlation test.

	PFR		NFR		FR=PRF+NFR	
	r_s	p sig. (2-tailed)	r_s	p sig. (2-tailed)	r_s	p sig. (2-tailed)
2D visual discomfort change	0.034	0.744	0.130	0.208	0.064	0.536
3D visual discomfort change	-0.190	0.063	0.011	0.918	-0.175	0.089
3D visual discomfort - 2D visual discomfort	-0.215	0.035	-0.058	0.577	-0.216	0.035
2D headache change	-0.007	0.946	-0.015	0.886	-0.009	0.929
3D headache change	-0.130	0.207	-0.067	0.515	-0.126	0.219
3D headache change - 2D headache change	-0.104	0.311	-0.070	0.500	-0.100	0.333
2D VIMS change	-0.013	0.903	0.062	0.545	-0.005	0.964
3D VIMS change	-0.096	0.350	-0.172	0.094	-0.109	0.290
3D VIMS change - 2D VIMS change	-0.057	0.581	-0.130	0.205	-0.068	0.508

r_s - Spearman correlation coefficient, p - probability value

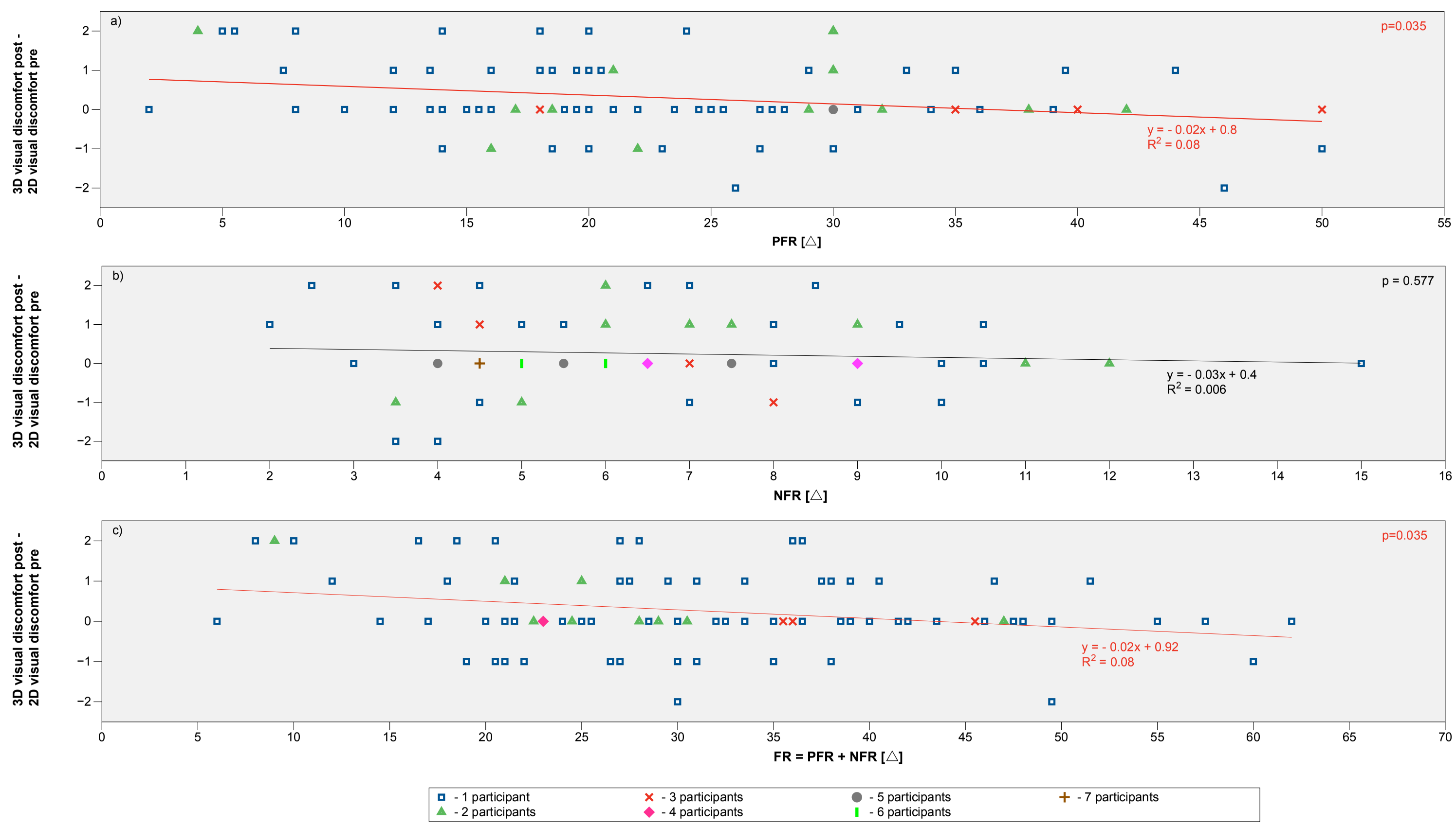


Figure 5.6: The visual discomfort difference among two session (3D discomfort change – 2D discomfort change) and: a) positive fusional reserve, b) negative fusional reserve, c) total fusional reserve.

5.3.2 Susceptibility to discomfort and fusional vergence

Based on the difference in discomfort change between the 2D and 3D conditions, participants were divided into two groups; those who did (Group 1) and those who did not (Group 2) report a greater symptoms increase in the 3D condition than the 2D condition (Figures 5.7 - 5.9). The difference between the groups in relation to PFR, NFR, FR (PRF+NFR) are shown in tables 5.4 - 5.6.

General visual discomfort

In terms of visual discomfort (table 5.4), the average fusional reserve (FR) was higher in the group not susceptible to visual discomfort than in the group susceptible to visual discomfort. The difference between these two groups was statistically significant ($p = 0.008$; the independent t-test). If we look at the PFR and the NFR independently, the PFR was significantly higher in the group not susceptible to visual discomfort ($p = 0.01$; the independent t-test). The NFR was also slightly higher in the group not susceptible to visual discomfort, but this difference was not statistically significant ($p = 0.44$; the Mann - Whitney test).

Headache

With regard to headache (table 5.5), the total fusional reserve (RF) was higher in the group not susceptible to headaches. However, this difference was not statistically significant ($p = 0.16$; the independent t-test). The PFR was also higher in the group not susceptible to headache, but again this was not statistically significant ($p = 0.15$; the independent t-test). The NFR was similar in both groups; no statistically significant differences were found ($p = 0.63$; the Mann - Whitney test).

VIMS

In the case of VIMS (table 5.6) the total fusional reserve (RF) was slightly higher in the group not susceptible to VIMS. However, these differences were not statistically significant ($p = 0.34$; the independent t-test). The PFR and NFR were also slightly greater in the group not susceptible to VIMS, but in both cases the difference between the groups was again not statistically significant ($p = 0.43$ [PFR; the independent t-test], $p = 0.22$ [NFR; the Mann - Whitney test]).

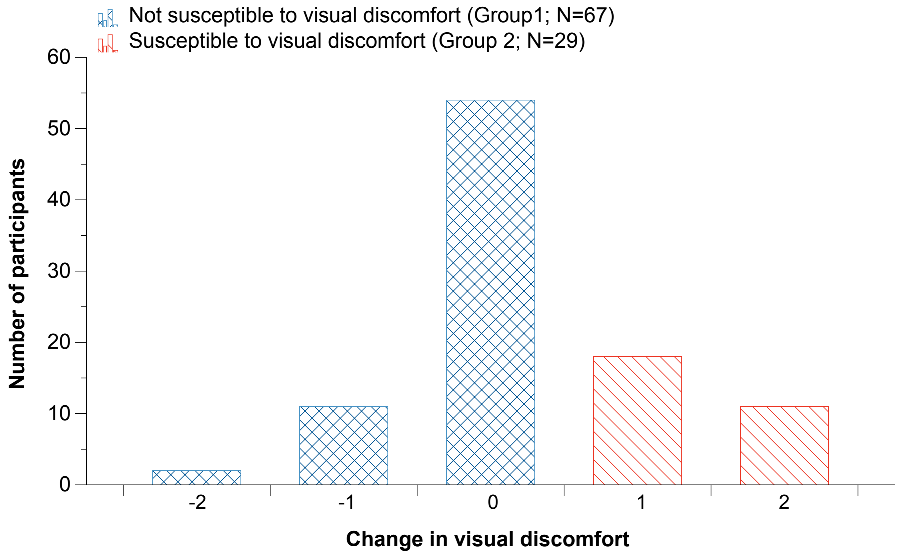


Figure 5.7: The number of participants showing each amount of difference in change in visual discomfort between the 2D and 3D conditions.

Table 5.4: Category classification for visual discomfort score change

	Susceptible to visual discomfort		Not susceptible to visual discomfort			
	Mean	SD	Mean	SD	p sig.(2-tailed)	
PFR	20.4	10.8	26.7	11.0	0.01	*independent t-test*
NFR	5.9	2.1	6.5	2.4	0.44	*Mann-Whitney test*
PR=PFR+NFR	26.3	11.5	33.2	11.5	0.008	*independent t-test*

PFR - positive fusional reserve, NFR - negative fusional reserve,
FR - total fusional reserve (FR=PFR+NFR)

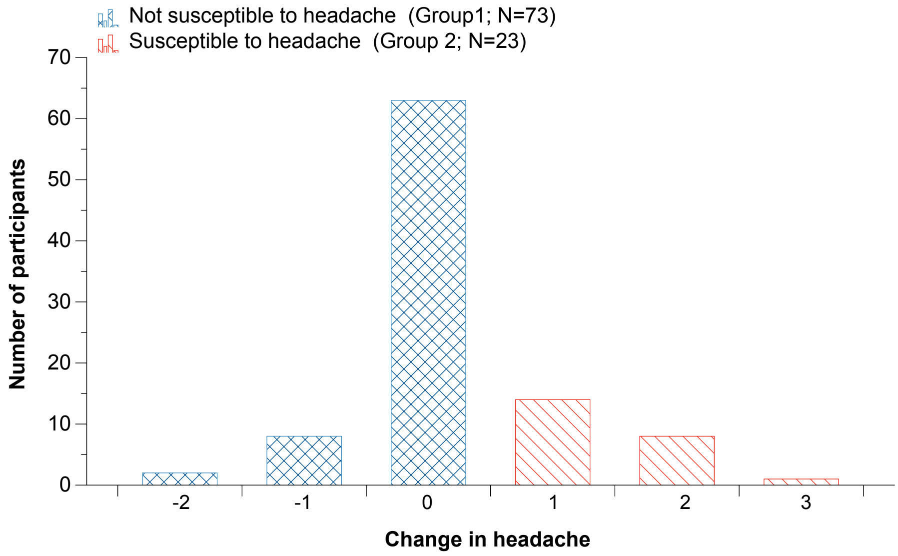


Figure 5.8: The number of participants showing each amount of difference in change in headache between the 2D and 3D conditions.

Table 5.5: Category classification for headache score change

	Susceptible to headache		Not susceptible to headache			
	Mean	SD	Mean	SD	p sig.(2-tailed)	
PFR	21.9	10.2	25.8	11.5	0.15	*independent t-test*
NFR	6.3	2.9	6.3	2.2	0.63	*Mann-Whitney test*
PR=PFR+NFR	28.2	10.4	32.1	12.3	0.16	*independent t-test*

PFR - positive fusional reserve, NFR - negative fusional reserve,
FR - total fusional reserve (FR=PFR+NFR)

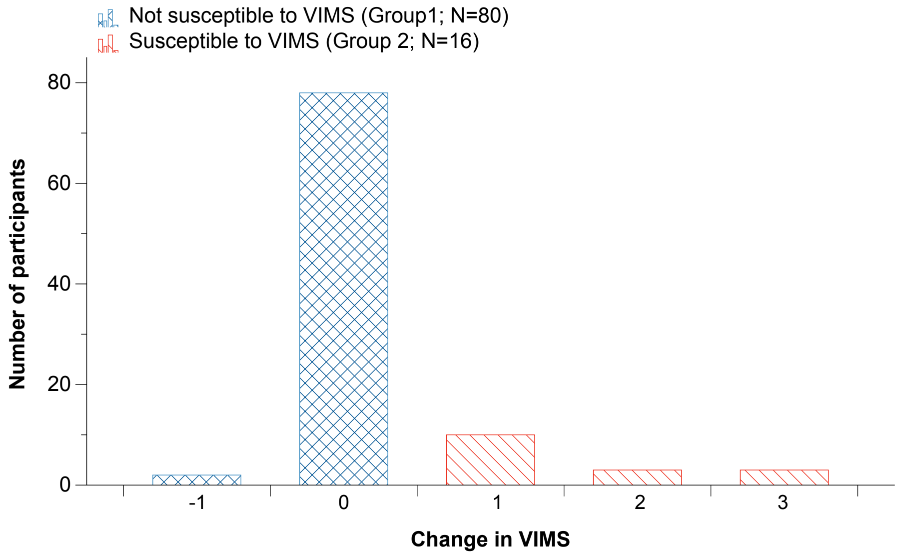


Figure 5.9: The number of participants showing each amount of difference in change in VIMS between the 2D and 3D conditions.

Table 5.6: Category classification for VIMS score change

	Susceptible to VIMS		Not susceptible to VIMS			
	Mean	SD	Mean	SD	p sig.(2-tailed)	
PFR	22.8	10.7	25.2	11.4	0.43	*independent t-test*
NFR	5.7	2.0	6.5	2.4	0.22	*Mann - Whitney test*
PR=PFR+NFR	28.5	10.6	31.7	12.1	0.34	*independent t-test*

PFR - positive fusional reserve, NFR - negative fusional reserve,
FR - total fusional reserve (FR=PFR+NFR)

5.4 Discussion

The main aim of this study was to determine whether the participants' fusional capability, as measured by their fusional reserve has an impact on discomfort whilst watching 3D stereoscopic stimulation.

The magnitude of the parallax in commercially available movies in not fixed but rather varies over the time of the movie's duration. Hence the viewer is required to continuously change vergence (convergence and divergence) to keep perceiving a singular image. Too large a parallax may exceed the viewers' fusion range, especially when a strong 3D effect in the movie scene is intended. In our experiment it was hypothesised that participants with a limited fusion reserve will have to put more effort to fuse the images on a 3D stereoscopic screen than the participants with a wider fusion range. It was assumed that the participant with the narrower fusion range would experience more visual discomfort than the participant with a wider fusion range.

The first observation which can be made from the results of this experiment is that there are large differences in the fusional range between participants. This was observed in case of PFR as well as NFR, however the range of PFR was much wider than the range of NFR as one would expect.

There was no significant correlation between visual discomfort whilst watching 2D and 3D movies and PFR, NFR or FR (PFR + NFR). On the other hand, when the difference in visual discomfort between the 3D condition and the 2D condition was taken into account a significant correlation was found between visual discomfort difference (3D VD − 2D VD) and both PFR and total FR (PFR + NFR). However, there was no statistically significant correlation between the visual discomfort change (3D VD − 2D VD) and NFR.

In the next step of our analysis, participants were split into those who did and those who did not show a greater change in visual discomfort in the 3D condition. Analysis of this data shows that participants not susceptible to visual discomfort had statistically significantly higher PFR and FR than participants not susceptible to visual discomfort.

The overall conclusion of the study is that participants' capability to vergence has a significant impact on visual comfort. Interestingly, this was found only in the case of convergent but not divergent eye movement. A likely explanation of these findings is that the presented stimuli required more convergent eye movement and less divergent eye movement. Participants were possibly less frequently required to fuse images presented behind the screen than in front of the screen. Another explanation is that the variability between participants in terms of NFR was much smaller than in terms of PFR. Hence, the effect of NFR on visual discomfort was more difficult to observe. On the other hand, as was mentioned in the introduction, reduced PFR can suggest that some nonstrabismic binocular vision anomalies occurred. It can be speculated that symptoms associated with this binocular vision disorder (see table 5.1) intensify while viewing 3D stereoscopic stimuli in relation to symptoms reported while watching 2D stimuli.

The results are consistent with knowledge of the zone of clear, comfortable, single binocular vision (ZCSBV). Based on this it can be predicted that participants with normal binocular vision will not experience visual discomfort during the viewing of 3D stereoscopic stimulations, as long as apparent parallax does not exceed their fusional range (comfort zone)(Howarth 2011). On the other hand, vision training/orthoptic exercises have been shown to improve the strength of positive fusional reserves and reduce symptoms related to asthenopia (Scheiman et al. 2005a,b, Scheiman & Wick 2008, Cooper & Feldman 2009). It can be expected that watching 3D stereoscopic stimuli (e.g. movies, games etc.) can also have a positive impact on fusional reserve.

Additionally, the impact of individual fusional range on headache and VIMS was analysed. This was mainly motivated by the fact that some of the symptoms associated with binocular vision problems are related to headache and VIMS (see table 5.1). In this case however we failed to find any correlation between fusion range and headache or between fusion range and VIMS. Furthermore, there was no statically significant difference in terms of fusional reserve between participants susceptible and not susceptible to headache and between participants susceptible and not susceptible to VIMS. Based on this it can be concluded that the increase of headache or VIMS in the 3D condition compared with the 2D condition is not related to participants' fusion capability.

The experiment conducted was mainly focused on the level of discomfort experienced (3D-2D) and the participants fusion capacity. However, in the further analysis of this problem it would be useful to see whether discomfort experienced by participants is acceptable to them and whether the viewers, despite experienced discomfort, can enjoy the 3D movie. The answer to this question might be useful in two ways. Firstly, this information can be helpful to determine the amount of parallax, which give participants an enjoyable 3D experience. Secondly, it can determine whether vision training based on 3D stereoscopic technology can by enjoyable for people with binocular vision problems . The next issue, which is worth considering in terms of further research, relates to the findings from the previous study (please see figure 4.6). In the previous study it was observed that the largest number of participants who reported a greater visual discomfort in the 3D condition compared to the 2D condition was observed for the movie Grand Canyon Adventure [2008]. This observation could be attributed to the vertical (unwanted) parallax, which was larger in this movie. Therefore in the further analysis of the effect of 3D stereoscopic stimuli on discomfort it is important to analyze not only the effects of vertical parallax on discomfort but also the effect of participants vertical capacity to vergence and discomfort.

To measure fusional reserve a 3D stereoscopic test developed by the author was used. The main motivation behind creating this test was to stimulate the convergent and divergent eye movement in the same way as happens during the watching of 3D stereoscopic movies or games. Moreover, the technique used in this study eliminates problems which occur when Risley prisms or a prism bar are used (chromatic aberrations, large steplike changes of prismatic power especially in terms of prism bar) and allows examination of fusional reserve in much wider range than when standard methods are used. Based on our observations it can also be concluded that 3D stereoscopic technology can be easily adapted for binocular vision measurement, allowing the measure of fusional reserve up to 50 Δ.

Chapter 6

Accommodation discrepancy whilst viewing 3D stereoscopic stimuli

Purpose: Stereoscopic 3D displays provide each eye with two slightly different images produced on a flat screen. The horizontal separation (parallax) between the left and the right image allows stimuli to be perceived in front of, or behind the screen. Change in the amount of horizontal parallax causes the displayed stimulus to change its position. Viewing a stimulus whose position alters produces a change in the stimulus to vergence, but no change in the stimulus to the accommodation system (the distance between the screen and the viewer is fixed). However, the accommodation and vergence systems are coupled and the stimulus to vergence response also drives the accommodation response. Similarly the stimulus to accommodation response also drives the vergence response. Ramsdale & Charman (1988) have shown that convergence input does influence accommodation response. Moreover, target proximity (awareness of the nearness of the object of regard) also has an influence on the oculomotor system (PIA - proximally induced accommodation[1], PIV - proximally induced vergence) (Rosenfield

[1]Proximal accommodation - proximally induced accommodation (PIA). Is the amount of accommodation induced by an individuals awareness of the proximity of an object (Keirl & Christie 2007). For example the viewer may accommodate at the distance at which they believe the target to be located. Proximal accommodation is not voluntary although it is evoked when

et al. 1991). As a consequence accommodation response may not be equal to the accommodation stimulus during the viewing of 3D stereoscopic stimuli.

More recent studies reported that substantial inter-subject variation in the accommodative response occurs during the viewing of 3D stereoscopic stimuli. The following variations were observed: accommodation overshoot, oscillation and a stable accommodation response (Inoue & Ohzu 1997, Ukai & Kato 2002, Okada et al. 2006, Torii et al. 2008, Fukushima et al. 2009).

The current chapter aimed to examine the response of the accommodation system to the change in the 3D stimulus position and to determine whether any of the changes would account for the visual discomfort reported during the viewing of 3D stimuli.

a person voluntarily changes gaze from an object at one apparent distance to an object at another apparent distance (Howard 2012).

6.1 Introduction

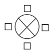
In the real world the stimulus to accommodation and the stimulus to convergence are identical. By contrast the 3D stereoscopic display produces a stimulus to accommodation provided by the image on the screen, and a stimulus to convergence provided by the geometrical location of the image (Rushton et al. 1994, Ukai & Howarth 2008, Hoffman et al. 2008, Lambooij et al. 2009, Howarth 2011, Yang et al. 2012). Modelling of the accommodation and convergence system suggests that the accommodation response consists of two components: fast - driven by binocular disparity (the stimulus to convergence), and slow - driven by the blur in the retinal image (Khosroyani & Hung 2002). The fast component response to the step target disparity[1] with an open-loop movement nearly reaches the desired level, and then the slow component uses closed-loop feedback to reduce the residual error and provide an accurate steady-state response (Hung & Ciuffreda 2002). When the fast component is active, the slow component is disabled and vice versa (Khosroyani & Hung 2002). Hoffman et al. (2008) suggested that during the viewing of 3D stimulus the fast and slow components attempt to drive accommodation to different values because stimuli to accommodation and stimuli to convergence do not match. The disparity-driven component produces a rapid response to the accommodation state that does not minimise blur. Subsequently the slow component senses the error and feeds the cross-coupled system to correct the overshoot or undershoot produced in the initial phase (or by the initial response).

A number of studies have shown substantial inter-subject variation in the accommodative response during the viewing of 3D stereoscopic stimulus. Three forms of dynamic accommodation response were reported in previous studies. These are: accommodation overshoot, oscillation and a stable response (Inoue & Ohzu 1997, Ukai & Kato 2002, Okada et al. 2006, Torii et al. 2008, Fukushima et al. 2009). Moreover, occasionally an initial erroneous direction of accommodation response was observed (Torii et al. 2008). Table 6.1 presents an overview of similar experiments reported in the literature. Figure 6.1 schematically illustrates accommodation overshoot when stimulus changes from being on the screen

[1]disparity does not change (increase/decrease) smoothly/progressively but in steps.

to being in front of it.

Table 6.1: An overview of previous experiments where accommodation overshoot was observed with stimulus changed from being on the screen to being in front of it (negative parallax).

Researchers	target used	no. of participants in the experiment	no. of participants experiencing accommodation overshoot
Inoue & Ohzu (1997)		3	1
Ukai & Kato (2002)		3	1
Okada et al. (2006)		5	?
Torii et al. (2008)		7	4
Fukushima et al. (2009)		8	3

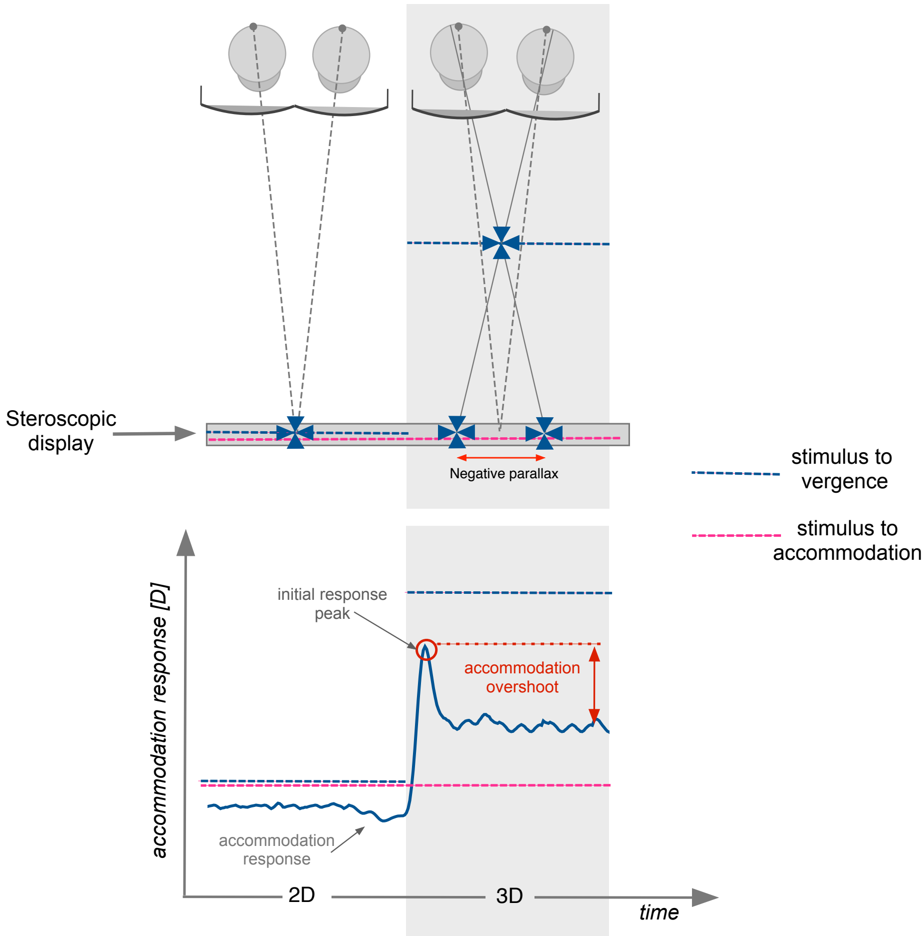


Figure 6.1: An illustration of accommodation overshoot for initial accommodation response with the stimulus change from on the screen to in front of it.

Inoue & Ohzu (1997) used an infrared optometer (Nidek AR-1100) to measure the accommodation response during the viewing of a visual target (a white-filled square with crossed lines) displayed on a CRT monitor with shutter system. In the experiment, after the target changed from being located at the position of the screen to being located in front of it, accommodation overshoot was observed. In the experiment only three participants were tested and the analysis of results took into account only one of them.

Ukai & Kato (2002) used a video refractor (PR-1000,Topcon, Japan) to measure accommodation response during the viewing of a visual target (a cross and a circle, which subtend a visual angle of 1.0° surrounded by four squares that have no disparity) displayed on a LCD monitor via an image splitter. In the experiment accommodation overshoot and oscillations were observed when the target moved from being located at the position of the screen to being located in front it. Again data only for one participant were presented in the study.

Okada et al. (2006) used a modified autorefractor (Shin-Nippon, Japan) to measure dynamic accommodation response during the viewing of a black Maltese Cross displayed against a white background on a stereoscopic liquid crystal display. The display had a parallax barrier, which generated two images presented to each eye separately. They hypothesised that the static accommodation response during the viewing of the 3D stimulus is the balance point between convergence-driven accommodation that pulls accommodation toward the viewer, and defocus-driven accommodation that pulls it to stay at the screen position (this is consistent with the earlier findings of Ramsdale & Charman (1988)). Their participants viewed a Maltese Cross target at three levels of Gaussian blur[1] (0 - no blur, 16 and 32 minutes of arc). The perceived position of the Maltese Cross moved between being located at the position of the screen to being located in front of it (negative parallax). Researchers reported that static accommodation was closely matched to the screen position when the target was sharp and closely matched to the convergence stimulus when the target was blurred. The results of Okada et al. (2006) are presented schematically on figure 6.2. It was also reported that accommodation overshoot was observed when the target had a high or a medium spatial frequency. However, the magnitude of overshoot was not clear due to difficulties in aligning the refractor during convergent eye movement.

[1]Gaussian blur is a low pass filter. It removes high spatial frequency components from the image. Mathematically Gaussian blur is equivalent to the "weighted average" of each pixel's neighbourhood.

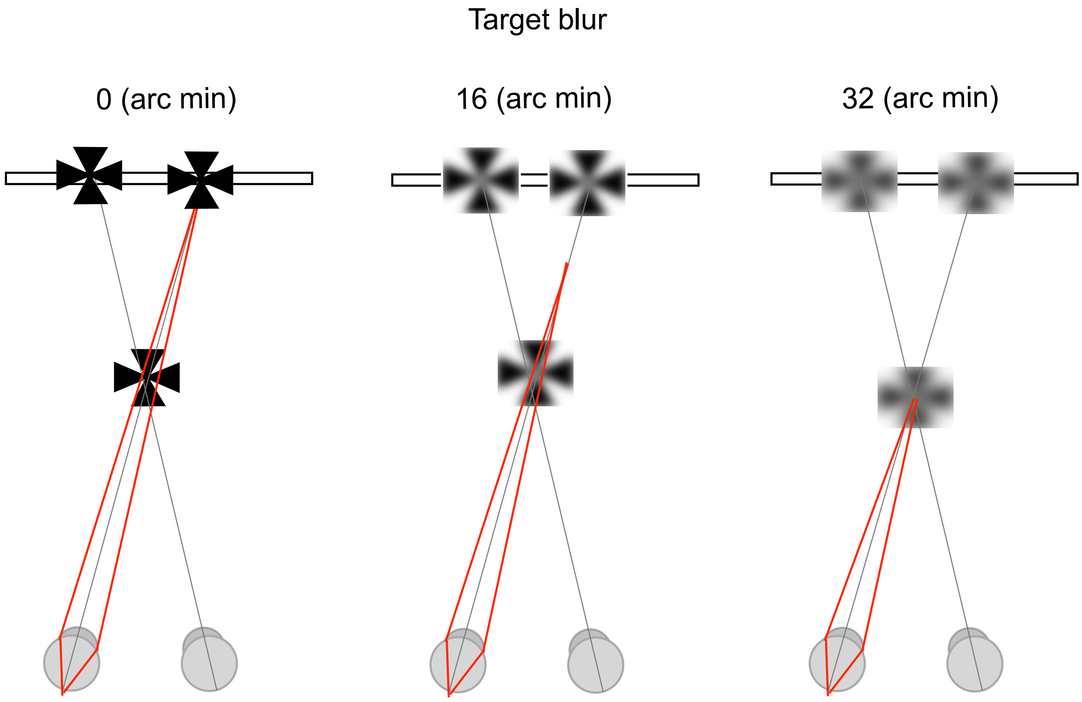


Figure 6.2: Accommodative static responses when viewing 3D stereoscopic image depends on the target blur (based on Okada et al. (2006)). The static accommodation response during the viewing of the 3D stimulus is the balance point between convergence-driven accommodation that pulls accommodation toward the viewer, and defocus-driven accommodation that pulls it to stay at the screen position

Torii et al. (2008) used a modified video refraction unit (PR-1000, Topcon, Japan) to measure the dynamic accommodative response during the viewing of a black Maltese Cross displayed against a white background on a stereoscopic liquid display with parallax barrier. The perceived position of the Maltese Cross moved repeatedly in a step-wise manner from being located at the position of the screen to being located in front of the screen. The Maltese Crosses were presented with the following levels of Gaussian blur: 0 (no blur), 16 and 32 minutes of arc (min arc). For comparison, the responses were compared with responses to stimuli presented in non-stereoscopic mode[1] (2D stimulus presented with use of a semi-transparent mirror).

[1]In non-stereoscopic mode the parallax barrier was switched off.

The hypothesis proposed was again that the transient response to step stimuli is initiated by convergence-driven accommodation and subsequently followed by the slow component of accommodation modulated by blur. Accommodation overshoot was evident in four out of seven subjects when the stimulus was presented in stereoscopic mode and in the case of one subject when the stimulus was presented in non-stereoscopic mode. One participant experienced accommodation oscillation when the target was sharp. Torii et al. (2008) also showed that the static accommodation response grew with an increase of target blur in the case of four participants and did not change with an increase of target blur in the case of two participants.

In terms of the overshoot maximum no clear trend was observed. One participant showed a decrease of overshoot peak with an increase of target blur; one participant presented the opposite effect; three participants showed a decrease of overshoot peak for 16 min arc Gaussian blur, but an increase of overshoot peak for 32 min arc Gaussian blur. Convergence-accommodation in this experiment was not measured.

The experiments of Okada et al. (2006) and Torii et al. (2008) have been expanded by Fukushima et al. (2009) who used the same experimental setup to measure accommodation response while viewing 3D stimuli as Torii et al. (2008). In their experiment a sharp, black Maltese Cross on a white background (high contrast) was presented in stereoscopic mode and in non-stereoscopic mode. In the stereoscopic mode the perceived position of Maltese Cross moved between being located at the position of the screen to be located in front of it. They hypothesised that the accommodation overshoot is influenced by the CA/C ratio[1] as follows: "an initial convergence response, induced by proximity of the 3D stereoscopic image, generates convergence-driven accommodation proportional to CA/C ratio; the associated transient defocus subsequently decay to a balanced position between defocus-induced and convergence-induced accommodation". The researchers found a positive correlation between CA/C ratio and accommodation overshoot when the stimulus was presented only in stereoscopic mode. In this experiment accommodation overshoot of at least 0.3 D was observed in three out

[1] The CA/C ratio is defined as the amount of accommodation that is stimulated by convergence (CA - convergence accommodation) per unit change in convergence (C).

of eight participants when the 3D stereoscopic stimulus was presented.

Based on the results of these experiments it appears that dynamic accommodation response during the viewing of the 3D stimulus is characterised by temporary accommodation overshoot for some people (approximately one third of participants (see table 6.1)).

The results of previous studies have led to the idea that people with a high CA/C ratio during the initial accommodation, respond more strongly to convergence stimuli than people with a low CA/C ratio which produces temporary accommodation overshoot. The amount of accommodation overshoot may also be expected to be influenced by the spatial-frequency content of the stimulus, but this issue is not clear.

In all of these studies, the only response that has been studied is to a change in the geometric position of the stimulus from "on the screen" to "in front of it". If we change the position of the stimulus from being located "in front of the screen" to being located "on the screen", a decrease of accommodation should be expected. In this situation there is a mismatch between the stimulus to accommodation and the stimulus to convergence at the starting point but there is no mismatch when the stimulus returns to the 2D position. Because there is no conflict there is perhaps no expectation of a consistent accommodation overshoot or undershoot. On the other hand, there is a fast change of the image from the conflicting position, which could also have an influence on the initial accommodation response. In these circumstances accommodation undershoot may be expected among participants. In the past, this direction of stimulus change was only briefly discussed by Torii et al. (2008). An additional consideration here is that all of the above studies have only used a stimulus which moves from the screen to a position in front of it (negative parallax). However, the data in chapter 4 show that films can contain both negative parallax (image perceived in front of the screen) and positive parallax (image perceived behind the screen)(see figure 4.2). To date, no research has been done on accommodation responses when the stimulus is moved to a position behind the screen (positive parallax).

In the current experiment it is hypothesised that when the perceived position of the stimulus changes from being located at the position of the screen to being located behind the screen, an accommodation undershoot will be observed. Consequently, when the perceived position of the stimulus changes from being located behind the screen to being located at the position of the screen, accommodation overshoot should be observed. Additionally, the effect of the spatial-frequency content of the stimulus on accommodation discrepancy will be analysed.

The final question to be addressed relates to the link between accommodation discrepancy and visual discomfort. It is clear that when the distance between the viewer and the screen is small, accommodation plays an important role when viewing 3D stereoscopic stimuli (as it does with 2D stimuli). Whether an imprecision in accommodation response can, in itself, produce visual discomfort is not known. Accommodation overshoot was observed (as was described above) as a temporary excessive response to stimuli presented in front of the screen. In the literature it can be found that people who experience accommodative excess suffer from blurred vision; headache; eyestrain, and; difficulty focusing from far to near (Scheiman & Wick 2008). It can be seen that some of these symptoms are those reported during the viewing of 3D stimuli. However in our experiment, a transient excessive response (accommodation overshoot), not all accommodation responses are analysed. It is not known what number of accommodation overshoots participants may experience whilst viewing 3D stereoscopic movies. However, the characteristics of changes in perspective during the viewing of 3D movies suggests that participants (with high CA/C ratio) may experience a correspondingly high number of accommodation overshoots.

To sum up, this chapter addresses the following questions:

- Is accommodation discrepancy observed when the stimulus position changes from “on the screen” to “in front of the screen”?
- Is accommodation discrepancy observed when the stimulus position changes from “in front of the screen” to “on the screen”?
- Is accommodation discrepancy observed when the stimulus position changes from “on the screen” to “behind the screen”?
- Is accommodation discrepancy observed when the stimulus position changes from “behind the screen” to “on the screen”?

- Does the spatial-frequency content of the stimulus have an influence on accommodation discrepancy?
- Is accommodation response discrepancy influenced by individual CA/C ratio?
- Do participants who experience accommodation response discrepancy also report more visual discomfort during the viewing of a 3D movie than those who do not?

To answer these questions the experiment was split into two parts. In the first, the response of the accommodation system to a change in stimulus location was measured and accommodation discrepancy was calculated. In the second part the same group of participants watched a movie. Experienced discomfort was then assessed. Finally the participants' discomfort was evaluated in the context of the participants accommodation discrepancy.

6.2 Methods

6.2.1 Apparatus

The stimuli were presented on an Acer GD245HQ computer screen using a NVIDIA GeForce GTX580 graphic card (www.nvidia.com). The display was viewed through active shutter glasses. The lenses in these glasses darken and lighten alternately in synchrony with the computer screen, providing a separate image for each eye at a refresh rate of 60 Hz.

Accommodative responses were measured dynamically at a rate of 25 Hz using the PowerRefractor. The PowerRefractor operates on the principle of eccentric photorefraction. It consists of video camera and rows of infrared LEDs arranged eccentrically to the optical axis of the camera (figure 6.3).

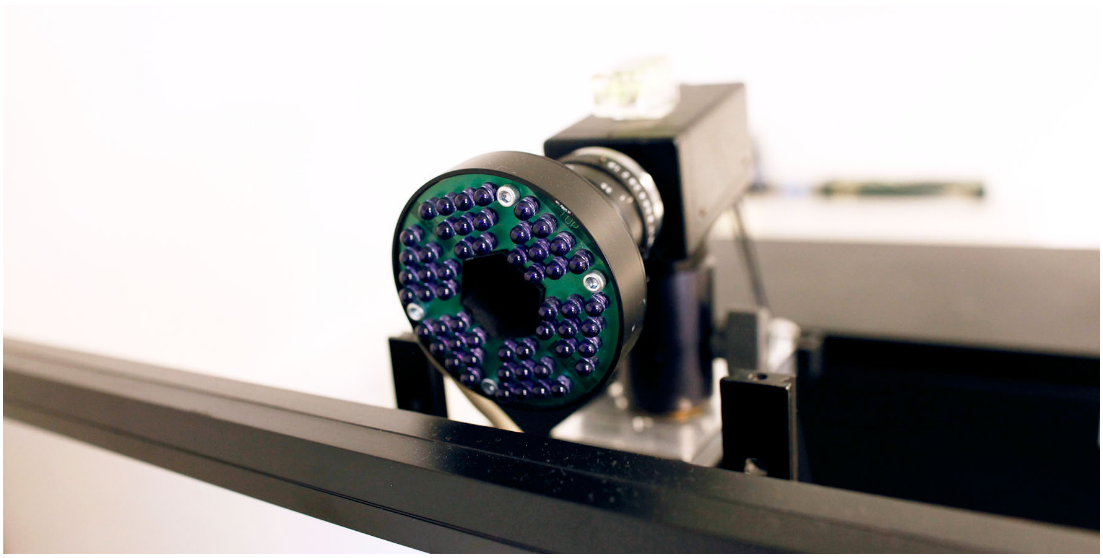


Figure 6.3: The PowerRefractor camera.

The infrared from the photorefractor is reflected from the retina and forms a brightness profile along the vertical meridian of the pupil. Based on the slope of the profile the accommodation state of the eye is determined (Schaeffel et al. 1993, Wolffsohn et al. 2002). If the eye is accurately focused at the camera distance, no reflected rays enter the camera aperture and the pupil is flatly illuminated (figure 6.4 a). However, if the eye is focused in front of camera the reflected light is divergent and only rays from the bottom of the pupil can enter the camera aperture (because the lower part of camera apertures is occluded by a black mask). A luminance gradient is created in the pupil with most light in the bottom of the pupil (figure 6.4 b). Consequently, if the eye is focused more distant than the camera, only rays from the top of the pupil can enter the camera aperture. A luminance gradient is created in the pupil with most of the light in the top of the pupil (figure 6.4 c).

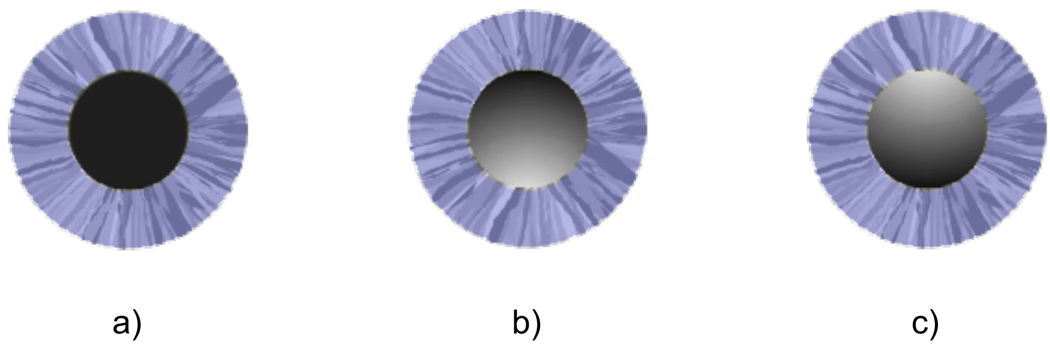


Figure 6.4: Topical reflexes observed in eccentric photorefraction a) the eye is focused on the camera lens, b) the eye is focused closer than the camera, c) the eye is focused more distant than the camera.

During the experiment the photorefraction camera was attached to the top of the 3D stereoscopic screen which was located 1 metre from the subject (figure 6.5). The participant's head position was stabilised using a chinrest. PC number 1 generated the sequences of 3D stimuli on the screen. PC number 2 was used to control correctness of the adjustment of the experimental setup. If the adjustment was correct a green frame appeared around the pupil, whereas if the adjustment was not correct a red frame appeared around the pupil (see figure 6.8). Measurement failed if the pupil size was smaller than $< 3.7 \pm 1.0$ mm, if the pupil was covered by the eyelid or if the light reflection occurred on the 3D glasses. PC number 2 was also used to acquire the experimental data. Image analysis was carried out using dedicated software developed in LabView 2010.

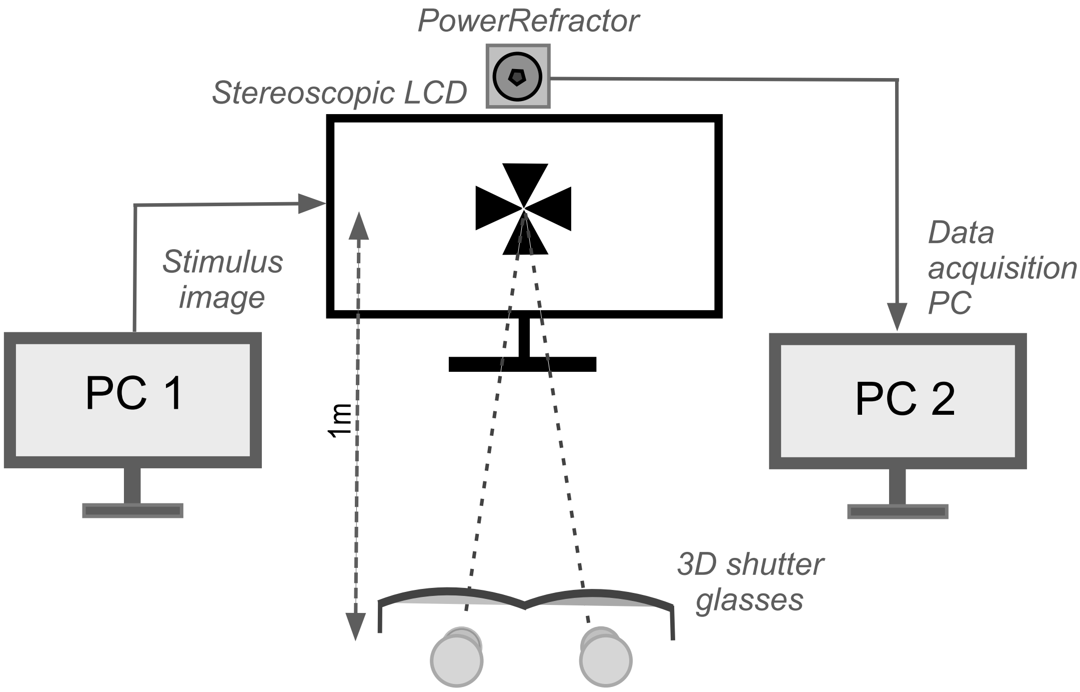


Figure 6.5: Schematic drawing of the apparatus

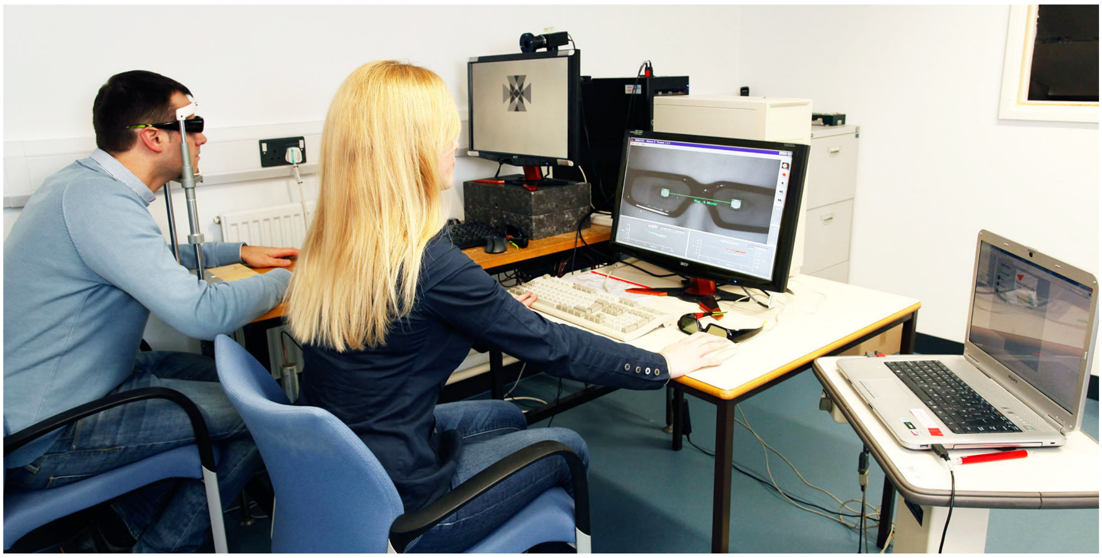


Figure 6.6: Experimental setup

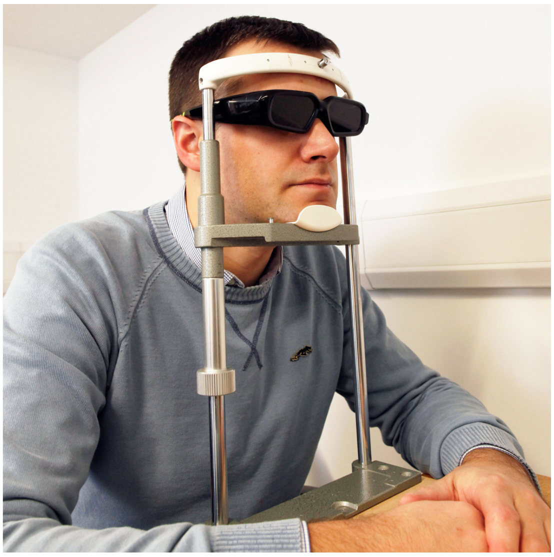


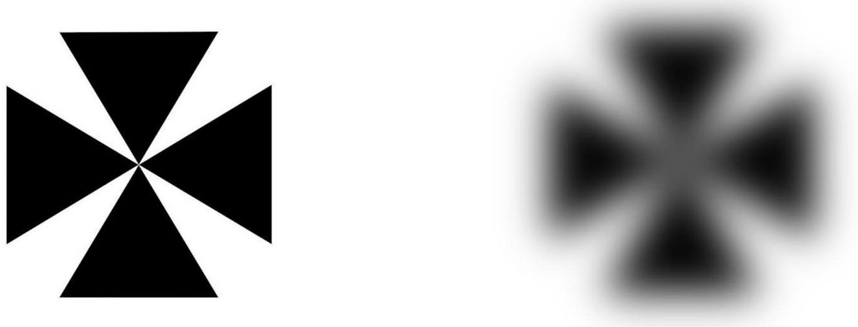
Figure 6.7: A participant positioned to perform the experiment, his head was stabilised using a chin rest.

Figure 6.8: PC 2 used to control correctness of adjustment of the experimental setup.

6.2.2 Stimuli

6.2.2.1 Maltese cross

Two variants of a Maltese Cross were presented on the 3D stereoscopic computer screen: a black Maltese Cross displayed against a white background and a yellow Maltese Cross displayed against a green background. The second target was generated specifically to limit the impact of cross-talk. The angular subtense of each Maltese Cross was 6.5° in both width and height. The targets were created in Autodesk 3DS Studio Max software (see appendix C). The Maltese Crosses were presented with two levels of Gaussian blur. Blurred images were created by applying a Gaussian filter to originals. Image processing was followed in Image J software package. Gaussian blur levels used in the experiment were 0 (no blur) and 19 min arc. Figures 6.9 and 6.10 show examples of sharp and blurred targets.



a) b)

Figure 6.9: Black Maltese crosses displayed against a white background a) no blur b) 19 min arc Gaussian blur.

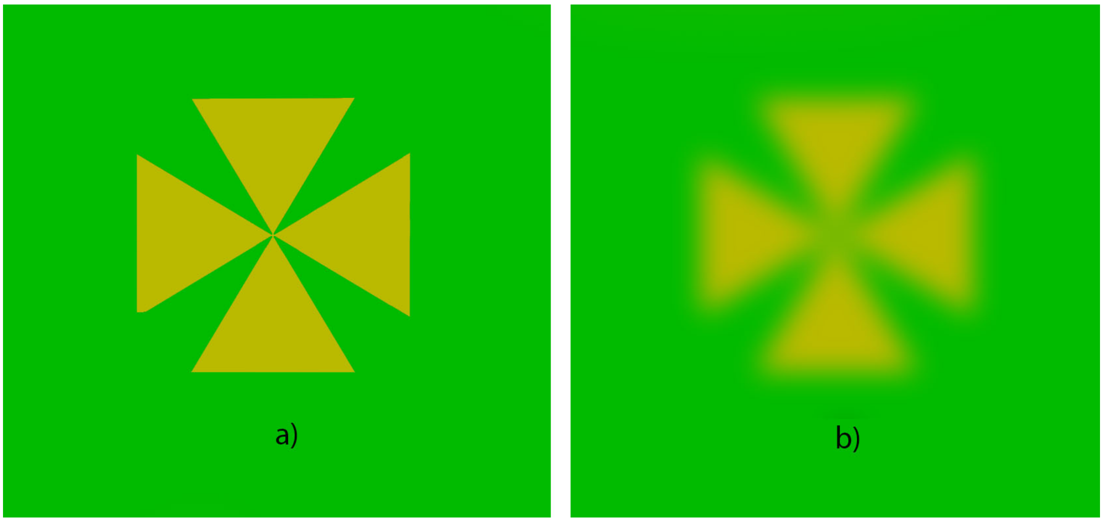


Figure 6.10: Yellow Maltese crosses displayed against a green background a) no blur b) 19 min arc Gaussian blur

6.2.2.2 3D/2D Movies

Thirteen fragments of popular movies (see table 6.2) were selected and shown to the participants on two separate occasions. On one the movies were presented stereoscopically in 3D, and on the other it was in 2D (as a control condition). Each condition was applied on a different day, with half of the participants viewing the 3D condition first, and other half the 2D condition first. In each case the movies were watched for 36 minutes 12 seconds. As can be seen in figure 6.11 some of the movies had a much wider range of parallax than others. Fragments of various 3D movies were selected to create a credible representation of parallax range and to remove the effect of movie-specific content on discomfort. Selected fragments also differed in terms of type of movie (fantasy, comedy, science fiction, action, adventure, thriller, romantic). The movie fragments used were relatively short and in isolation should not have a significant effect on discomfort measurement. In the experiment discomfort was measured after viewing the whole series of movies. Moreover, some of the movies had been originally created in 3D (live action footage, CGI) while the others had been synthetically converted from 2D format to 3D format (table 6.2). In our experiment we did not target differences between different 3D content creation technologies, and for that reason, the amount of native 3D and 2D→3D converted movies was balanced.

If we treat all the movie fragments as one stimulus then the mean negative parallax was 2.77±1.88mm and the mean positive parallax was 6.38±3.38mm. The maximum negative parallax was 62.32mm (Rio (2011)) and the maximum positive parallax was 42.86mm (Immortals (2011)) (figure 6.11). Parallax in the movies has been analysed by CS MSU Graphics & Media Lab team (Lomonosov Moscow State University, Russia)

Table 6.2: Movies presented in the experiment

Movies	Time	Technique
Gulliver's Travels (2010) a	1min 48sec	2D-3D conversion
Gulliver's Travels (2010) b	1min 28sec	2D-3D conversion
I, Robot (2012) a	3min 45sec	2D-3D conversion
I, Robot (2012) b	1min 20sec	2D-3D conversion
Ice Age (2009) a	1min 56sec	Created in 3D
Ice Age (2009) b	2min 22sec	Created in 3D
Immortals (2011)	4min 14sec	2D-3D conversion
Avatar (2009)	6min 38sec	Created in 3D
Prometheus (2012)	2min 48sec	Created in 3D
Rio (2011)	3min 32 sec	Created in 3D
The Darkest Hour (2011)	1min 33sec	Created in 3D
The Chronicles of Narnia (2010)	2min 43sec	2D-3D conversion
Titanic (2012)	2min	2D-3D conversion

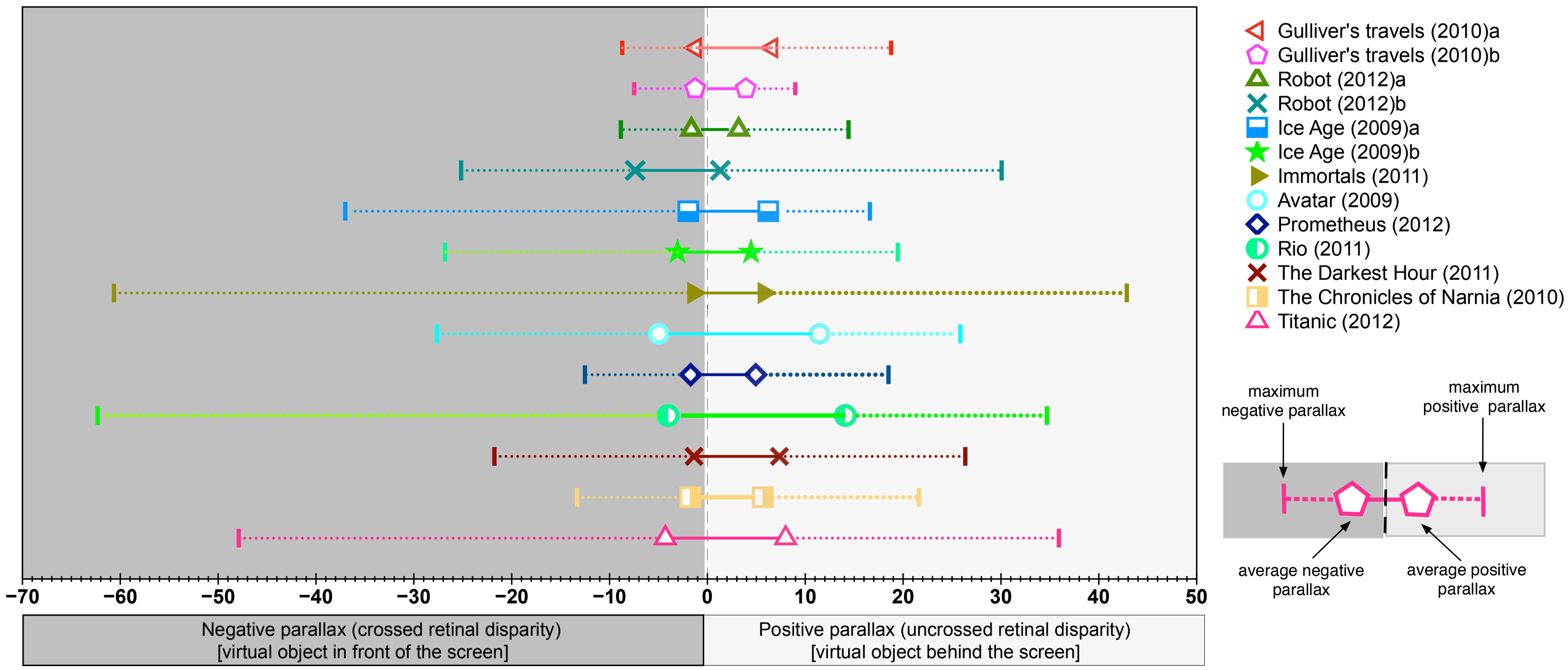


Figure 6.11: Average and maximum horizontal parallax used in the 3D movies [mm] (scaled for Acer GD245HQ; 23.6")

6.2.3 Measurement of CA/C ratio

The CA/C ratio is defined as the amount of accommodation that is stimulated by convergence (CA - convergence accommodation) per unit change in convergence (C). In 1940, Fry defined convergence accommodation as "the amount of accommodation which is fully associated with convergence when the need for exact focusing has been eliminated". The procedure of measurement of CA/C ratio requires an adequate means of opening the accommodation loop while convergence is stimulated. Opening the accommodation loop can be done by making blur-driven accommodation ineffective. This may be achieved by looking through a pinhole (an artificial pupil) (Ward & Charman 1987, Winn et al. 1991). Pinholes $\leqslant$ 0.5 mm produce a large depth of focus and so there is no blur feedback to guide the accommodation response. An alternative method of opening the accommodation loop is by stabilising the blur stimulus to accommodation using the difference of Gaussian (DoG) target (Kotulak & Schor 1987, Tsuetaki & Schor 1987, Baker & Gilmartin 2002). Several studies have verified that DoG target with 0.2-0.1 c/deg do not provide a stimulus to blur driven accommodation (Tsuetaki & Schor 1987, Rosenfield 1989, Baker & Gilmartin 2002).

In this study, to open the accommodation loop a 0.1 c/deg, difference of Gaussian target (DoG) was used (figure 6.12). The target was generated using Octave software package (see appendix E). The DoG target subtended an angle of 16.8° in both width and height at 1m.

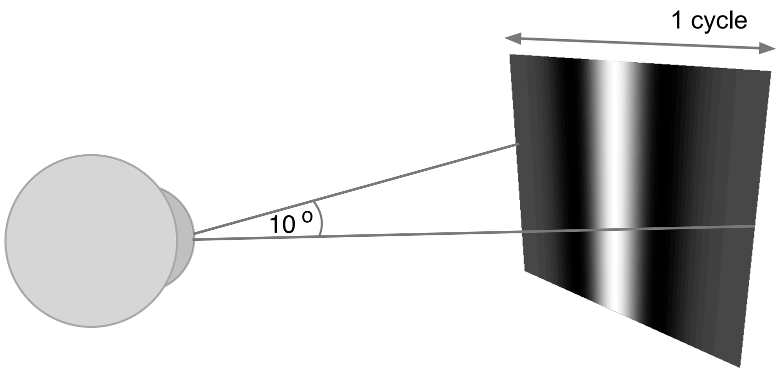


Figure 6.12: An observer's eye looking at a 0.1 c/deg DoG target, which resemble a bright, blurred, vertical bar with a dark, blurred vertical bar on either side.

Two DoG targets were displayed on the 3D stereoscopic screen (the same screen as the one used to display the Maltese Crosses and the movies). One DoG target was displayed for the right eye and one DoG target for the left eye figure (6.13). Targets were viewed through active shutter glasses. The vergence of the DoG targets was controlled by horizontal parallax between the targets. When these were presented with negative parallax three magnitudes were used 3,6 and 8 cm (equivalent to 3,6 and 8 $\triangle$ base-out). When targets were presented with positive parallax two magnitudes were used: 3, 6 cm (equivalent to 3 and 6 $\triangle$ base-in).

The DoG target does not stimulate the accommodation system, and so when the parallax was introduced the stimulus to convergence changed but stimulus to accommodation remained constant. Thus any change in accommodation state must have been a consequence of a change in convergence-driven accommodation.

Accommodation was measured using the same instrument (see figure 6.5) as those used to measure dynamic accommodation responses. For each convergence stimuli the accommodative response was measured for 5 s.

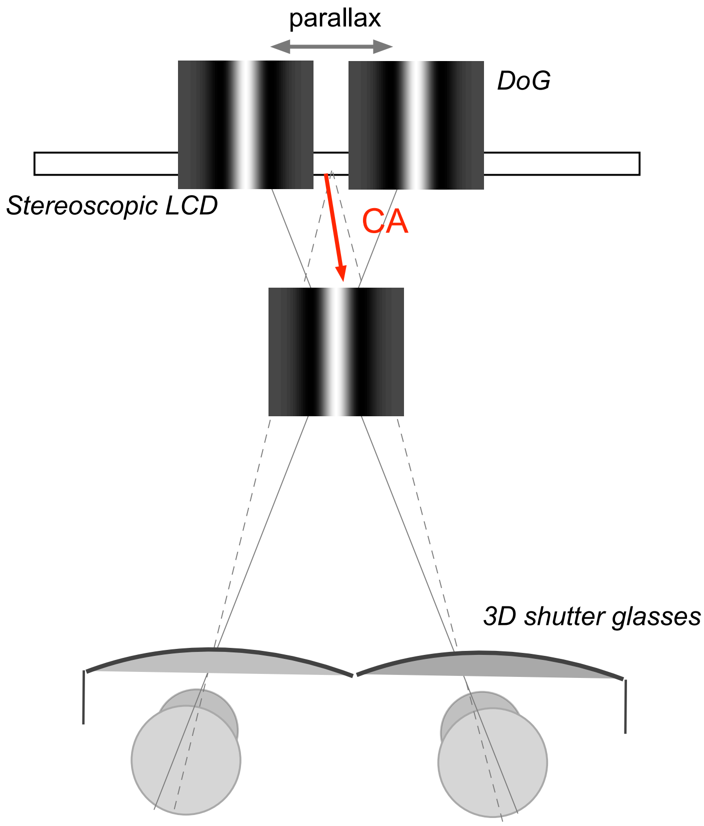


Figure 6.13: Measurement of CA/C ratio. Convergence accommodation (CA)-accommodation induced directly by a change in convergence (C).

6.2.4 Measurements of accommodation discrepancy response

The accommodation discrepancy response was measured under two conditions (four variants in total). Figure 6.14 presents the schematic drawing of each condition.

In condition one the stimulus was presented with negative parallax (crossed retinal disparity) which produces a single image located geometrically "in front of the screen". In this situation the image is shifted to the right for the left eye and to the left for right eye (see 6.14 top row, middle column).

In condition two the stimulus was presented with positive parallax (uncrossed retinal disparity) which produces a single image located "behind the screen". In this situation the image is shifted to the left for the left eye and to the right for the right eye. (see 6.14 top row, middle column).

For each condition the stimulus was changed from 2D format (i.e. the right and left eye images being located at the same position on the screen) to 3D format (i.e. different locations, as described above) (2D→3D) and then changed back from 3D format to 2D format (3D→2D). During the initial six seconds of measurement the stimulus was presented in 2D format, from the sixth to twelfth seconds the stimulus was presented in 3D format, and for the last six seconds the stimulus was presented in 3D format. In the first set of trials (condition 1 in figure 6.14) the stimulus was shown firstly with negative parallax with values 40mm, 56mm, 72mm in turn. The second set of trials (condition 2 in figure 6.14) used positive parallax with values: 40mm, 56mm, 72mm. The stimuli were presented in the same order for all participants.

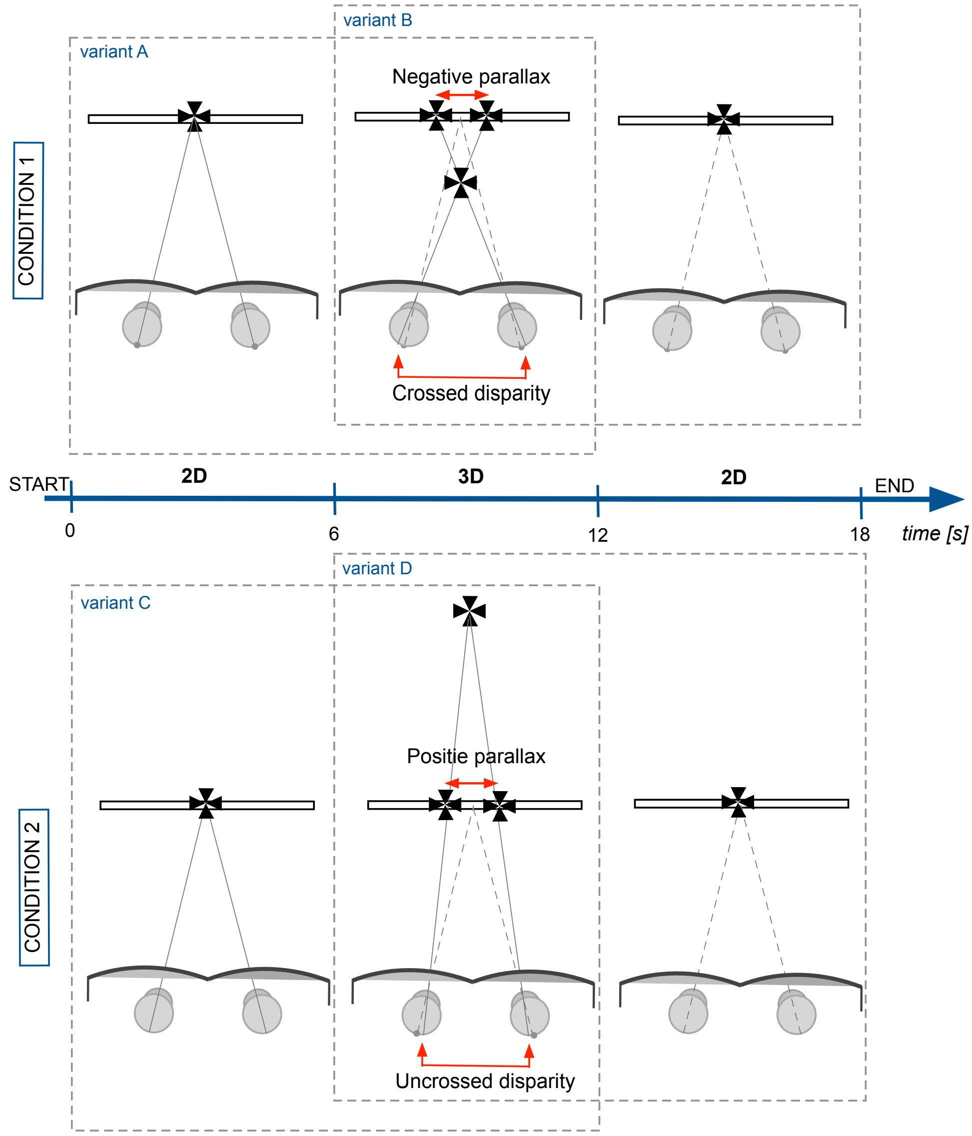


Figure 6.14: Measurement procedure for accommodation discrepancy response.

6.2.5 Participants

Fourteen pre-presbyopic people participated in the experiment. They were aged between 19 and 34 (mean age: 23.7 ± 4.9 years). All participants had normal vision and did not report binocular vision anomalies. Participants were requested to maintain, if possible, binocular single vision during all trials.

92.9% of participants were able to fuse the Maltese Cross target when the negative parallax (crossed retinal disparity) was used and 71.4% of the participants were able to fuse the Maltese Cross target when the positive parallax (uncrossed retinal disparity) was used.

Two potential participants were excluded from the experiment because their pupil size was too small which prevented accommodation measurement. All subjects signed a consent form after a full explanation of the experiment.

6.2.6 Analysis of accommodation response discrepancy

Analysis of accommodation discrepancy was conducted using the method presented by Fukushima et al. (2009). In the current experiment the accommodation discrepancy was measured in four variants.

In the first variant the perceived position of the stimulus changed from being located at the position of the screen to being located in front of the screen (see figure 6.14 - variant A). In this situation the accommodation discrepancy was termed accommodation overshoot.

In the second variant the perceived position of the stimulus changed from being located in front of the screen to being located at the position of the screen (see figure 6.14 - variant B). In this situation the accommodation discrepancy was termed accommodation undershoot.

In the third variant the perceived position of the stimulus changed from being located at the position of the screen to being located behind the screen (see figure 6.14 - variant C). In this situation the accommodation discrepancy was termed accommodation undershoot.

In the fourth variant the perceived position of the stimulus change from being located behind the screen to being located at the position of the screen (see figure 6.14 - variant D). In this situation the accommodation discrepancy was termed accommodation overshoot.

The accommodation discrepancy was calculated as the difference between initial response peak and static response (initial response peak - static response).

If the accommodation discrepancy was negative, over/under-accommodation was not observed. Figure 6.15 shows the schematic diagram used for calculations of accommodation overshoot when the stimulus changes from being on the screen to being in front of it (negative parallax).

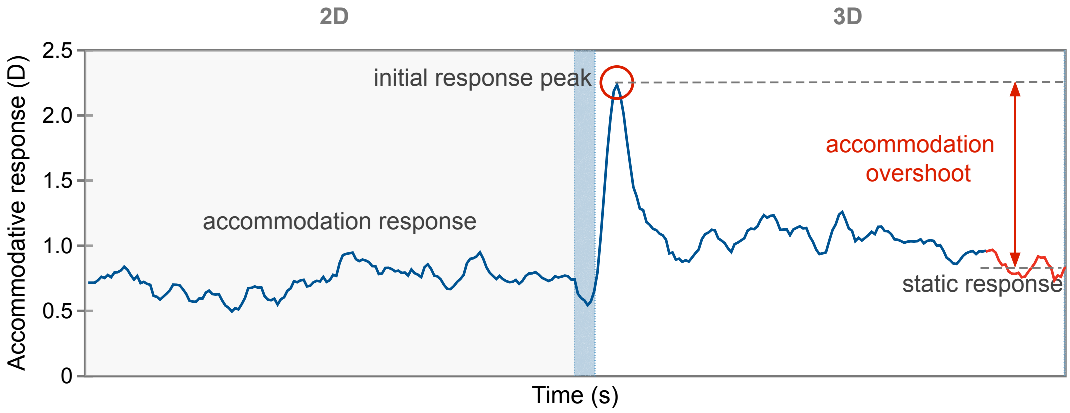


Figure 6.15: Accommodation discrepancy calculation with stimulus change from being on the screen to being in front of it. The accommodation discrepancy was defined as (accommodation overshoot)=(initial response peak)-(static response). Blue shaded area - response delay zone.

The initial response peak was defined as the first local maximum to occur later than 0.25 s after the stimulus change from being on the screen to being in front of it (this is shown in figure 6.15 as the blue shaded area - the response delay zone). The static response was defined as the average response between the 11th and 12th second of observation (accommodation just before the end of the 3D condition). This is shown as red lines in figure 6.15.

Figure 6.16 shows the schematic diagram used for calculating accommodation undershoot with a stimulus change from being in front of the screen to being on the screen.

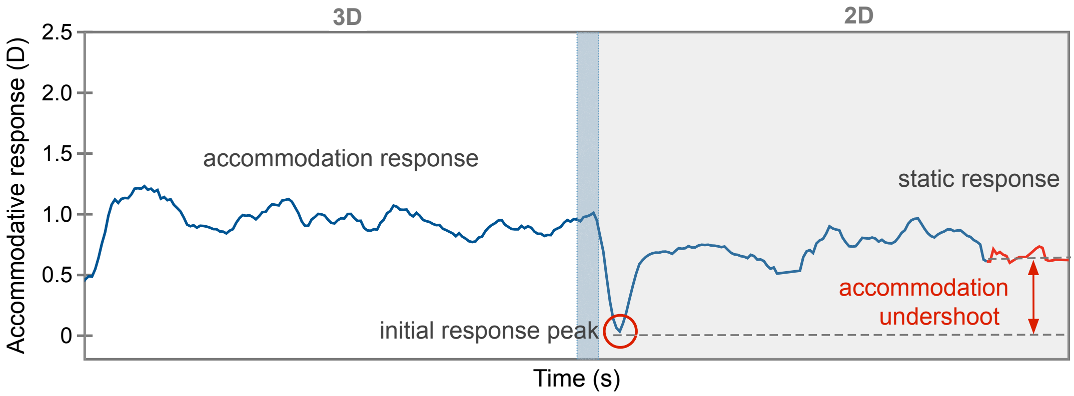


Figure 6.16: Accommodation discrepancy calculation with stimulus change from being in front of the screen to being on the screen. The accommodation inaccuracy was defined as (accommodation undershoot)=(initial response peak)-(static response). Blue shaded area - response delay zone.

The initial response peak was defined as the first local minimum to occur later than 0.25 s after the stimulus change from being in front of the screen to being on the screen. The static response was defined as the average response in the last 1s of measurement/observation (accommodation just before the end of the 2D condition).

The same procedure was used to calculate accommodation discrepancy when the perceived position of the stimulus changed from being located at the position of the screen to being located behind the screen and back again.

The justification for assessing the first local maximum/minimum to occur 0.25s after stimulus change from 2D format to 3D format and from 3D format to 2D format (2D⇆3D) is based on convergence latency as defined in (Fukushima et al. 2009) (0.2 s in Schor's model (Schor 1992)).

6.3 Results

6.3.1 Accommodation responses discrepancy

The results section is organised as follows. First the overall (pooled)[1] data will be examined. Second the effect of target spatial frequency (blurred or sharp target) will be determined. Third the effect of individual CA/C ratio on accommodation discrepancy will be examined. Fourth the effect of accommodation discrepancy on visual discomfort will be analysed.

In our experiment five different forms of dynamic accommodative responses were seen during viewing of 3D stereoscopic stimuli. These were: stable response, overshoot, undershoot, erroneous accommodative response and oscillation. Please see figures 6.20 - 6.26.

Figure 6.17 shows the mean accommodation response discrepancy when the stimulus was presented with negative parallax (top) and with positive parallax (bottom).

Negative parallax

The mean accommodation overshoot seen when the stimulus changed from “on the screen” to “in front of the screen” was 0.26±0.34 [SD] D (see figure 6.17 top, left), and the mean accommodation undershoot when the stimulus changed from “in front of the screen” to “on the screen” was 0.04±0.19 [SD] D (see figure 6.17 top, right). One participant could not fuse the images when the maximum parallax (72mm) was used.

[1] As will be shown, there is little effect of blur or colour on accommodation discrepancy. The same stimulus seen for all four variants will have only a small difference in magnitude, so pooling the results together for an initial analysis of the data will minimise the noise of the data

Positive parallax

The mean accommodation undershoot seen when the stimulus changed from being "on the screen" to being "behind the screen" was 0.00±0.17 [SD] D (see figure 6.17 bottom, left), and the mean accommodation overshoot when the stimulus changed from "behind the screen" to "on the screen" was 0.28±0.40 [SD] D (see figure 6.17 bottom, right). Four participants could not fuse the images when the maximum parallax was used and one participant when the medium (56 mm) parallax was used.

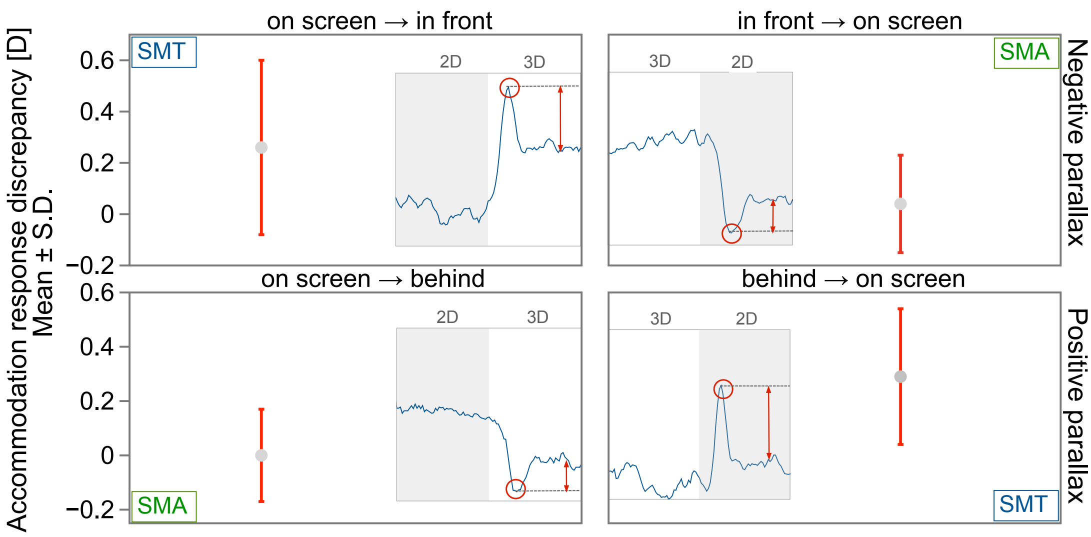


Figure 6.17: Mean accommodation response discrepancy for negative parallax (top) and positive parallax (bottom). SMT - the stimulus moved towards the viewer, SMA - the stimulus moved away from the viewer.

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When the stimulus changed from "in front of the screen" to "on the screen" and from "on the screen"to "behind the screen" some participants experienced an anomalous initial accommodation response in the wrong direction, before changing in the correct direction. In both of these situations the stimulus moved away from the person. An anomalous response was never seen when the stimulus moved towards the person.

These responses are presented separately in figure 6.18. The mean erroneous accommodation response was 0.99±0.48 [SD] D and 0.42±0.38 [SD] D for stimulus change from “in front of the screen” to “on the screen” and from “on the screen” to “behind the screen”, respectively. An initial accommodation response in the wrong direction was observed frequently for four of the participants, occasionally for four of the participants, and only once for the other four participants. Data where the participants initially accommodated in the wrong direction are excluded from further analysis in this chapter.

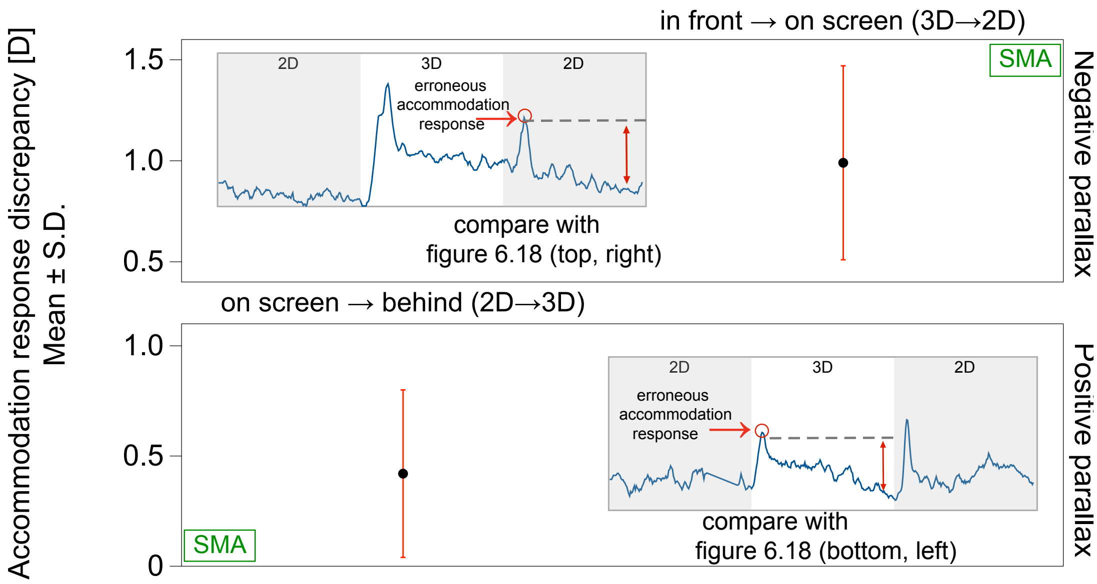

Figure 6.18: Mean erroneous accommodation response for stimulus presented with negative parallax (top) and presented with positive parallax (bottom). Next to the plots examples of erroneous accommodation responses are shown. SMA - the stimulus moved away from the viewer.

To sum up, five different forms of dynamic accommodative responses were seen during the viewing of 3D stereoscopic stimuli. These were: stable response, overshoot, undershoot, erroneous accommodative response and oscillation. Figures 6.19 to 6.26 show examples of accommodation response in negative and positive parallax.

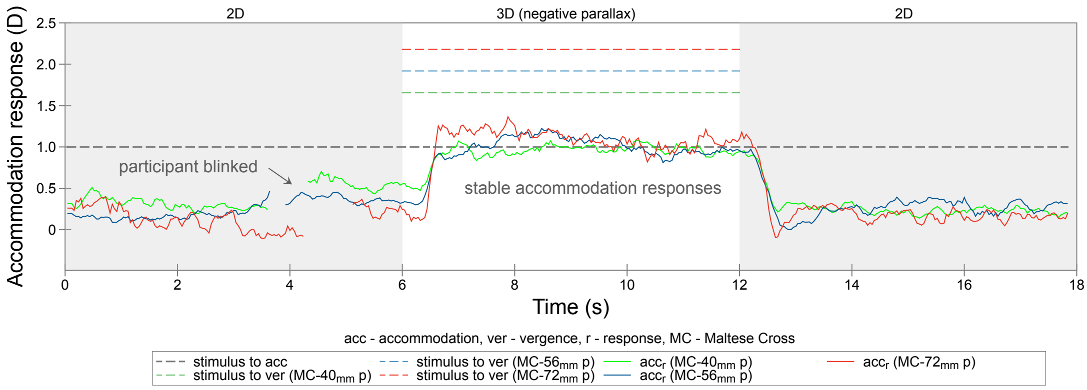

Figure 6.19: Stable accommodation response: Initial accommodation responses when the stimulus changes from "on the screen" to "in front of the screen" are almost identical to static accommodation response. When the stimulus changes to a position from "in front of the screen" to "on the screen" very small accommodation undershoots are observed.

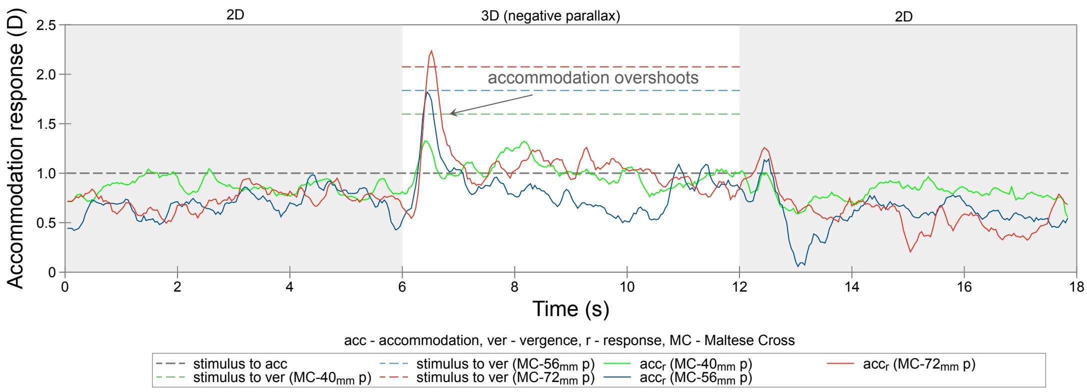

Figure 6.20: Overshoot: Accommodation overshoots when the stimulus changes from "on the screen" to "in front of the screen". When the stimulus changes from "in front of the screen" to "on the screen" an initial accommodation response increases in the opposite direction to expected and then decreases as expected.

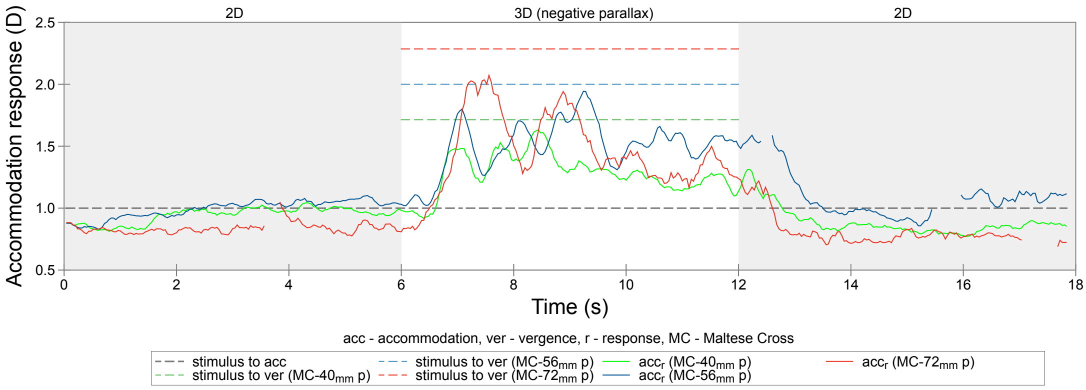

Figure 6.21: Overshoot: When the stimulus changes position from "on the screen" to "in front of it" there are accommodation overshoots followed by decreasing accommodation oscillation.

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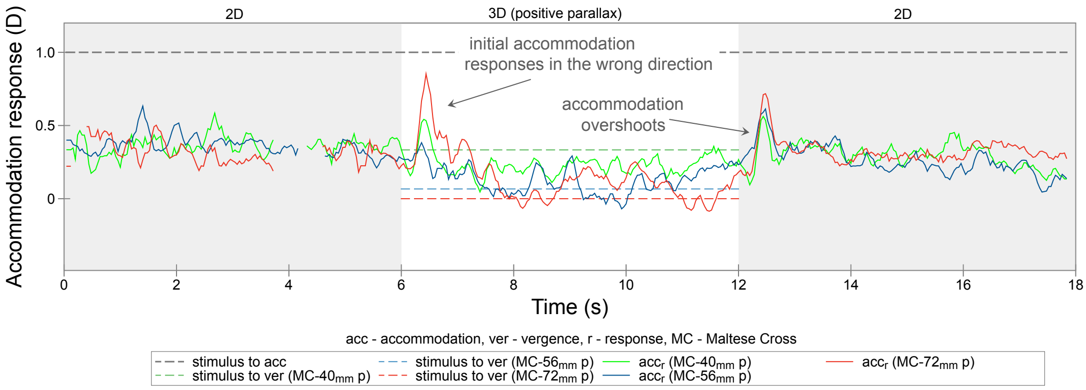

Figure 6.22: Erroneous accommodation response: Initial accommodation responses are in the opposite direction to that expected after the stimulus changes from "on the screen" to "behind the screen". Accommodation overshoots: There are accommodation overshoots after the stimulus changes back to being "on the screen".

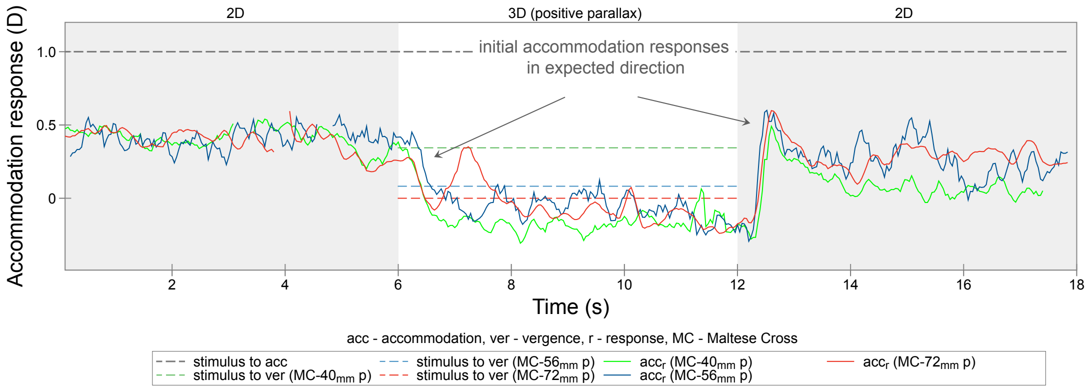

Figure 6.23: Initial accommodation responses are in the expected direction after the stimulus changes from "on the screen" to "behind the screen" and after the stimulus returns to "on the screen". Accommodation oscillations are larger at the end of the trial than before (2D condition). Thus may suggest that these individuals found the 3D task demanding.

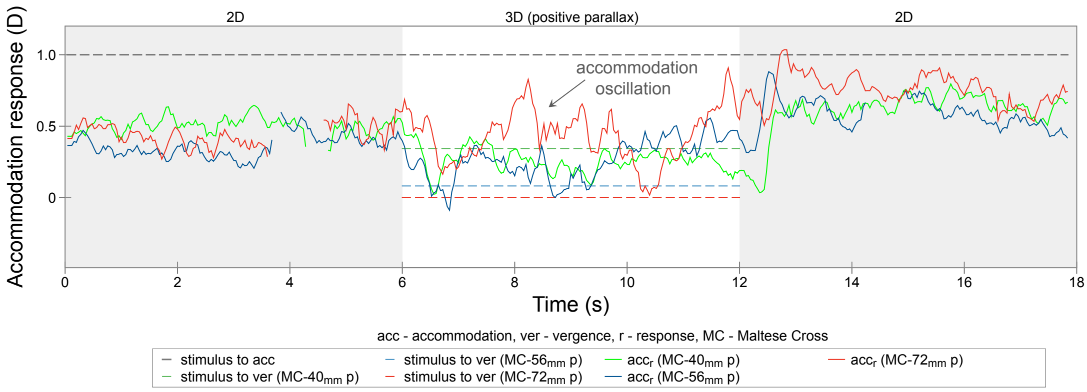

Figure 6.24: Oscillations: Large accommodation oscillation when the stimulus is presented with the largest parallax (the red line). Oscillations can be explained by difficulties in fusing the 3D stereoscopic image (Ukai & Kato 2002, Okada et al. 2006, Torii et al. 2008). Accommodation oscillations are smaller when the stimulus is presented with a smaller magnitude of parallax (42mm parallax - the green line, 56mm parallax - the blue line).

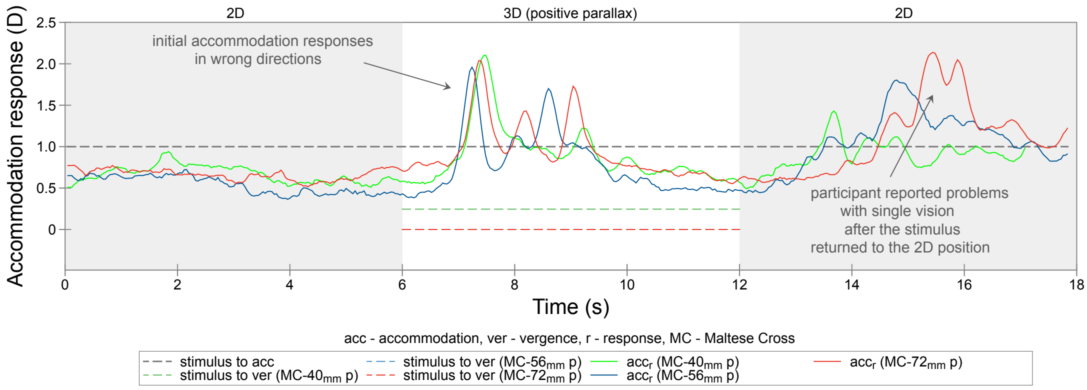

Figure 6.25: Erroneous initial accommodation responses and oscillations before a stabilising accommodation response. Oscillations before the stabilising accommodative response indicate that the participant needed more time to fuse the stimuli. Oscillation can also be seen when the stimulus returned to the 2D position. In this case the participant reported problems with single vision when the stimulus change from “behind” to being “on the screen”.

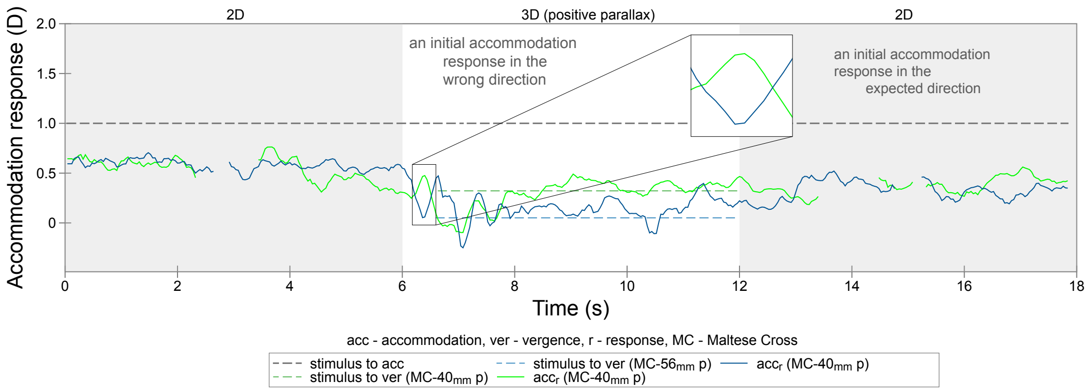

Figure 6.26: The participant experiences an initial accommodation response in the wrong direction for a stimulus presented with 40 mm parallax, while the direction of an initial accommodation response is correct for a stimulus presented with 56 mm parallax (an interesting observation). The erroneous initial accommodation response is discussed further in the discussion section.

6.3.2 Accommodation response discrepancy and spatial frequency

Figure 6.27 presents average accommodation response discrepancy observed for participants stimulated by a black Maltese Cross displayed against a white background (B&W) and a yellow Maltese Cross displayed against a green background (Y&G). Each of these stimuli have been presented in two variants: sharp (S) and blurred (B).

- Negative parallax

The mean accommodation overshoot seen when a black Maltese Cross changed from on the screen to in front of the screen was: 0.31±0.26 [SD] when a sharp stimulus was used and 0.26±0.30 [SD] when a blurred stimulus was used. A paired t-test showed that the difference between sharp and blurred black Maltese Crosses was not statistically significant (p=0.187). The mean accommodation overshoot seen when a yellow Maltese Cross changed from on the screen to in front of the screen was: 0.32±0.17[SD] when a sharp stimulus was used and 0.11±24 [SD] when a blurred stimulus was used. A paired t-test showed that the difference between sharp and blurred yellow Maltese Crosses was statistically significant (p=0.022). The mean accommodation undershoot seen when a black Maltese Cross changed from in front to on screen was: 0.09±0.11[SD] when a sharp stimulus was used and 0.01±0.16 [SD] when a blurred stimulus was used. A paired t-test showed that the difference between sharp and blurred black Maltese Crosses was not statistically significant (p=0.128). The mean accommodation undershoot seen when a yellow Maltese Cross changed from in front to on screen was: 0.1±0.17 [SD] when a sharp stimulus was used and 0.01±0.11[SD] when a blurred stimulus was used. A paired t-test showed that the difference between sharp and blurred black Maltese Crosses was not statistically significant (p=0.167).

- Positive parallax

The mean accommodation undershoot seen when a black Maltese Cross changed from on the screen to behind the screen was: 0.02±0.11[SD] when a sharp stimulus was used and 0.02±0.08[SD] when a blurred stimulus was used. A paired t-test showed that the difference between sharp and blurred black Maltese Crosses was not statistically significant (p=0.844). The mean accommodation undershoot seen when a yellow Maltese Cross changed from on the screen to behind the screen was: 0.08±0.16[SD] when a sharp stimulus was used and -0.02±0.09[SD] when a blurred stimulus was used. A paired t-test showed that the difference between sharp and blurred black Maltese Crosses was not statistically significant (p=0.308). The mean accommodation overshoot seen when a black Maltese Cross changed from behind the screen to on the screen was: 0.32±0.37[SD] when a sharp stimulus was used and 0.39±0.47[SD] when a blurred stimulus was used. A paired t-test showed that the difference between sharp and blurred black Maltese Crosses was not statistically significant (p=0.238). The mean accommodation overshoot seen when a yellow Maltese Cross changed from behind the screen to on the screen was: 0.14±0.13[SD] when a sharp stimulus was used and 0.17±0.21[SD] when a blurred stimulus was used. A paired t-test showed that the difference between sharp and blurred black Maltese Crosses was not statistically significant (p=0.511).

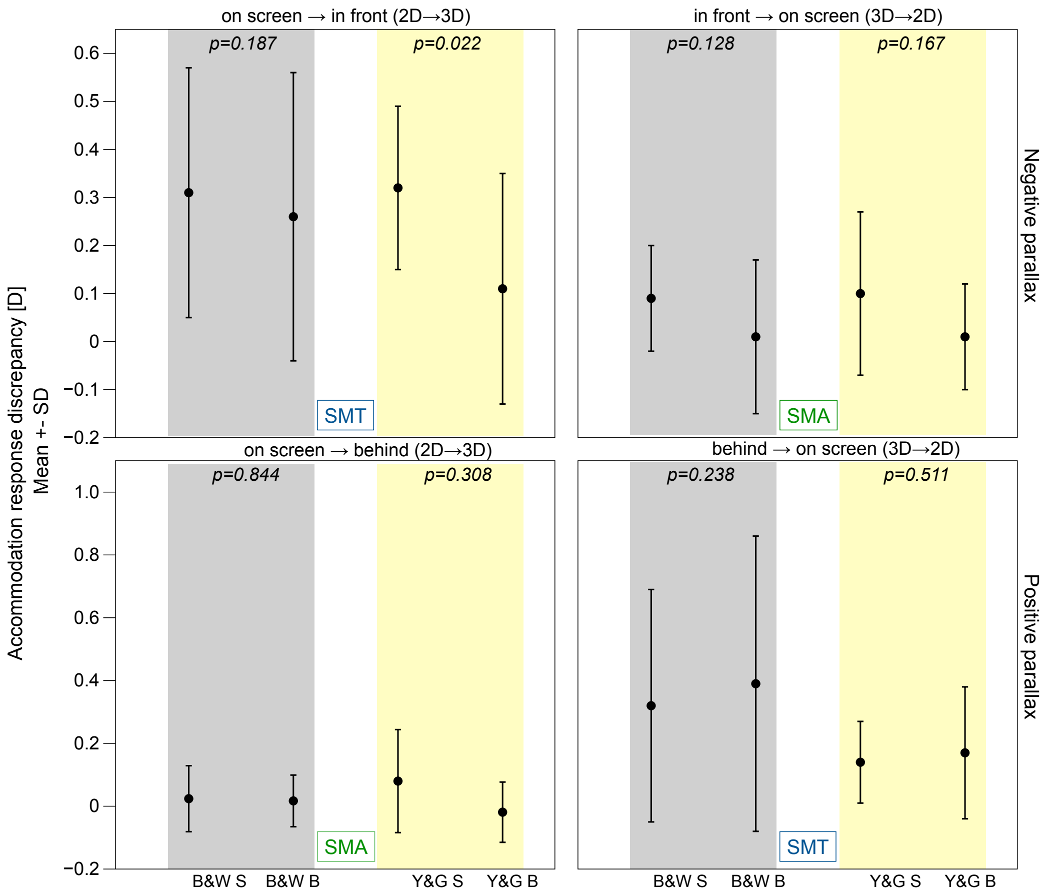

Figure 6.27: Accommodation response discrepancy. SMT - the stimulus moved towards the viewer, SMA - the stimulus moved away from the viewer. B&W - a black Maltese Cross displayed against a white background,Y&G - a yellow Maltese Cross displayed against a green background, S - sharp, B - blurred

6.3.3 Accommodation response discrepancy and CA/C ratio

Figure 6.28 shows the relationship between accommodation response discrepancy and CA/C ratio for stimulus presented with negative parallax (top row) and positive parallax (bottom row). When the stimulus was presented with negative parallax there was a significant positive correlation between CA/C ratio and accommodation response discrepancy ($r = 0.62$, $p = 0.019$, two-tailed; Pearson's correlation test), when the stimulus change from "on screen → in front" (2D→3D). There was no significant correlation between accommodation response discrepancy and CA/C ratio when the stimulus changed back from "in front → on screen" ($p > 0.05$, two-tailed; Pearson's correlation test).

In the positive parallax, when the stimulus changed from "on screen → behind" (2D→3D) there was no significant correlation between CA/C ratio and accommodation response inaccuracy ($p > 0.05$, two-tailed; Pearson's correlation test). When the stimulus change from "behind → on screen" (3D→2D) there was a significant positive correlation between accommodation response inaccuracy and CA/C ratio ($r = 0.60$, $p = 0.023$, two tailed; Pearson's correlation test).

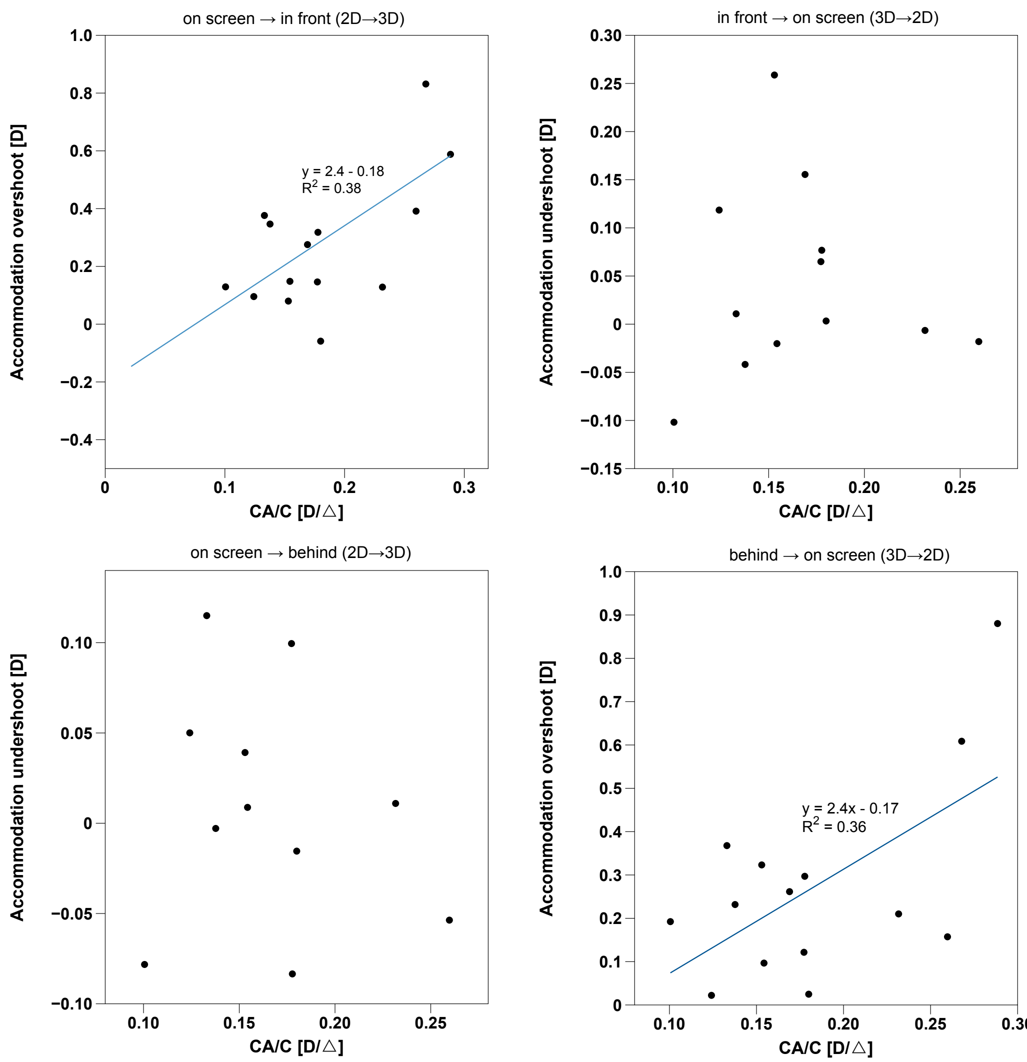

Figure 6.28: The correlation between accommodation response discrepancy and CA/C ratio for: negative parallax - crossed retinal disparity (top row), positive parallax - uncrossed retinal disparity (bottom row).

6.3.4 Discomfort

6.3.4.1 2D viewing condition

After viewing the movies in the 2D condition, seven participants reported no difference in general visual discomfort from that reported before watching the movies. Four people reported a slight decrease in general visual discomfort (1 on a scale of 6), three people reported a slight increase in general visual discomfort (1 and 2 scale point). There was no significant difference in visual discomfort between pre- and post- viewing in the 2D condition ($p = 1.000$; Wilcoxon). There was no significant correlation between the mean accommodation response discrepancy and visual discomfort change ($r_s = 0.148$, $p = 0.615$; Spearman's correlation test).

Eleven people reported no change in level of headache between pre- and post-viewing in the 2D condition. One subject reported a slight decrease in headache and two subjects reported a slight increase of headache. There was no significant difference in headache between pre- and post- viewing in the 2D condition ($p = 0.414$; Wilcoxon).

Thirteen participants did not feel the difference in VIMS between pre- and post- viewing in the 2D condition. One subject reported a slight increase and one subject reported a moderate increase. There was no significant difference in headache between pre- and post- viewing in the 2D condition ($p = 0.317$; Wilcoxon).

6.3.4.2 3D viewing condition

After viewing the movies in the 3D condition, two participants reported no difference in general visual discomfort from that reported before watching the movies.

One participant reported a slight decrease and eleven participants reported a slight increase in general visual discomfort. The values of the discomfort medians were 0.5 (IQR = 1.0) and 1.0 (IQR = 1.0) in pre- and post- stimuli, respectively. There was a significant difference in visual discomfort between pre and post viewing in the 3D condition (p = 0.005; Wilcoxon). There was no significant correlation between the mean accommodation response discrepancy and visual discomfort change (r_s = - 0.119, p = 0.686; Spearman's correlation test).

Eleven participants reported the same level of headache before and after viewing the movie in the 3D condition. Three participants reported a slight increase in headache and nobody reported a decrease. The values of the headache medians were 0.0 (IQR = 0.25) and 0.0 (IQR = 1.0) in pre- and post- stimuli, respectively. There was no significant difference in headache between pre- and post- viewing in the 3D condition (p = 0.102; Wilcoxon).

Twelve participants did not feel any difference in VIMS between pre and post viewing in the 3D condition. One subject reported a slight increase and one subject reported a moderate increase in VIMS. The values of the VIMS were 0.0 (IQR = 0.0) and 0.0 (IQR = 1.0) in pre- and post- stimuli, respectively. There was no significant difference in VIMS between pre- and post- viewing in the 3D condition (p = 0.180; Wilcoxon).

6.3.4.3 Difference in discomfort between the 2D and 3D conditions

When comparing the change in discomfort over two sessions, four participants showed the same level of visual discomfort in the 3D condition as in the 2D condition. Nine participants reported a greater amount of visual discomfort in the 3D condition, and one showed a lesser amount of discomfort in the 3D condition. The increased discomfort change in the 3D condition in comparison with the 2D condition was statistically significant (p = 0.013; Wilcoxon). There was no significant correlation between averaged accommodation response discrepancy and visual discomfort change (r_s = - 0.275, p = 0.342; Spearman's correlation test).

With regard to headache, nine participants did not feel any difference between the 3D and 2D conditions. Three reported a greater amount of headache in the 3D condition, and two reported a lesser amount of headache in the 3D condition. There was no significant difference in headache between the 3D and 2D conditions ($p = 0.334$; Wilcoxon).

In terms of VIMS twelve participants reported no difference between the 3D and 2D conditions. Two participants reported a greater amount of VIMS in the 3D condition and nobody reported a decrease. However, the difference seen in VIMS between the 3D and 2D conditions was not statistically significant ($p = 0.180$; Wilcoxon).

6.3.5 Discomfort and accommodation response discrepancy

Research question: Do participants who experienced accommodation response discrepancy also report more visual discomfort during the viewing of 3D movie than those who do not ?

Based on the difference in discomfort change between the 2D and 3D conditions, participants were divided into two groups; those who did (Group 1) and those who did not (Group 2[1]) perceive a greater change in discomfort in the 3D condition than in the 2D condition (figure 6.29).

[1]Group 2 - participants who experienced the same level of discomfort in the 3D condition as in the 2D condition or participants who experienced less discomfort in the 3D condition than the 2D condition.

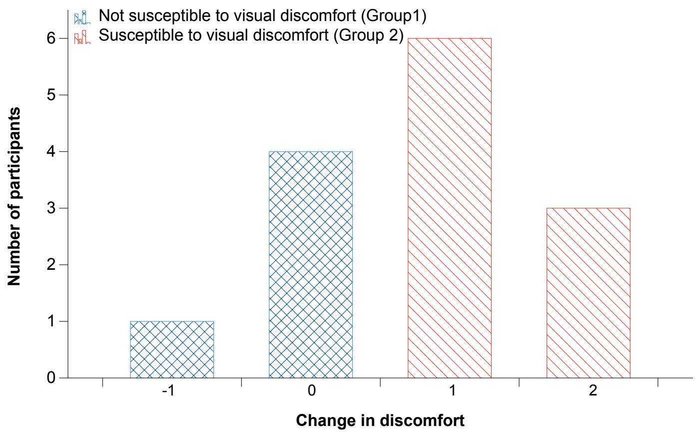

Figure 6.29: The number of participants showing each amount of difference in discomfort between the 2D and 3D conditions.

The difference between the groups in relation to accommodation response discrepancy observed in a number of conditions have been examined. Table 6.3 shows the category classification for visual discomfort change in terms of accommodation response discrepancy occurring when the stimulus is changed from 2D→3D and back again. The accommodation response discrepancy was slightly higher in the group susceptible to visual discomfort than in the group not susceptible to visual discomfort, but this was not statistically significant.

Table 6.3: Category classification for visual discomfort score change.

	Parallax		Not susceptible to visual discomfort		Susceptible to visual discomfort		independent t-test
			Mean	SD	Mean	SD	p sig.(2-tailed)
Accommodation response inaccuracy [D]	Negative	on screen → in front	0.25	0.32	0.27	0.16	0.871
		in front → on screen	0.02	0.15	0.03	0.08	0.858
	Positive	on screen → behind	-0.04	0.11	-0.02	0.10	0.630
		behind → on screen	0.27	0.21	0.27	0.25	0.978
	Average		0.13	0.09	0.18	0.21	0.600

6.4 Discussion

The main aims of this study were to examine the response of the accommodation system to the change in 3D stimuli position, and to determine whether accommodation discrepancy can have an influence on visual discomfort whilst viewing 3D stereoscopic stimuli.

In our experiment five different forms of dynamic accommodative response were seen during the viewing of 3D stereoscopic stimuli. These are: stable response, accommodation overshoot, accommodation undershoot, oscillations and erroneous accommodative response. A striking feature of figures 6.19 - 6.25 which show these responses is that the same subject showed the same response pattern for all three parallax conditions, which indicates that the responses were not simply random changes.

On the whole, accommodation discrepancy was larger when the stimulus changed from "on the screen" to "in front of the screen" and when the stimulus changed form "behind the screen" to "on the screen". This suggests than a fast stimulus moving towards the viewer has stronger effect on accommodation discrepancy than one moving away from the viewer.

When the stimulus changed from "in front of the screen" to "on the screen" and from "on the screen" to "behind the screen" an erroneous initial accommodation response was sometimes observed. In other words an error was made in choosing of the correct direction of the initial accommodation. Initial incorrect accommodation responses were previously observed under monocular viewing conditions by Stark & Takahashi (1965), Bour (1981). Recently, Torii et al. (2008) also reported initial erroneous responses (frequently in one subject when the stimulus change from "in front of the screen" to "on the screen" under binocular viewing conditions. Stark & Takahashi (1965), Bour (1981), Torii et al. (2008) explained the initial incorrect accommodation response by suggesting that the lack of monocular depth cues (linear perspective, relative size, light and shadows, overlapping, texture gradient) can produce this kind of phenomenon.

The same mechanism could explain the results in the current study as the stimulus was also free from any monocular depth cues. However, it is puzzling that the vergence change of the stimulus produced an accommodation change in the wrong direction, because one would expect the vergence-accommodation signal to be an "odd-error"[1] signal, unlike blur alone which is an "even-error" signal.

In the current studies, accommodation oscillations were observed in both conditions: when the stimulus was presented with either a negative or a positive parallax. Previously, accommodation oscillations were reported when the stimulus was presented in front of the screen by Ukai & Kato (2002), Okada et al. (2006), Torii et al. (2008). These researchers suggested that oscillations indicate difficulty in fusing images presented on the stereoscopic display. The ability to fuse stereoscopic images depends on the participant's fusion range and it is reasonable to expect that, as the fusional range gets closer to its limits, accommodation oscillations will occur. It was found that horizontal oscillations increased with increasing parallax (see example on figure 6.24). This is consistent with the expectation that accommodation oscillation increases with difficulty in fusing images. Occasionally, accommodation oscillations were observed when the image returned to the 2D position. In these cases participants reported temporary problems obtaining a single vision of the stimulus (see example on figure 6.25). (This may suggest that an individual found the 3D task very demanding and more time was needed for the accommodation response to return to normal). Moreover, it was observed that more people (N=4) could not fuse the images when the maximum positive parallax was used than when the maximum negative parallax (N=1) was used. This is consistent with the previous study (see chapter 5), where it was found that participants had a lower ability to fuse images by divergence than by convergence (this is consistent with the norms for fusional reserve (Evans et al. 2007, Elliott 2013)). Fewer participants failed to fuse a blurred stimulus than a sharp stimulus. This can be explained by the fact that Panum's fusional area is expanded at low spatial frequency (Schor et al. 1984) and so blurred images with

[1]An error signal with both magnitude and sign information is called "odd-error"signal. An error signal with only magnitude and no sign information is called an "even-error" signal.

large parallax are easier to fuse than sharp images with the same parallax.

In the experiment, the effect of spatial-frequency content of the stimulus on accommodation discrepancy was tested. It is worth remembering that the static accommodation response during the viewing of a 3D stimulus balances between convergence-driven accommodation which pulls accommodation toward the stimulus and defocus-driven accommodation that pulls it to stay at the position of screen (Ramsdale & Charman 1988, Okada et al. 2006). As the stimulus is more blurred, the defocus - driven accommodation should become weaker and convergence - driven accommodation should become stronger. Hence, when the stimulus is blurred the accommodation overshoot is expected to be diminished, when compared with the response to a sharp stimulus.

In the experiment conducted, when the stimulus changed its position from "on the screen" to "in front of the screen", it was found that the accommodation overshoot was smaller when the blurred stimulus was used. However, a statistically significant difference between the sharp and the blurred stimulus was only found in the case of a yellow Maltese Cross displayed against a green background (Y&G), and not in the case of a black Maltese Cross displayed against a white background (B&W). An explanation for these differences is that the Y&G blurred Maltese cross is a weaker stimulus to defocus driven accommodation than the B&W blurred Maltese Cross, because the contrast between the target and background is smaller. It can be expected that more blur added to the B&W stimulus would increase the difference in accommodation overshoot between the sharp and the blurred stimulus.

When the stimulus changes its position from "in front of the screen" to "on the screen", there is a mismatch between the stimulus to accommodation and the stimulus to convergence at the starting point but not at the finishing point. In this case, the accommodation discrepancy (undershoot) may be diminished only if the static accommodation response depends on the spatial-frequency component of the stimulus presented "on the screen". From previous studies (Okada et al. 2006, Torii et al. 2008) no effect of the spatial-frequency component on accommodation was expected, when the stimulus was presented “on the screen”. In the study conducted no statistically significant difference in the magnitude of the accommodation undershoot was found, between the sharp and blurred stimulus. Under this condition, minimal accommodation discrepancies (undershoots) were observed.

When the stimulus position changed from “on the screen” to the “behind the screen”, it was expected that the accommodation discrepancy (undershoot) would be smaller for the blurred than for the sharp stimulus. Collected data revealed very small differences between the responses to sharp and blurred stimulus. Under this condition, minimal accommodation discrepancies (undershoots) were observed.

When the stimulus position changed from “behind the screen” to “on the screen”, the mismatch between the stimulus to accommodation and the stimulus to convergence is only present at the starting point. There is no mismatch between the stimulus to accommodation and the stimulus to convergence when the stimulus returns to the 2D position. In this case, no effect of the spatial-frequency component on accommodation discrepancy (overshoot) was expected. No statistically significant differences in the magnitude of the accommodation overshoot caused by the sharp and the blurred stimulus was seen.

Overall, the effect of the spatial-frequency component on accommodation discrepancy was only observed when the stimulus changed its position from “on the screen” to “in front of the screen”. No significant difference in the magnitude of accommodation discrepancies was observed for the three other stimulus change variants.

The effect of the individual CA/C ratio on the accommodation response discrepancy was tested. When the stimulus position changed from “on the screen” to “in front of the screen”, and when it changed from “behind the screen” to “on the screen”, the accommodation discrepancy increased with an increase of the CA/C ratio. However, a correlation between the accommodation discrepancy and CA/C ratio was not found when the stimulus position changed from "in front of the screen" to "on the screen" or when it changed from "behind the screen" to "on the screen". In other words accommodation discrepancy was correlated with the CA/C ratio when the stimulus changed its position in a direction "towards" the viewer, but was not correlated with the CA/C ratio when the stimulus changes its position in the direction "opposite" to the viewer. Previously, Fukushima et al. (2009) reported that accommodation discrepancy (accommodation overshoot) was correlated with CA/C ratio when the stimuli changed its position from "on the screen" to "in front of the screen" (in Fukushima et al. (2009) different conditions were not tested). Our results, combined with the results presented by Fukushima et al. (2009) strongly indicate, that there is an appreciable variability of accommodation discrepancy between individuals. Moreover, it can be concluded that accommodation discrepancy is influenced by the viewer's CA/C ratio but only when the the stimulus changes its position in a direction "towards" the viewer. The lack of correlation between the CA/C ratio and the accommodation discrepancy when the stimulus changes its position in the direction "opposite" to the viewer can be explained by the fact that the process of focusing from "near to far" differs from the process of focusing from "far to near"[1]. Focusing "from far to near" is an active process, whereas focusing "from near to far" is a passive process. Hence the accommodation discrepancy, when the stimulus changes its position in the direction "opposite" to the viewer may not be associated with the CA/C ratio in the same way as when the stimulus changes its position in the direction "towards" the viewer. It is worth noting that the accommodation discrepancy observed was much smaller when the stimulus changed its position in the direction "opposite" to the viewer than when the stimulus changed its position in the direction "towards" the viewer. This also indicates that the process of focusing from "from far to near" differs from the

[1]The only active element in the process of accommodation is the ciliary muscle, whereas all other elements act in a passive manner. Increase of accommodation: when focusing "from far to near" the ciliary muscle contract. This process reduces the tension on the zonular fibres, allowing the elastic lens to increase its curvature (the power of the lens increases). Decrease of accommodation: when focusing from "from near to far" the ciliary muscle relax. This process increases the tension on the zonular fibres causing the lens to flatten (the power of the lens decreases).

process of focusing "from near to far".

Turning now to the relationship between visual discomfort and the viewing of 3D stimuli, 64% of participants reported more visual discomfort when viewing a 3D stimuli than a 2D stimuli. The increase of discomfort for 3D conditions against the increase of discomfort in 2D conditions was slight (1,2 scale points). The same level of visual discomfort in 2D and 3D conditions was reported by 29% of participants and 7% reported a decrease of visual discomfort in 3D conditions compared to 2D conditions.

In our experiment it was expected that people who experienced accommodation discrepancy during the viewing of 3D stimuli would experience more visual discomfort when viewing 3D stimuli compared with 2D stimuli. To explore this hypothesis participants were dichotomised into those who did and those who did not show a greater change in discomfort in the 3D stereoscopic condition. Analysis of the data shows that accommodation discrepancy was slightly higher in the group where the visual discomfort was reported, but the differences were not statistically significant. Therefore, accommodation anomalies (accommodation overshoot, accommodation undershoot) cannot account for the symptoms reported when a 3D stereoscopic movie was viewed. In our experiment the initial, incorrect accommodation response was not considered a reason for visual discomfort during the viewing of 3D stimuli. Commercially available 3D stereoscopic stimuli (movies, games, etc.) usually contain a lot of monocular depth cues. It thus seems unlikely that during the viewing of 3D stereoscopic movie an erroneous initial accommodation response will be observed.

Although, our experiment did not show a clear link between visual discomfort and accommodation discrepancy, it is still possible that a relationship could exist under different conditions. For example accommodation discrepancy may have a stronger impact on visual discomfort when the distance between the participant and the 3D device is small (e.g. Nintendo 3DS). However, it is not expected that accommodation discrepancy may have a significant effect on visual discomfort for larger distances (for example during the viewing of 3D television or 3D movies in cinema).

Chapter 7

Summary and conclusions

3D effects are like sweet candies. Everyone likes chocolate, but we all get sick if we eat too much at once. When you are cooking, you use sugar with caution. There are some meals where you dont want any, there are some cakes that deserve super-sugary frosting; and then, you dont serve them as a starter.

Phil McNally - leading pioneer of 3D animation

(Mendiburu 2011)

...and some people are diabetic

Purpose: The aim of this chapter is to summarise and highlight the main findings from the research described in this thesis. The applications of the research are also discussed.

This thesis has presented the outcome of investigations undertaken to examine the effect of 3D stereoscopic stimulation on visual discomfort. The essential questions asked in this work were whether participants experienced more discomfort whilst watching 3D stereoscopic stimuli than whilst watching 2D stimuli, and if so why. To answer these questions discomfort was assessed before and after both 2D and 3D viewing conditions. This approach eliminated two common methodological limitations of previous studies. These limitations are:

- lack of pre-session data: collection of post-sessional data only does not give a clear picture of whether symptoms arise during the viewing of stimuli or whether participants were experiencing symptoms prior to the onset of the experiment
- assessment of discomfort only in the 3D condition: as all potential causes of 2D discomfort are also present during 3D stimulation, assessment of 3D discomfort should take into account the difference between 2D and 3D discomfort.

An additional limitation of previous studies has been the use of inappropriate measurement tools (i.e. SSQ). This issue was addressed by employing redesigned questionnaires to evaluate visual discomfort, headache, and visually induced motion sickness (VIMS).

The results produced fill the gap in terms of current knowledge of individual differences between discomfort reported in the 3D and 2D conditions. More discomfort was reported in the 3D condition than the 2D condition (by 35% of participants in terms of visual discomfort, by 24% of participants in terms of headache and by 17% of participants in terms of VIMS) symptoms.

In the experiments conducted, several hypotheses were proposed relating to the characteristics of presented stimuli and their expected physiological effect on participant eye response and reported discomfort.

In the first experiment the stereoscopic stimuli (a game, Ziro) contained only positive parallax. The advantage of using this game was that it does not produce the sensation of vection so it was unlikely that viewers would experience visually-induced motion sickness (VIMS).

Participants played the same game in the 3D format, and in the 2D format as a control condition. The first hypothesis was based on the characteristics of the stereoscopic condition, and it was expected that the viewing of 3D stereoscopic stimuli, located geometrically behind the screen, would induce exophoric heterophoria changes. The second hypothesis was that those participants whose heterophoria changed as a consequence of adaptation during the viewing of the stereoscopic stimuli would experience less visual discomfort than those whose heterophoria did not change. This study found:

- a statistically significant increase in visual discomfort change in the 3D condition in comparison with the 2D condition
- a statistically significant change in heterophoria under the 3D condition compared with the 2D condition
- appreciable variability in the magnitude of this adaptation among individuals but no correlation between the amount of heterophoria change and visual discomfort change

To conclude, the study revealed that heterophoria can change as a result of viewing of 3D stereoscopic stimuli, however this change does not account for the symptoms reported.

In the second experiment two theories of 3D symptom production (vergence-accommodation mismatch theory and visual-vestibular mismatch theory) were examined. Three commercially available movies were used as stimuli: “Grand Canyon Adventure” [2008], “Avatar” [2009] and “Pirates of the Caribbean: On Stranger Tides” [2011]. The vergence-accommodation mismatch theory predicts that a greater mismatch between the stimulus to accommodation and the stimulus to vergence would produce greater symptoms in visual discomfort whilst viewing in the 3D condition than in the 2D condition. To test this theory, analysis of the magnitude of vergence-accommodation mismatch to the presented stimuli was conducted. The analysis showed that:

- out of the three presented movies the smallest average vergence-accommodation mismatch with negative as well as with positive parallax was found in the movie "Pirates of the Caribbean" [2011].
- the size of vergence-accommodation conflict with both negative parallax and positive parallax decreased as viewing distance increased

It was expected that the group who watched the stimulus with the smallest vergence-accommodation mismatch would experience less visual discomfort than the group who watched the stimulus with the largest vergence-accommodation mismatch. However, this was not confirmed by the results as there were no statistically significant differences in visual discomfort between the 3D condition and 2D condition in relation to the watched movies. In the group who watched Pirates of the Caribbean [2011] fewer people reported an increase in visual discomfort in the 3D condition compared to the 2D condition than for those who watched Grand Canyon Adventure [2008]. However, in the group who watched the movie Avatar [2009], slightly fewer people reported an increase of symptoms in the 3D condition over the 2D condition when compared with Pirates of the Caribbean [2011]. This observation indicates that differences in vergence-accommodation mismatch between the movies can not be considered as an indicator of visual discomfort reported by participants.

In the same experiment a larger proportion of younger viewers (21 to 39 years old) reported visual discomfort than was reported by older (40 years old and above) viewers. In addition, the amount of discomfort reported by younger viewers was higher.

As the amplitude of accommodation declines with age (presbyopia), older people have a decoupled accommodation-vergence response in everyday life. As a consequence changing vergence without changing accommodation could be easier or more efficient for presbyopic, than for pre-presbyopic people. While viewing 3D stereoscopic stimuli, the mismatch between stimulus to accommodation and stimulus to vergence is the same despite the participants' age, but the response to the presented stimuli differs. The difference in reported discomfort between the two groups is consistent with the suggestion that it is the visual system's response to a stimulus, rather than the stimulus itself, that gives rise to the discomfort.

In terms of visually induced motion sickness theory it was expected that 3D stimuli would produce a greater sense of vection, increasing the sensory conflict and producing greater VIMS symptoms. Participants with a closer seating position reported more VIMS symptoms than these sitting further away whilst viewing 3D stimuli. This observation is consistent with a study conducted by Howarth & Harvey (2007). In the current experiment and in the experiment conducted by Howarth & Harvey (2007), a larger part of the visual field was stimulated and more VIMS was reported. Based on these observations it can be concluded that the amount of visual field stimulated during 3D presentations affects VIMS, and so viewing distance is an important factor in terms of viewing comfort.

A further finding was the increase of headache in the 3D condition compared with the 2D condition. The difference in headache symptoms correlated with the difference in visual discomfort and VIMS reported by participants in the 3D condition compared to the 2D condition. This suggests that headache whilst viewing in 3D might be caused by the same factors which lead to visual discomfort and VIMS.

The next hypothesis relates to the participants' fusion capability as measured by their fusional reserve. It was expected that participants with a limited fusional range would experience more visual discomfort than participants with a wider fusion range. The hypothesis was confirmed, but only in the case of convergent and not divergent fusional reserves. This can be explained by the fact that the divergent eye movement was not required often enough to produce discomfort during the movies. It is worth noting that only in one movie did the extreme positive parallax exceed the participants inter-pupillary distance. Another explanation is that the variability between participants in terms of negative fusional range was much smaller than in terms of positive fusional range. Hence, the effect of negative fusional vergence on visual discomfort was more difficult to observe. No correlation was found between individual fusion range and VIMS or headache. It was therefore concluded that the increase of headache or VIMS in the 3D condition when compared with the 2D condition was not related to participants' fusion capability.

The aim of the final experiment was to examine responses of the accommodation system to changes in 3D stimulus position and to determine whether discrepancies (i.e. accommodation overshoot, accommodation undershoot) could account for the visual discomfort experienced during 3D stereoscopic viewing. The accommodation discrepancy seen was larger for perceived forward movement than for perceived backward movement. The accommodation response discrepancy was slightly higher in the group susceptible to visual discomfort than in the group not susceptible to visual discomfort, but this was not statistically significant. Although these accommodation anomalies were observed during 3D stereoscopic stimulation, no evidence has been found to suggest that they explain the symptoms reported.

To sum up, the research presented in this thesis has enhanced the knowledge of visual discomfort caused by 3D stereoscopic stimuli. Visual discomfort whilst viewing 3D stimuli is a complex issue and is influenced by many factors. However, it should be highlighted that the knowledge about an increase of discomfort in the 3D condition compared with the 2D condition can be used in a positive way. This aspect as well as other applications of the research will be further discussed in section 7.1 The view of the discomfort genesis which dominates previous studies is that it is caused by the conflict between the stimulus to accommodation and the stimulus to vergence. Comparing the size of the conflict in various movies with optometric knowledge of the visual systems response indicates that this conflict should not be a problem for most people. However, if a person has a reduced ability to fuse disparate images (a lower capacity of their vergence system) they would be expected to show symptoms.

7.1 Application of research

There is a wide range of possible applications of findings from the research presented within this thesis. The most important of these are described below:

- Analysis of the data suggests that discomfort experienced by people during 3D stereoscopic stimulation may be indicative of binocular vision problems. Therefore, 3D technology might be used as a screening method to diagnose untreated binocular vision disorders. This could be especially important for children whose binocular vision is not always checked during routine eye examinations. Poor binocular vision (i.e. convergence insufficiency) may have a negative impact on health-related quality of life, potentially interfering with reading and near work performed at school, at work, and/or during leisure (Scheiman & CITT Study Group 2009). Visual discomfort arising during 3D stimulation may therefore enable early recognition of binocular vision problems and rapid initiation of relevant treatment which is crucial for a successful outcome.

- The study presented in chapter 3 showed that heterophoria changes as a result of viewing 3D stereoscopic stimuli. This knowledge can be applied to further research to develop new ways of treating phoria.

  Binocular vision therapy based on 3D technology is likely to be more engaging and attractive especially to young participants. This might contribute to better results than those achieved by standard treatment methods for patients with binocular vision conditions.

- The experiment conducted in chapter 4 showed that participants with a closer sitting position reported more VIMS symptoms than participants sitting farther away whilst viewing 3D stimuli. This observation can be used to reduce VIMS symptoms during 3D stereoscopic stimulation by educating people to sit farther back if they are susceptible to VIMS or have previously experienced VIMS symptom during 3D stereoscopic stimulation.

- To test the hypotheses on which this work is based, special binocular vision tests and stimuli were required and therefore developed by the author. The tests were displayed on a 3D stereoscopic screen and viewed by participants equipped with 3D stereoscopic glasses. This approach of assessing binocular vision eliminated many of the problems which occur when standard examination methods are used (e.g. chromatic aberrations, large steplike changes of prismatic power especially in terms of a prism bar). Moreover, binocular vision tests presented on the 3D screen allowed examination of a much wider range than standard methods. Studies conducted in this PhD showed that 3D stereoscopic technology can be easily adopted to binocular vision measurements and in the development of new types of binocular vision tests (for example to measure fusional vergence, heterophoria, fixation disparity). Figure 7.1 present a schematic construction of these tests.

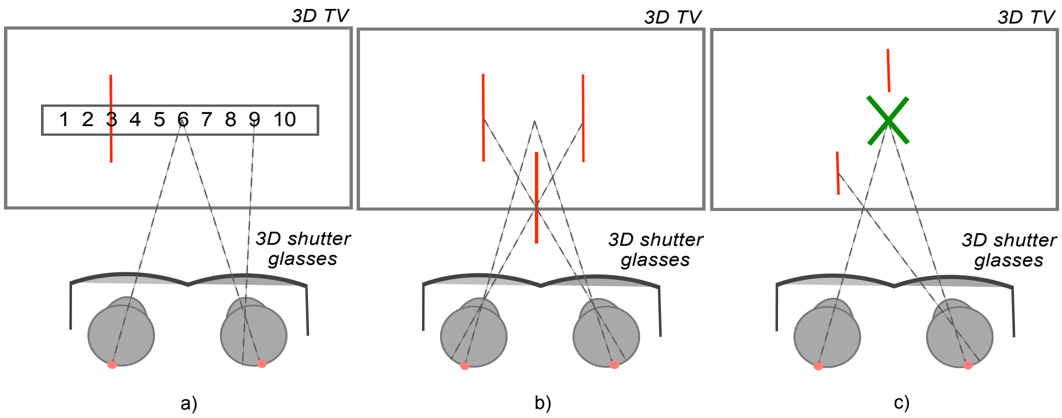

Figure 7.1: Schematic construction of tests, which can be used to measure binocular vision by using 3D stereoscopic technology. a) Horizontal heterophoria test. The same principle can be used to measure vertical heterophoria b) Horizontal fusional vergence test. The same principle can be used to measure vertical fusion vergence. c) Fixation disparity test. To detect and measure fixation disparity (e.g. by asking participants to align red markers).

- This research has contributed to the current knowledge about eye response to 3D stereoscopic stimuli. Within this thesis it has been shown that as a result of viewing 3D stereoscopic stimuli heterophoria and accommodation responses change. In terms of heterophoria change was observed in the exo direction when the stimulus was presented behind the screen. It is expected that if the stimulus was presented in front of the screen, heterophoria would change in the eso direction. Further experimental work is required to confirm this hypothesis. In terms of accommodation responses it was shown that there are five different forms of dynamic accommodation response during the viewing of 3D stimuli. These are: stable response, accommodation overshoot, accommodation undershoot, oscillation and erroneous accommodation response. It was also observed that accommodation discrepancy was larger when the stimulus changed from on the screen to in front of the screen and when the stimulus changed from behind the screen to on the screen. In terms of CA/C ratio and accommodation discrepancy it was found that accommodation discrepancy was correlated with the CA/C ratio when the stimulus changed its position in direction towards the viewer, but was not correlated with the CA/C ratio when the stimulus changed its position in the direction opposite to the viewer. Furthermore it was shown that participants fusional vergence has an effect on experienced visual discomfort.

- As was mentioned in the introduction, 3D technology suffers from a lack of standardisation. There is a lack of agreement on definitions for technical requirements for the creation of 3D stereoscopic content and there are no objective tests which can be used to assess the quality of 3D content and the quality of 3D enabled devices. Finally there are no formally agreed procedures to test discomfort experienced by people exposed to 3D stimuli. Therefore the material presented in this thesis should be of interest to standardisation bodies.

Appendix A

Analysis of vergence-accommodation mismatch

Table 1: Description of parameters shown in figure 2

$R_{(eye)}$	right eye
$L_{(eye)}$	left eye
$I_{(np)}$	image with negative parallax
$I_{(pp)}$	image with positive parallax
$ID_{(np)}$	distance between screen and visual image (negative parallax)
$ID_{(pp)}$	distance between screen and visual image (positive parallax)
$IE_{(np)}$	distance between eyes and visual image (negative parallax)
$IE_{(pp)}$	distance between eyes and visual image (positive parallax)
SD	distance between eyes and screen
pd	pupillary distance
w	screen width
p	parallax
$M_{(np)}$	vergence-accommodation mismatch (negative parallax)
$M_{(pp)}$	vergence-accommodation mismatch (positive parallax)

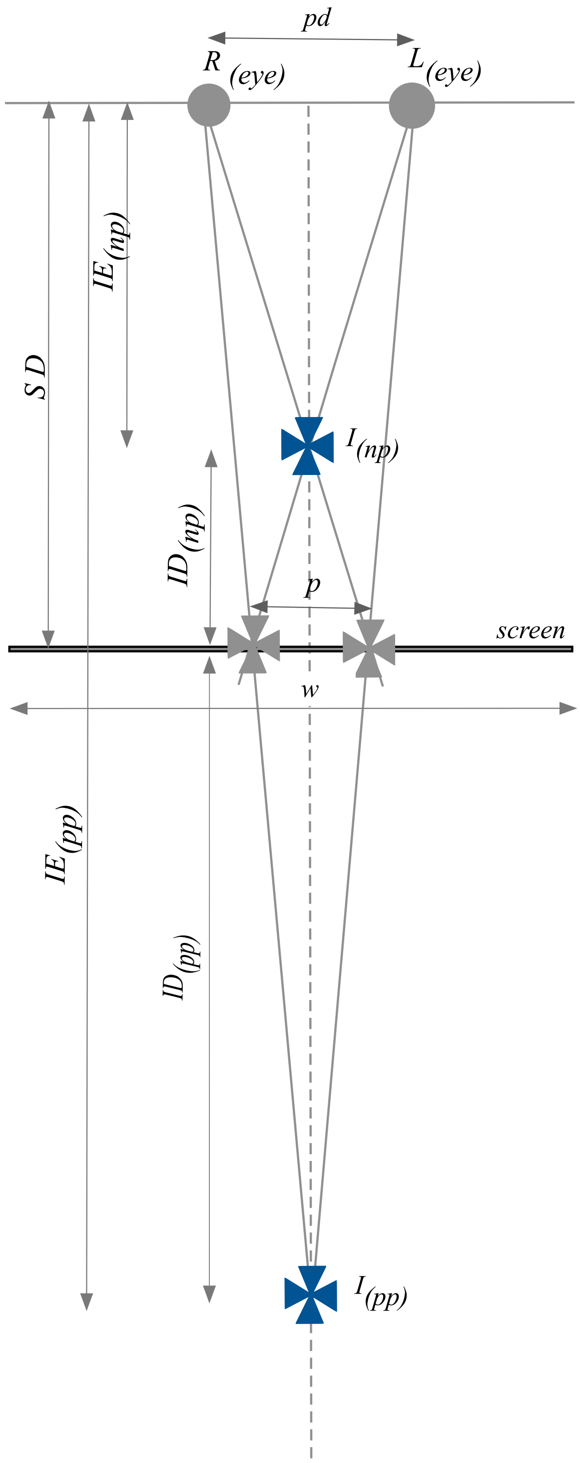

Figure 2: Schematic of visual system whilst viewing 3D steroscopic stimuli

- Derivation of formula for the image presented with negative parallax

The distance between the screen and the virtual image ($ID_{(np)}$) was calculated using the formula shown below which was generated from figure 2.

$ID_{(np)} = f(SD, p, pd, w)$

$$\frac{\frac{pd}{2}}{SD - ID_{(np)}} = \frac{\frac{p}{2}}{ID_{(np)}}$$

$$\frac{pd}{SD - ID_{(np)}} = \frac{p}{ID_{(np)}}$$

$$pd \cdot ID_{(np)} = p(SD - ID_{(np)})$$

$$SD - ID_{(np)} = \frac{pd \cdot ID_{(np)}}{p}$$

$$SD = ID_{(np)}\left(\frac{pd}{p} + 1\right)$$

$$ID_{(np)} = \frac{SD}{\left(\frac{pd}{p} + 1\right)}$$

The distance between the eyes and the virtual image (negative parallax) was calculated using the formula:

$IE_{np} = f(SD, ID_{(np)})$

$$IE_{(np)} = SD - ID_{(np)}$$

Vergence - accommodation mismatch was calculated using the formula:

$M_{(np)} = f(IE_{np}, SE)$

$$M_{(np)} = SD - IE_{(np)}$$

- Derivation of formula for the image presented with positive parallax

The distance between the screen and the virtual image ($ID_{(pp)}$) was calculated using the formula shown below which was generated from figure 2.

$ID_{(pp)} = f(SD, p, pd, w)$

$$\frac{\frac{pd}{2}}{SD + ID_{(pp)}} = \frac{\frac{p}{2}}{ID_{(pp)}}$$

$$\frac{pd}{SD + ID_{(pp)}} = \frac{p}{ID_{(pp)}}$$

$$pd \cdot ID_{(pp)} = p(SD + ID_{(pp)})$$

$$SD + ID_{(pp)} = \frac{pd \cdot ID_{(pp)}}{p}$$

$$SD = ID_{(pp)}\left(\frac{pd}{p} - 1\right)$$

$$ID_{(pp)} = \frac{SD}{\left(\frac{pd}{p} - 1\right)}$$

The distance between the eyes and the virtual image (positive parallax) was calculated using the formula:

$IE_{pp} = f(SD, ID_{(pp)})$

$$IE_{(pp)} = SD + ID_{(pp)}$$

Vergence - accommodation mismatch was calculated using the formula:

$M_{(pp)} = f(IE_{(pp)}, SE)$

$$M_{(pp)} = SD - IE_{(pp)}$$

Appendix B

Development of the fusional reserve test

To develop the 3D stereoscopic fusional reserve test the Image J software was used. The core part of the Image J script is shown below (see script 1)

This script creates a single frame of the fusional reserve test. The script was adjusted to create frames with the required position of the two columns displayed in relation to the participant's position.

```
open("/Users/edyta/Desktop/green_background.png");

//setTool("rectangle");
makeRectangle(960, 250, 9, 600);
run("Properties... ", "name=[] stroke=yellow width=1 fill=yellow");
run("Add Selection...", "stroke=yellow width=1 fill=yellow");
//setTool("rectangle");

makeRectangle(960+1920,250, 9, 600);
run("Properties... ", "name=[] stroke=yellow width=1 fill=yellow");
run("Add Selection...", "stroke=yellow width=1 fill=yellow");
run("Select None");

setColor(100,200,100);
setFont("Arial", 80);
x=1700; y=1000;
drawString("0", x, y);
drawString("0", x+1920, y);

saveAs("Jpeg", "/Users/edyta/Desktop/Fusional
reserve/000_fusional_reserve.jpg");
close();
```

Script 1: The core part of the fusional reserve test.

Appendix C

Experimental setup to create specific 3D stereoscopic stimuli

To create a setup with specific 3D stimuli the Autodesk 3ds Max and Image J software was used. The Autodesk 3ds Max is a professional 3D computer graphic software for creating 3D images, models and animations. The software allows for determining and controlling camera separation, convergence distance, convergence point, image geometry, image texture, image colours, scene lighting, etc. An advantage of the computer generated 3D stimuli over "real world" 3D stimuli (e.g. created by using physical cameras) is that the CGI are not biased by alignment imperfections of a real stereographic camera rig. Figure 3 shows the Autodesk 3ds Max interface. The workspace contains four windows: top view, perspective view, right camera view, and left camera view. Right and left camera images generated by Autodesk 3ds Max were blended together with use of a script written in Image J to create stereographic JPEG files (see script 2). Nvidia 3d viewer was used to present the generated stimuli to the participants.

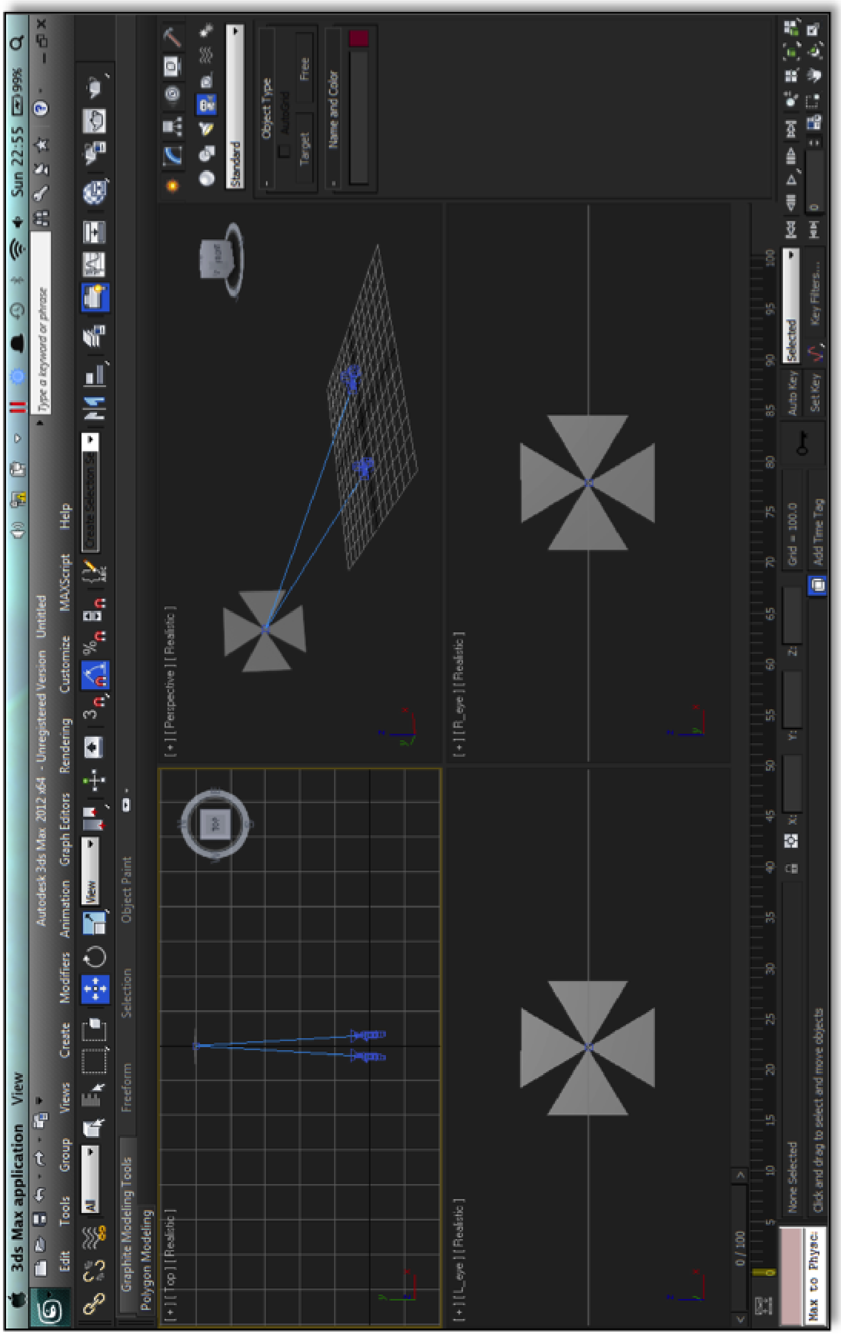

Figure 3: Autodesk 3ds Max interface

```
open("/Users/edyta/Documents/3dsMax/renderoutput/L_eye.png")
;
open("/Users/edyta/Documents/3dsMax/renderoutput/R_eye.png")
;
newImage("L+R", "RGB White", 3840, 1080, 1);

selectWindow("R_eye.png");
run("Select All");
run("Copy");
selectWindow("L+R");
makeRectangle(0, 0, 1920, 1080);
run("Paste");

selectWindow("L_eye.png");
run("Select All");
run("Copy");
selectWindow("L+R");
makeRectangle(1920, 0, 1920, 1080);
run("Paste");

saveAs("PNG",
"/Users/edyta/Documents/3dsMax/renderoutput/L+R.png");
saveAs("JPEG",
"/Users/edyta/Documents/3dsMax/renderoutput/L+R.jps");

close();
close();
close();
run("Close");
run("Close");
```

Script 2: Code written in Image J to blend right and left camera images.

Appendix D

Development of cross-talk free image

To develop an image which was free of cross-talk an analysis of a TN LCD screen with a shutter glasses system was conducted. Based on the results of this analysis, appropriate colours for background and stimulus were selected. Figure 4 illustrates the structure and operation principle of the TN LCD screen. Molecules of liquid crystals, when placed in the electric field, change their orientation. This changes the direction of light polarisation and when this change equals 90 degrees, the majority of the backlight is transmitted to the front of the screen. When the electric field disappears, the liquid crystal molecules relax. Horizontally polarised backlight cannot pass through the vertical polariser at the front of the display.

In a colour LCD each pixel consist of three sub-pixels with a colour filter (red, green, blue). The colour presented on the display and perceived by the human eye depends on the level of transmission of three sub-pixels. The different levels of brightness required to create a full colour image are achieved by changing the voltage applied to the liquid crystals. The voltage is controlled by a thin film transistor (TFT) for each sub-pixel separately.

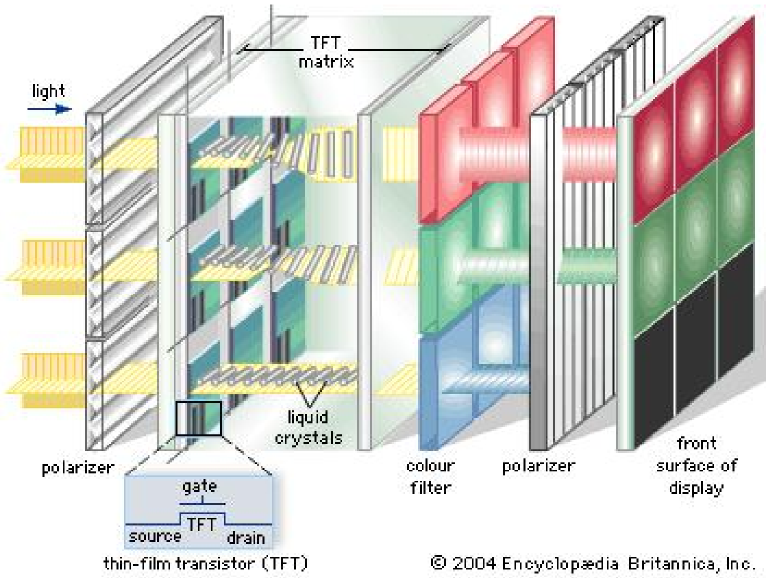

Figure 4: Device structure and operation principle of a TN LCD display. The TN LCD is composed of: a backlight illumination source, a front and rear linear polarizer (the polarising direction of rear polarizer is arranged at a right angle to the polarising direction), liquid crystal sandwiched between two sheets of glass, transparent thin film transistor (TFT) and electrodes deposited on the surface of the glass sheets.

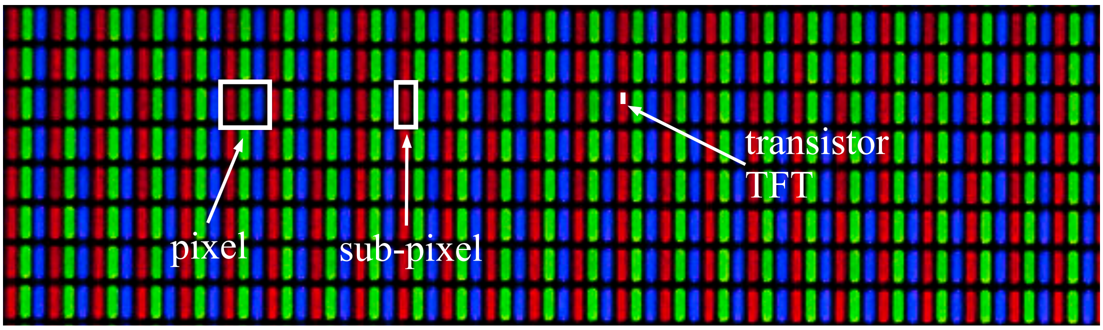

Figure 5: Magnification of the LCD screen.

Pixels switching is much more complex when the time-sequential (shutter) 3D LCD is considered. In time-sequential 3D LCD the image on the screen is refreshed 120 times per second. To achieve a black stimuli on the white background, the liquid crystal molecules have to be rotated from 90° to 0°. Because of the inertia of the liquid crystals, the time needed for molecules reorientation is defined and is greater than 0. Taking into account the physical mechanisms standing behind the 3D LCD display, it was expected that a reduction of the difference in transmission levels between the pixels creating a stimulus and pixels creating the background would decrease the visibility of the cross-talk.

Under normal light conditions (photopic vision) the eye is most sensitive to 550 nm (green colour), therefore it was further expected that the cross-talk created by variations in brightness of a green sub-pixel would be more noticeable than the cross-talk created by the red or the blue sub-pixels. For this reason transmission of a green sub-pixel was fixed at its maximum level for both background and stimulus.

Red and blue sub-pixels transmissions were varied by 20% to test whether the generated cross-talk differed between them (see figure 6).

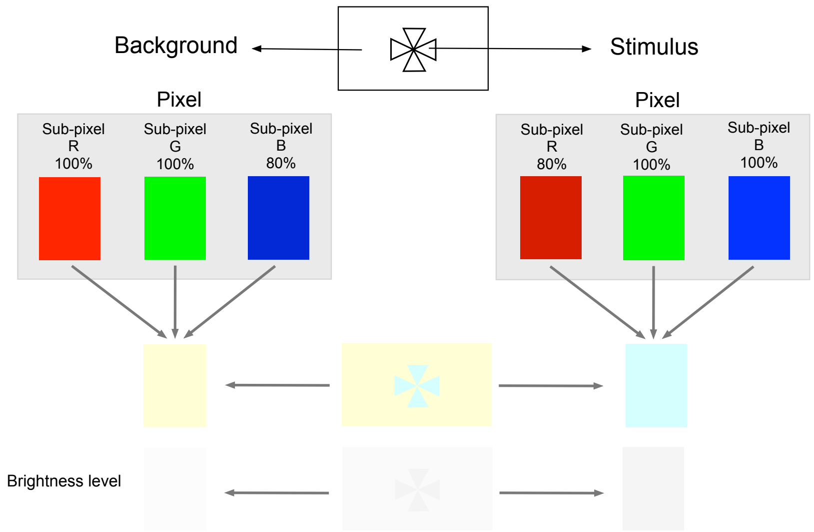

Figure 6: Example combinations of pixel transmissions producing a cross-talk free image.

The results produced were comparable in terms of generated cross-talk and contrast. While this operation reduced the visibility of cross-talk, it also reduced contrast between the image and the background. The human eye is more sensitive to a difference in contrast than to a difference in colour. For this reason the next step was to improve the contrast between the stimulus and the background. To achieve a difference in contrast the sum of pixels transmission needed to be different for the background and the stimulus (see figures 8 and 7).

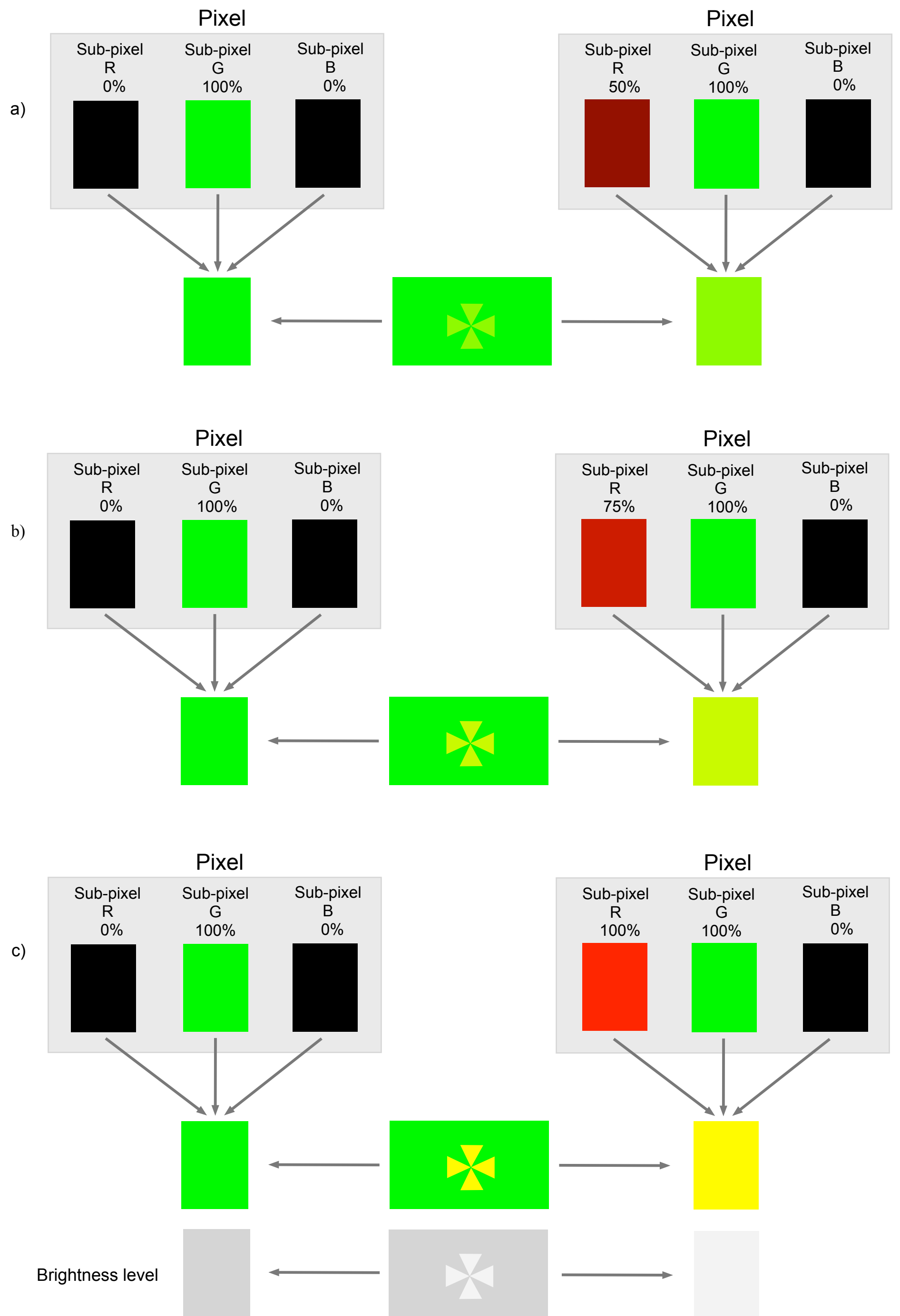

Figure 7: Example combinations of pixel transmissions producing a cross-talk free image. Changing red sub-pixel transmission to 50% (a) in relation to the background produced no cross-talk but also no contrast. Changing red sub-pixel transmission to 75% (b) and to 100% (c) in relation to the background increased contrast but not the visibility of cross-talk.

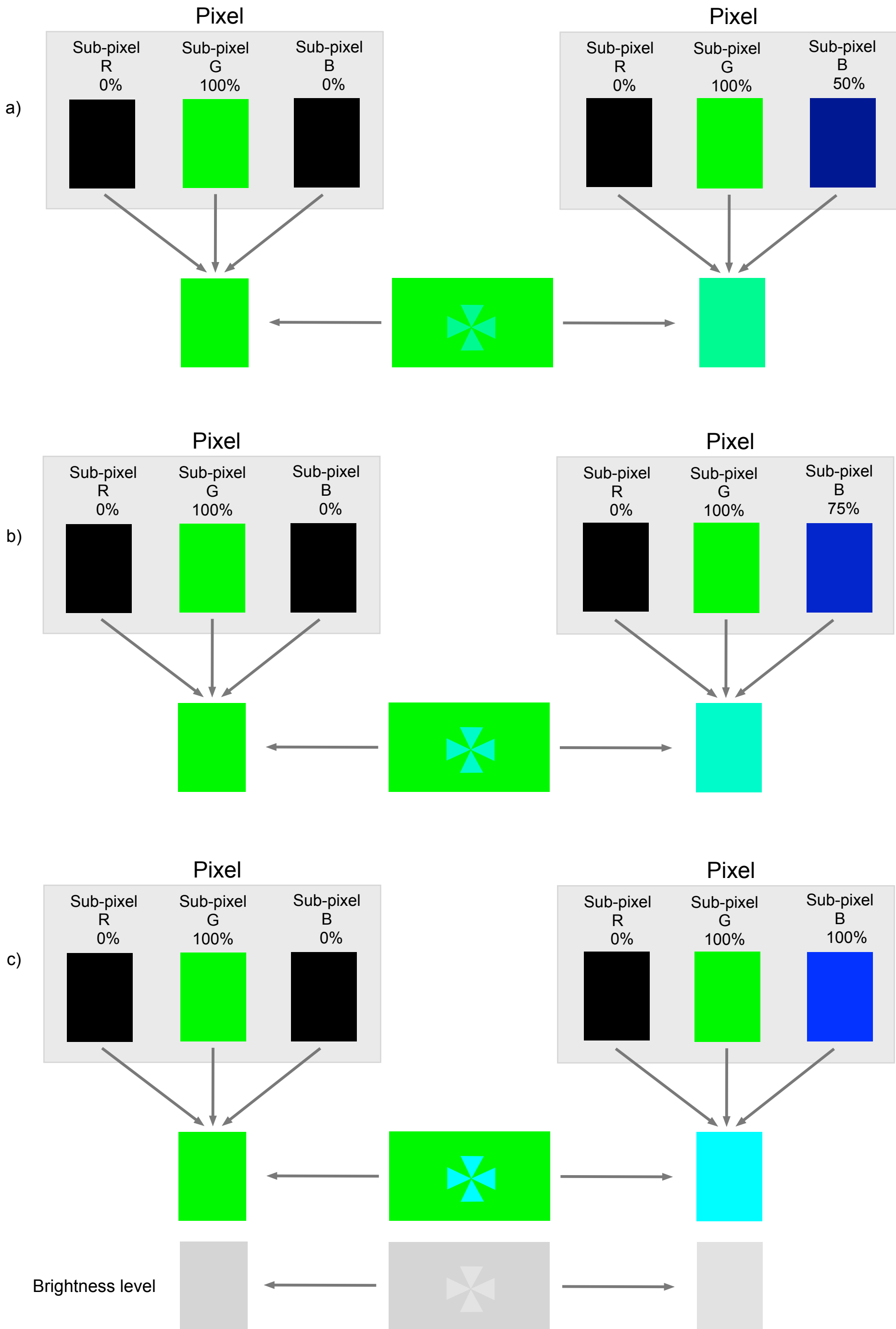

Figure 8: Example combinations of pixel transmissions producing a cross-talk free image. Changing blue sub-pixel transmission to 50% (a) in relation to the background produced no cross-talk but also no contrast. Changing blue sub-pixel transmission to 75% (b) and to 100% (c) in relation to the background increased contrast but not the visibility of cross-talk.

Even when the red/blue sub-pixel transmission was changed from 0% to 100% no cross-talk was observed. Moreover, it was found that reducing red/blue pixel transmission below 50% caused very little change in the colour of the stimulus, but further improved contrast.

The red sub-pixel was chosen as a second active sub-pixel for the stimulus. The main reason for this choice was that eye sensitivity to red colour is lower than to blue colour, therefore the cross-talk created by the red colour should be less visible. A second reason for choosing the red sub-pixel over the blue sub-pixel was that this combination produced a slightly higher contrast between the stimulus and background. To sum up R:0%, G:100%, B:0% sub-pixels were chosen as optimal for the background and R:100%, G:100%, B: 0% sub-pixels were chosen as optimal for the stimulus.

Appendix E

Generation of Difference of Gaussian (DoG) target

The DoG target was generated by using Octave software package (an open-source computer program for numerical computations and graphics, a free alternative to MATLAB).

The DoG was obtained by subtracting a broad Gaussian luminance profile from a narrow one (Wilson (1978)), using the following formula:

$$DOG_{(x)} = 3exp(-x^2/\sigma^2) - 2exp(-x^2/2.25\sigma^2) + k$$

in which k is the mean luminance, σ is the space contrast and the ratio of space contrast of the broad Gaussian to the narrow one 1.5:1.0. The DoG target was generated using script 3.

In the next step two DoG targets generated in Octave software were blended together with use of a script written in Image J to create a stereographic JPEG file (see script 4). The script was adjusted to create frames with the two DoG positioned to achieve the desired parallax on the screen.

```
function DoG(r, XX, YY)
%r - width of stimulus on the screen
%XX - width of an output image
%YY - height of an output image

%set value of sigma
sig=1;

% calculate step size
s=2*r*sig/XX;

% range of the input array
x = -r*sig: s :r*sig;

% calculate values of a difference of Gaussian blur function for each
argument
y = 3*exp(-(x.^2/sig.^2)) - 2*exp(-(x.^2/(2.25*sig.^2)));

%rewrite  results from the vector y to the array z to create 2D image
for i = 1:YY, z(i,:) = y;
end

% find minimum  value of the z array
minVal = min(min(z))
%shift values of z so that the minimum is equal to zero
z=z-minVal;

% find maximum  value of the z array
maxVal=max(max(z))
%normalize values of the z array by its maximum value
z=z/maxVal;

% save  plot to the file
imwrite(z,'test.png','png');
endfunction
```

Script 3: Code written in Octave software to generate DoG target.

```
open("/Users/edyta/Desktop/DoG_background3840x1080.jpg");
open("/Users/edyta/Desktop/DoG_20130422/DoG.jpeg");

run("Select All");
run("Copy");
close();

selectWindow("DoG_background3840x1080.jpg");
//setTool("rectangle");


makeRectangle(628, 0, 664, 1080);
run("Paste");
run("Select None");


selectWindow("DoG_background3840x1080.jpg");
//setTool("rectangle");


makeRectangle(628+1920, 0, 664, 1080);
run("Paste");
run("Select None");

saveAs("Jpeg", "/Users/edyta/Desktop/DoG_DoG/DoG_00.jpg");
```

Script 4: Code written in Image J to blend DoG target for the left eye and DoG target for the right eye (an example frame).

Appendix F

Application of research

There is a wide range of possible applications for the findings of the research presented within this thesis. The most important of these are described below:

- Analysis of the data suggests that discomfort experienced by people during 3D stereoscopic stimulation may be indicative of binocular vision problems. Therefore, 3D technology might be used as a screening method to diagnose untreated binocular vision disorders. This could be especially important for children whose binocular vision is not always checked during routine eye examinations. Poor binocular vision (i.e. convergence insufficiency) may have a negative impact on health-related quality of life, potentially interfering with reading and near work performed at school, at work, and/or during leisure (Scheiman & CITT Study Group 2009). Visual discomfort arising during 3D stimulation may therefore enable early recognition of binocular vision problems and rapid initiation of relevant treatment which is crucial for a successful outcome.

- The study presented in chapter 3 showed that heterophoria changes as a result of viewing 3D stereoscopic stimuli. This knowledge can be applied to further research to develop new ways of treating phoria.

Binocular vision therapy based on 3D technology is likely to be more engaging and attractive especially to young participants. This might contribute to better results than those achieved by standard treatment methods for patients with binocular vision conditions.

- The experiment conducted in chapter 4 showed that participants with a closer sitting position reported more VIMS symptoms than participants sitting farther away whilst viewing 3D stimuli. This observation can be used to reduce VIMS symptoms during 3D stereoscopic stimulation by educating people to sit farther back if they are susceptible to VIMS or have previously experienced VIMS symptom during 3D stereoscopic stimulation.

- To test the hypotheses on which this work is based, special binocular vision tests and stimuli were required and therefore developed by the author. The tests were displayed on a 3D stereoscopic screen and viewed by participants equipped with 3D stereoscopic glasses. This approach of assessing binocular vision eliminated many of the problems which occur when standard examination methods are used (e.g. chromatic aberrations, large steplike changes of prismatic power especially in terms of a prism bar). Moreover, binocular vision tests presented on the 3D screen allowed examination of a much wider range than standard methods. Studies conducted in this PhD showed that 3D stereoscopic technology can be easily adopted to binocular vision measurements and in the development of new types of binocular vision tests.

- This research has contributed to the current knowledge about eye responses to 3D stereoscopic stimuli and discomfort during 3D stereoscopic stimulation. This can be further used in the development of standards relevant to the creation of 3D stereoscopic content.

  As was mentioned in the introduction, 3D technology suffers from a lack of standardisation. There is a lack of agreement on definitions for technical requirements for the creation of 3D stereoscopic content and there are no objective tests which can be used to assess the quality of 3D content and the quality of 3D enabled devices. Finally there are no formally agreed procedures to test discomfort experienced by people exposed to 3D stimuli. Therefore the material presented in this thesis should be of interest to standardisation bodies.

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