

MASTER

3D viewing experience

the induction and measurement of discomfort for stereoscopic content with motion on 3DTVs

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**3D Viewing Experience:
The Induction and Measurement of
Discomfort for Stereoscopic
Content with Motion on 3DTVs**

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3D Viewing Experience:

How to Induce and Measure Discomfort for

Stereoscopic Content with Motion on 3DTVs

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Abstract

This research investigates the impact of different types of on-screen motion that differ in motion direction (horizontal planar and depth motion), motion component (background and foreground motion), disparity, and velocity on visual discomfort. From literature we know that a significant number of people, as much as one out of five, may experience visual discomfort when watching particular stereoscopic content (Lambooi, Fortuin, IJsselsteijn, Evans, Heynderickx, 2010). On-screen motion is one of the potential causes of discomfort (Speranza, Tam, Renaud, & Hur, 2006; Ujike & Watanabe, 2011). A controlled laboratory experiment with 25 participants was conducted to test if and how motion and disparity parameters affected visual discomfort. Results on our post-effect measure suggested a high plasticity of the visual system. We argue that visual discomfort induced by certain stereoscopic content diminished almost immediately after exposure for our relative short exposures (30 sec). Moreover, we found indications that certain properties of stereoscopic motion might increase mental processing time.

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Chapter 1

Introduction

Stereoscopic displays are becoming more and more common in different types of environments. In the medical field stereoscopic displays are used for diagnosis, surgery and for instruction material, and in scientific visualization it is used in the fields of geology and molecular biology. While stereoscopic electronic displays are relative new, stereoscopic three-dimensional (3D) films have a longer history than many may think. They exist since the early 1900s but it took till the 1950s before they were prominently featured in the American cinema (Wavelength Media, 2010). However, this “golden era” was short-lived due to the high costs of technical equipment and production and because of the discomfort audiences experienced due to technical imperfections between the two image projections (Hayes, 2011). Over the last two decades 3D got more attention in cinemas due to IMAX productions, beginning with short-form films focused around animals, space, and water exploration, gradually there has been a real resurgence of narrative full feature 3D movies, the real turning point being James Cameron’s Avatar in 2009. More recently, television manufacturers started introducing 3D televisions that could bring similar 3D depth experiences to our houses. These TVs are 3D-enabled but are backwards compatible to play 2D high definition as well. An extensive range of 3D TV models has been introduced in the consumer market over the past years but the adoption rate is not as high as anticipated. Worldwide shipping rates are reaching 50 million between 2011 and 2012 and 100 million between 2013 and 2014 (IHS iSuppli Market Intelligence, 2011), which is mainly caused by the technology push from the television manufacturers.

After sound, full color, and wide-screen, 3D could be the next step in the technology-based evolutionary process of the TV. There is something to say for this high anticipation towards 3D because

research showed that 3D increases the feeling of presence or “being there” (Freeman & Avons, 2000; Freeman, Avons, Meddis, Pearson, & IJsselsteijn, 2000) and viewing experience (Seuntiëns, et al., 2005; Seuntiëns, Heynderickx, & IJsselsteijn, 2008). On the other hand, there can be negative aspects to viewing 3D such as visual discomfort and fatigue (e.g., Yano, Emoto, & Mitsuhashi, 2004; Emoto, Niida, & Okana, 2005; Speranza, Tam, Renaud, & Hur, 2006; Hoffman, Girshick, Akeley, & Banks, 2008). 3D TV manufacturers include extended safety warnings with their products to inform consumers of several possible health risks such as altered vision, nausea, and disorientation (e.g., Samsung, 2012). In addition, they mention that viewing 3D television may also cause motion sickness, perceptual after effects, disorientation, eye strain and decreased postural stability. It is argued that 3D TV can only gain momentum if both image quality and visual comfort are at least equal to its 2D counterpart (Meesters, IJsselsteijn, & Seuntiëns, 2004; Lambooi, Fortuin, IJsselsteijn, Evans, & Heynderickx, 2010). At this point manufacturers are still in the process of optimizing and improving their 3D televisions, in particular when providing a large depth range.

1.1 Problem definition

Though not everyone necessarily experiences visual discomfort when watching 3D TV, research has pointed out that about one out of five persons have a higher sensitivity to visual discomfort when watching stereoscopic content (Lambooi et al., 2010). On-screen motion is one of the potential causes of subjective visual discomfort for the general population (Speranza et al., 2006; Ujike & Watanabe, 2011) but it is still unclear why and how on-screen motion causes visual discomfort while viewing stereoscopic content. We are interested in how we can induce and measure visual discomfort with stereoscopic motion. This research tries to give additional human factors insights into how stereoscopic motion affects viewing discomfort. In particular, we are interested in the types of motion that can cause discomfort (i.e., global motion or local motion; planar motion or depth motion) as well as the critical velocity. We would like to

contribute to guidelines for developers of stereoscopic displays and content creators so more people can enjoy the full visual experience with minimal discomfort.

1.1 Structure of this thesis

This thesis is divided in 8 chapters, including the introduction introduction and recommendation for future research. In the next chapter we will discuss some of the background theory to give the reader a better understanding of the topic. This includes an introduction on the human visual system, a review of several determinants for visual discomfort, and some of the visual discomfort measures based on our literature survey. In the 3rd chapter we will present the rationale for this study and in chapter 4 we introduce our experiment. This chapter is followed by the results and discussion in chapter 5 and 6. The conclusions of this study are summarized in Chapter 7, while chapter 8 contains the recommendations for future work.

Chapter 2

Theory

This chapter contains the literature survey. In section 2.1 we discuss background information about the human visual system and depth perception. This is followed by a literature study about the visual discomfort determinants (section 2.2) and measurements (section 2.3). In section 2.4 we discuss visually induced motion sickness and postural imbalance, followed by a section describing our consideration for inducing visual discomfort (section 2.5). We conclude this chapter with a short summary of the literature (section 2.6).

2.1 A general overview of the human visual system

To be able to analyze why discomfort can occur while watching stereoscopic content we first need to explain how the human visual system works. In this chapter we will highlight the most important processes that bear relevance to visual discomfort induced by 3D TVs.

2.1.1 Visual field

The visual field or field of view (FOV) describes the entire area of the observable world that can be seen at any one moment. The human FOV consists of central vision, which includes the inner 30 degrees of vision and central fixation, and the peripheral visual field, which extends 100 degrees laterally, 60 degrees medially, 60 degrees upward, and 75 degrees downward (Spector, 1990, see Figure 1). The FOV is commonly described as the horizontal angle, which for humans lies between 180° and 200°. The center 120° can be used for binocular vision.

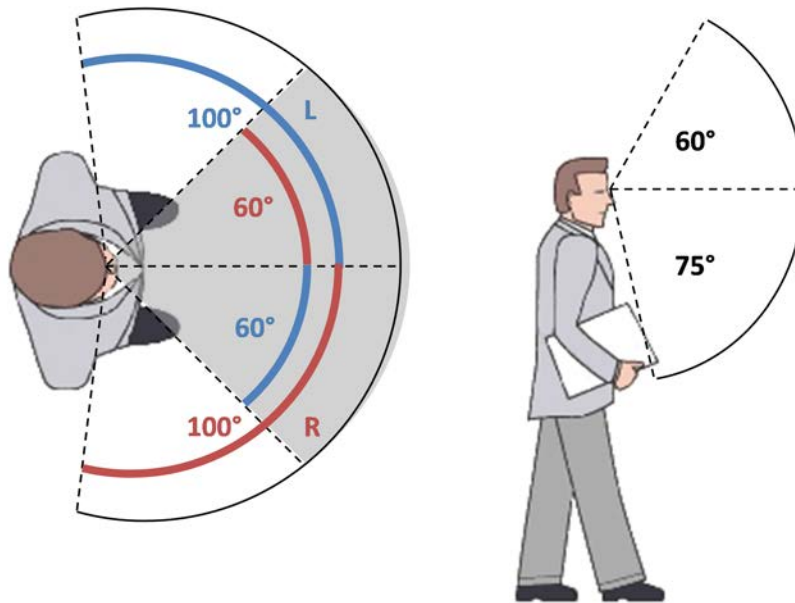


Figure 1. Schematic drawing of the normal visual field for humans which extends 100 degrees laterally, 60 degrees medially, 60 degrees upward, and 75 degrees downward (Spector, 1990).

Objects in the FOV can be described by their visual angle. For instance, the visual angle of a display, also called the display angle, tells us how much of the (horizontal) FOV is used to view the display. Important to note is that display angle and FOV are often used synonymously, which is incorrect and can cause some initial confusion. In this report we clearly separate FOV and display angle. Studies have shown that a larger display angle results in a higher feeling of presence (Prothero & Hoffman, 1995; IJsselsteijn, de Ridder, Freeman, Avons, & Bouwhuis, 2001) and postural responses (Hoshino M. , Takashi, Oyamada, Ohmi, & Yoshizawa, 1997), although the effect on postural response could not be replicated by IJsselsteijn et al. (2001).

2.1.2 Human depth perception

Human depth perception arises from a variety of depth cues, which are processed by the brain. These depth cues are typically classified in three ways. The most common classification is that between

Table 1. Depth cue classification grouped on common features (Blundell & Schwarz, 2005, p. 77; Mather, 2006, p. 271).

Depth cue	Classification scheme		
	Binocular / Monocular	Retinal image / Oculomotor	Parallax / Pictorial
Accommodation	Monocular	Oculomotor	-
(Con)vergence	Binocular	Oculomotor	-
Binocular disparity (stereopsis)	Binocular	Retinal image	Parallax
Motion parallax	Monocular	Retinal image (+ oculomotor)	Parallax
Height in the visual field	Monocular	Retinal image	Pictorial
Linear perspective	Monocular	Retinal image	Pictorial
Relative size	Monocular	Retinal image	Pictorial
Familiar size	Monocular	Retinal image	Pictorial
Occlusion (interposition)	Monocular	Retinal image	Pictorial
Shading and shadows	Monocular	Retinal image	Pictorial
Aerial perspective	Monocular	Retinal image	Pictorial
Image blur	Monocular	Retinal image	Pictorial
Texture gradient	Monocular	Retinal image	Pictorial

binocular and monocular cues, i.e. those cues that require input from both eyes and those cues that require input from just one eye. A second classification is that between retinal image and oculomotor cues. Retinal image cues are cues that can be identified merely by the image on the eye's retina. Oculomotor cues are identified due to feedback from the muscles used to control the vergence and accommodation of the eye. A third classification that is often used is that between pictorial and parallax cues. Pictorial cues are available in two-dimensional (2D) static images while parallax cues require a different viewpoint in either time or space. Of all these depth cues (see Table 1), binocular disparity, accommodation and vergence are of main interest for this study. A detailed review of these and other cues can be found in Mather (2006) and Blake and Sekuler (2002).

2.1.3 Binocular disparity

Binocular disparity refers to shift in image locations on the left and right eye's retina due to the lateral displacement of the eyes. The visual system receives a left eye and a right eye view of the visual scene, which are slightly different but largely overlap. The difference between identical points on those images allows the brain to extract depth information, which is used to generate our perception of depth (Patterson & Martin, 1992; Howard, 2002). Points that are fixated on with both eyes fall on identical portions of the retina, and thus have zero disparity. If a circle would be drawn between the point of focus and the eyes of the viewer we would get a focus circle (horopter) – see Figure 2.

The horopter contains all points that are the same geometrical (geometric horopter also known as the

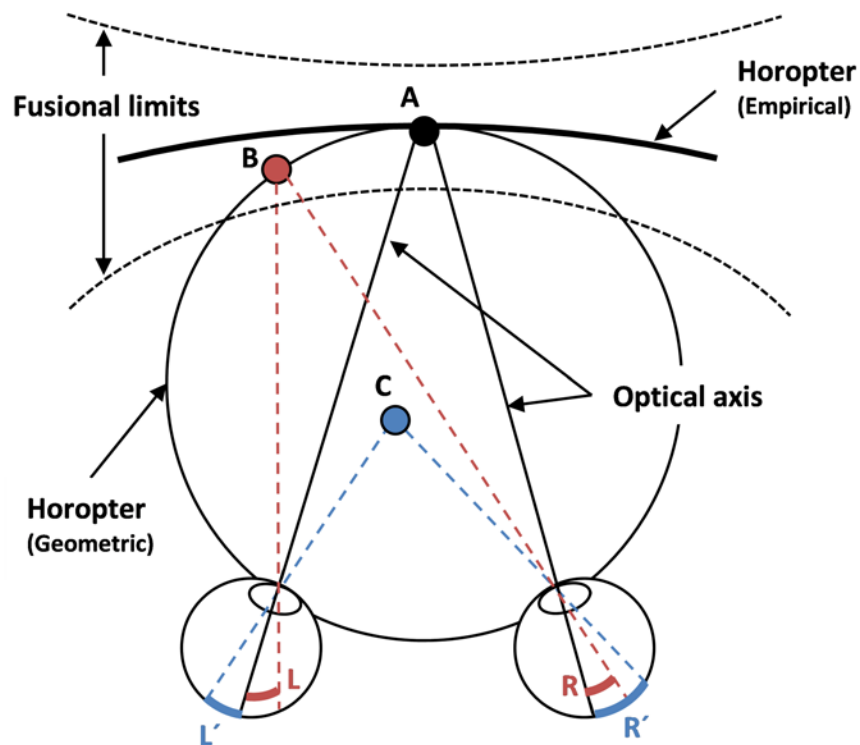


Figure 2. Binocular depth perception. The figure shows disparity on focused (on the horopter) points such as A and B, and non-focused (far off the horopter) points such as C (adapted from Riess, 2007). Notice that the offset from the optical axis is equal for focused points and differs for non-focused points.

Vieth-Müller circle) or perceived (empirical horopter) distance from the fixation point. Points nearer or farther than the geometrical horopter have retinal disparity, which means they will have different distances to the optical axes on the retina in each eye, see Figure 2. Point A and B are both on the horopter and have no retinal disparity. At small deviations from the horopter the brain will still be able to fuse the images into one percept, however at large deviations, double vision (diplopia) is likely to arise. Point C is outside the fusional limit and will be seen as a blurred, double image. The area around the horopter in which binocular fusion takes place is called Panum's fusional area or the zone of single binocular vision. Panum's fusional area does not have a fixed size, rather it depends on the spatial and temporal properties of the fixation target, such as exposure duration (Woo, 1974), spatial resolution (Schor, Wood, & Ogawa, 1984), and temporal frequency of disparity variation (Schor & Tyler, 1981). The limits of Panum's fusional area expand at increasing eccentricity from the fovea. The fovea is the area of clearest vision on the retina. Patterson and Martin (1992) showed in their research that at the fovea the limit of fusion is equal to a maximum disparity of only one-tenth of a degree, whereas at an eccentricity of 6° , it is one-third of a degree, and at 12° degrees of eccentricity without eye movements it is approximately two-thirds of a degree.

2.1.4 Ocular near triad

Whenever we look at an object and obtain clear, binocular single vision we make use of a combination of three types of eye responses: accommodation, vergence, and miosis. Together, these oculomotor systems are referred to as the ocular near triad. Accommodation can be defined as the alteration of the optical power of the lens to maintain a clear focused image of objects at different distances. Vergence can be defined as the movement of the eyes to the object of interest (Lambooij, IJsselsteijn, Fortuin, & Heynderickx, 2009). The eyes are said to converge when each eye turns inwards towards the nose and to diverge when each eye moves outwards towards the ears. Miosis are the pupillary

dynamics that interact with accommodation and vergence. The pupil constricts when viewing close objects and dilates when viewing far objects (Howard, 2002), affecting the depth of field of the eye.

The systems for accommodation and vergence are intrinsically and reflexively coupled (Fincham & Walton, 1957; Schor & Kotulak, 1986). For a certain amount of vergence, accommodation has a certain range, or depth of focus (Campbell, 1957), in which objects are perceived clearly. On the other hand, vergence can vary relative to a fixed condition of accommodation. The range of accommodation and vergence in which no excessive error in either system is presented, is called the zone of clear single binocular vision (Fry, 1939). Depth of focus is often interchanged with depth of field, which is not strange as these two concepts are strongly related. Where depth of focus describes the acceptable range of image distances (i.e., the distance between the lens and the image on the retina) for a given object distance (i.e., the distance between object and the lens), depth of field describes the acceptable range of object distances for a given image distance.

The accommodation and vergence coupling is generally modeled as two dual parallel feedback control systems that interact via crosslinks (Lambooij et al., 2009). One advantage of this coupling is increased speed of accommodation and vergence. Each process was found to be faster when cues from both processes could be combined than when only one type of cue was given (Cumming & Judge, 1986). Vergence is found to be mainly disparity driven, while accommodation is a process primarily driven by blur (Takeda, Hashimoto, Hiruma, & Fukui, 1999; Suryakumar, 2005).

2.1.5 Depth cue integration

The visual system combines and integrates all depth cues to provide an accurate, consistent, and unambiguous percept of the physical world. Many researchers have examined how the human visual system integrates depth cues to retrieve a 3D image from the two 2D retinal images (Howard & Rogers, 2002; Knill, 2007). However, a single unified theory is not yet established. Cutting & Vishton (1995) provide an overview of the relative importance of different depth cues at various distances (see Figure 3). They differentiate between personal space (≤ 2.4 m), action space (≤ 30 m), and vista space (> 30 m). Their results show that occlusion is intrinsically the most dominant cue at any distance. Binocular disparity comes second but only for short distances (< 1 m), after which it is exceeded in importance by motion parallax, height in the visual field, relative size, and other cues when increasing the distance. Notice that accommodation and vergence were grouped, and show an even smaller influence, which disappears after about ten meters. Although accommodation and vergence provide depth information,

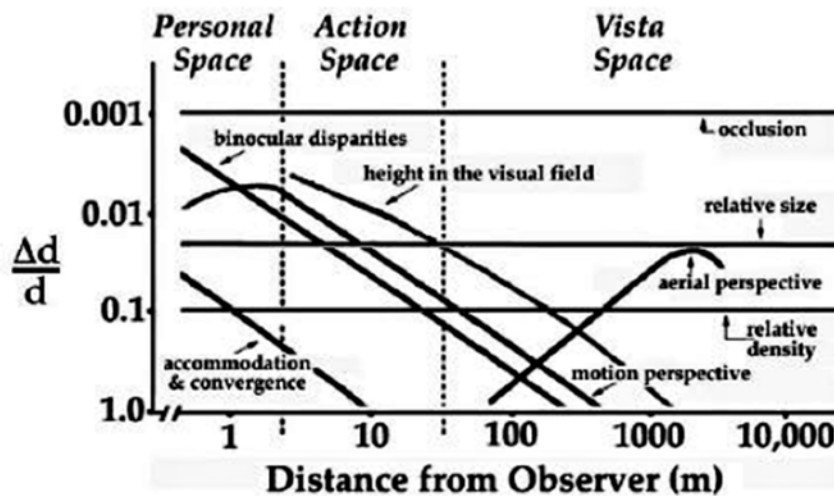


Figure 3. Just-discriminable depth thresholds as a function of the log of distance from the observer, from 0.5 to 5000 meters, for nine different sources of information about layout (taken from Cutting & Vishton, 1995). The researchers show that different sources of information have different weights in each of the three types of space around the moving observer.

they are negligible when other, more dominant, depth cues are present.

2.1.6 Individual differences

There exists a great variation between people's visual systems, which directly affects their ability to perceive stereoscopic depth (Lambooi et al., 2009). One of the clearest differences between people is the interpupillary distance. The distance between the eyes correlates to the amount of depth that can be seen in a certain situation. People with a small interpupillary distance (IPD) perceive more stereoscopic depth for a fixed set of objects at a fixed viewing distance than people with a large IPD. This means that for a fixed screen disparity, people with a small IPD will reach fusional limits more rapidly than people with a larger IPD. This is one of the main reasons why we should be extra cautious when letting children watch stereoscopic content. Dodgson (2004) reviewed and summarized past literature on the subject and did a statistical analysis on the ANSUR database of physiological measurements of 3982 subjects. Results showed that the vast majority of adults fall within the range of 50 to 70 mm, with a mean and median of approximately 63 mm. A range of 40 to 80 mm is recommended when it is needed to include adult outliers and children from five and up (Dodgson, 2004).

People could also suffer from one of many binocular anomalies. These binocular anomalies can be divided into two groups: those that typically prevent stereopsis, such as strabismus and amblyopia (i.e., squint and lazy eye) and those binocular anomalies that allow stereopsis but predispose the patient to visual complaints such as asthenopia (i.e., eye strain; Lambooi et al., 2010). People suffering from binocular anomalies that prevent stereopsis are unable to perceive stereoscopic depth. About 5-10% of the general population is estimated to be stereo-blind (Lambooi et al., 2009). In most cases this is caused by a medical condition such as strabismus in the first few years of life, in which the person is unable to maintain a binocular fixation. Because of this condition, very little binocular information is processed,

which causes the binocular cortical neurons to shift their sensitivity to monocular cues (Mather, 2006, p. 284-286). Individuals with only one functional eye are stereo-blind by definition.

People who suffer from one of the binocular anomalies that allow stereopsis do not necessarily suffer from visual complaints in normal viewing conditions at all. However, in unnatural viewing conditions, such as viewing stereoscopic content, visual complaints may arise or become more severe. This theory was supported by results from the research of Lambooi et al. (2010), where 39 participants underwent extensive optometric screening to differentiate between participants with moderate binocular status (MBS) and participants with good binocular status (GBS). Participants had to perform a reading task in both 2D and 3D. Before and after each reading task a questionnaire and eight optometric tests were administered. The researchers found that participants with MBS reported more visual discomfort than participants with GBS, they reported more visual discomfort in 3D than in 2D, and they reported more visual discomfort after the stimuli. The objective measures showed meaningful changes in fusion range for participants with MBS between 2D and 3D conditions. Finally, the number of words read was lower for both groups in 3D than in 2D. However, the difference was larger for participants with MBS indicating a worse performance than participants with GBS.

Other interpersonal differences that have an effect on the perception of stereoscopic depth are the Accommodative-Convergence over Accommodation (AC/A) ratio and pupil diameter. The AC/A ratio describes the change in convergence due to accommodation per change in accommodation, i.e., the magnitude of the crosslink-interaction. It seems that people with extremely high AC/A ratios have trouble with binocular fusion and depth perception (Bahn, San, Choi, Kham, & Chung, 2002). The pupil diameter generally depends on light level, age, gender and mental activity. A decrease in light flux falling onto the eye enlarges the pupil diameter, and as such decreases the quality of the image due to a diffraction decrease and a spherical aberration increase, and reduces the depth of field as well (Howard, 2002). The

reduction of the depth of field and, to a smaller extent, the reduction of quality increases the perceived blur for a given accommodative state, which in turn contributes to the depth perceived for each object in the scene.

2.2 *Visual discomfort determinants*

The physiological and psychological human health risks caused by images on TV, PC, or any other electronic displays have been researched before. With the introduction of stereoscopic displays this research was continued and expanded to protect people, especially children and other vulnerable persons, from possible risks. Some of the risks that should be considered are photosensitive seizures, visually induced motion sickness, and visual discomfort and fatigue caused by stereoscopic images.

The concepts visual discomfort and visual fatigue are often used interchangeably, which make them seem one and the same concept. However, we agree with Lambooij et al. (2009) that these concepts are actually slightly different. Visual fatigue is a concept that can be objectively measured while visual discomfort is its subjective counterpart. We therefore conform to the definitions given by Lambooij and colleagues who defined visual fatigue as the physiological strain resulting from excessive exertion of the visual system and who defined visual discomfort as the amount of strain people perceive as a result from excessive exertion of the visual system. In this paper we will predominantly focus on visual discomfort.

Researchers have indicated several possible causes for visual discomfort, but have grouped and labeled these slightly different. Tam, Speranza, Yano, Shimono, and Ono (2011) grouped factors that could negatively affect visual discomfort into five categories: (1) accommodation-vergence conflict, (2) parallax distribution, (3) binocular mismatches, (4) depth inconsistencies, and (5) perceptual and cognitive inconsistencies. The next sections will describe the first two categories in more detail, the other three categories are described in Appendix B. For more information on these topics see Lambooij et al. (2009) and Tam et al. (2011).

2.2.1 Accommodation-vergence conflict

Literature suggests that the most salient source of visual discomfort is the magnitude of the disparity contained in the stereoscopic image (e.g., Speranza et al., 2006). This artificial disparity causes conflicts in motor responses, which are thought to drive visual discomfort and fatigue (e.g., Hoffman, Girshick, Akeley, & Banks, 2008; Wann, Rushton, & Mon-Williams, 1995; Ukai & Howarth, 2008). The accommodation-vergence conflict theory describes that visual discomfort is caused by the conflict between vergence eye movements and the accommodation function of the visual system when watching stereoscopic images. In natural vision both convergence and accommodation are always fixed at the same object (the so called gaze point or focus point). If we plot the accommodation distance as a function of vergence distance this would result in a line of slope 'one', also known as the demand line or Donders' line (Donders, 1864). However, in artificial stereoscopic image observation convergence is fixed on the "perceived" location of the stereoscopic object while accommodation is fixed at the display surface such that objects there appear sharp (see Figure 4).

The plasticity of the accommodation-vergence system allows it to cope for some degree of conflict, especially when objects are within Panum's fusional area. When screen disparity is increased such that the retinal disparity of the object surpasses Panum's fusional area, then vergence movements will relocate the retinal disparity within Panum's fusional area and increase fusional limits. The larger the disparity, the larger the vergence response. Due to the coupling of both systems this change in vergence will cause accommodation to shift away from the display towards the point of convergence. If accommodation is shifted by an excessive amount, then the object depicted on the screen, will become blurred. The blurring will make corrective adjustment in accommodation necessary. This leads to the conflicting demands on accommodation, which severity depends on the associated vergence response. In short, the conflict between accommodation and vergence can result in three errors: loss of accommodation, which results in a blurred image, loss of fusion resulting in double vision, or both (Lambooij et al., 2009).

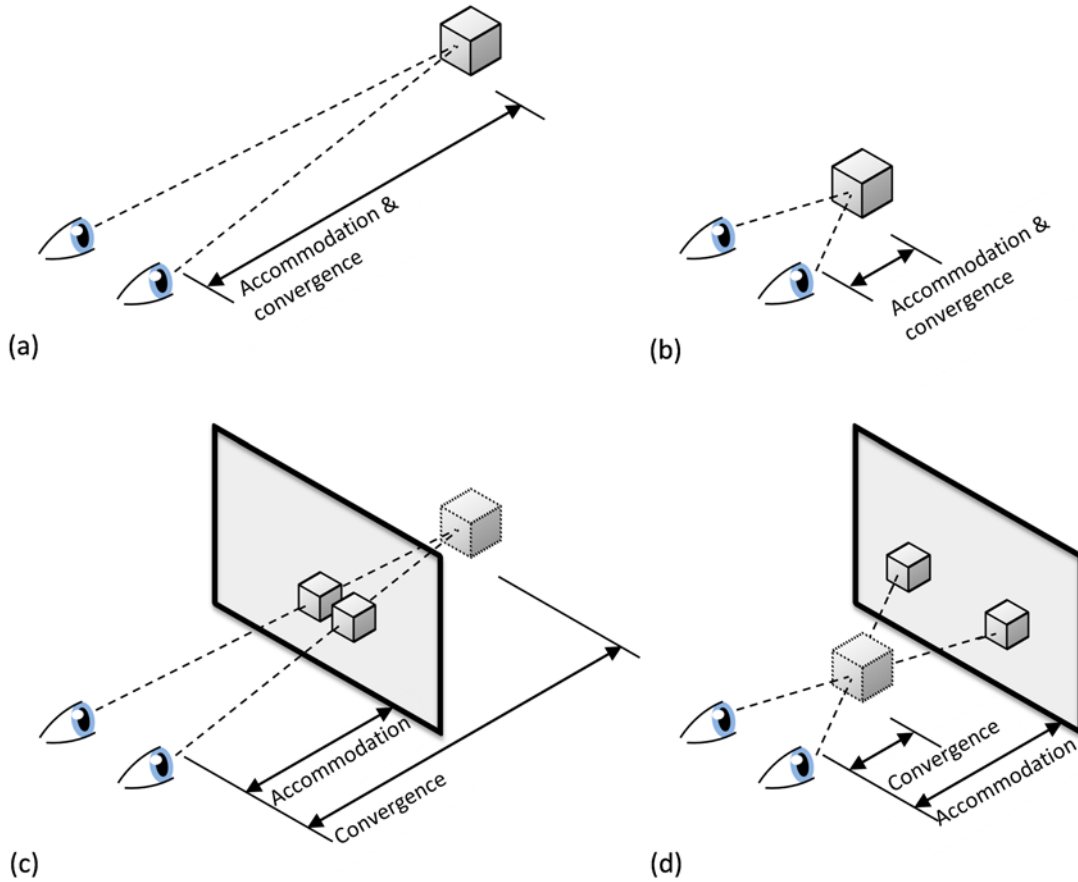


Figure 4. Schematic drawings of the accommodation-vergence conflict in stereoscopic viewing (adapted from Reichelt, Häussler, Fütterer, & Leister, 2010). In natural vision accommodation and vergence are fixed on the same object, both for object at far (a) and at close distance (b). When viewing stereoscopic images on a 3D TV, convergence is fixed on the stereoscopic object while accommodation is fixed on the display surface. Notice that the eyes are uncrossed when viewing stereoscopic objects behind the screen (c) and they are crossed when viewing stereoscopic object in front of the screen (d), these states are thus also known as crossed and uncrossed binocular disparity.

Tam et al. (2011) state that the accommodation-vergence conflict is reduced if the accommodation responses of the eye are minimized. This can be achieved by limiting the perceived depths of objects within the limits of the depth of field. Research presented results consistent with this theory, suggesting that a zone of comfortable viewing can be defined by the depth of field (Yano, Ide, Mitsuhashi, & Thwaites, 2002; Yano et al., 2004).

Zone of comfort

While Panum's fusional area marks the limit of the accommodative output under natural viewing conditions, comfortable viewing is not guaranteed. Research on optical corrections for patients that needed spectacles led Percival (1892) to define a subregion inside Panum's fusional area that could be identified as comfortable. This subregion consisted out of the middle third of Panum's fusional area and became known as Percival's zone of comfort (Percival, 1892). Later, this was converted to a recommendation for the maximum retinal disparities under normal viewing conditions. Disparities larger than 60-70 minutes of arc are generally seen as disparity values that are likely to induce visual discomfort in most viewers (Pastoor, 1993; Wopking, 1995). Nowadays, the conservative value of one degree is often used as a rule-of-thumb (Lambooij et al., 2009).

While the zone of comfort is often depicted as a clear-cut limit, this is not true. Shibata, Kim, Hoffman, and Banks (2011) examined how vergence-accommodation conflicts in stereo displays affect visual discomfort and fatigue. They argued that it is an oversimplification to describe the zone of comfort as dichotomous and proposed a continuous variant based on their data. It contains the same main properties as the dichotomous version but differs on three points. The continuous zone of comfort is shifted slightly toward positive conflicts (crossed disparity) at long distances and toward negative conflicts (uncrossed disparity) at short distances, the zone is narrower at long than at short distance, and the continuous zone is rotated slightly counterclockwise from the natural viewing or demand line (Shibata et al., 2011).

2.2.2 Parallax distribution

Visual discomfort seems not only induced by the absolute disparity magnitude but also by the variation of disparity magnitude over time and space, as would result from moving objects in a virtual environment, for instance. Ide et al., (2002) showed in their research that the features of the parallax

distribution are strongly related to the ease of viewing. These results were replicated in another research where participants watched 10 stereoscopic images in 2D and 3D (Nojiri, Yamanoue, Ide, Yano, & Okana, 2006). The researchers concluded that when viewing stereoscopic images on a HDTV, the upper part of the screen should be located further away than the bottom part and, in general, the entire image should be positioned behind the screen. In the second part of the study the researchers performed a continuous evaluation of comfort on participants who watched two stereoscopic films. Results showed that scenes that received low evaluations had large amounts of parallax or large variations in the amount of parallax (Nojiri et al., 2006).

The effect of time-varying disparities on visual discomfort was observed by several researchers (e.g., (Yano et al., 2002; Yano et al., 2004; Emoto et al., 2005; Speranza et al., 2006). The change in disparity magnitude over time is a major factor that contributes to visual fatigue (Emoto et al., 2005). It might actually be more important than the absolute magnitude of the disparity per se (Speranza et al., 2006). Speranza et al. found that this depth motion causes discomfort even when the component was displayed within depth of field range. Furthermore, their data suggested that periodical switches between crossed and uncrossed disparities, i.e. showing objects in front of and behind the screen respectively, and the rate of these changes might influence visual discomfort.

More recently, Lambooi, IJsselsteijn, and Heynderickx (2011) investigated the effect of time-variant content characteristics (e.g., motion and disparity) on the assessment of visual discomfort. They showed a 24 min. 3D movie to 24 participants and continuously measured visual comfort using a hand slider labeled with the adjective terms bad, poor, fair, good, and excellent. They used a 2 x 2 design in which they varied the initial maximum screen disparity of the 3D movie (high or low) and the ending maximum screen disparity, which was halved for 12 persons after 70% of the movie. Their results showed that for scenes without lateral or depth motion (e.g., talking people), visual discomfort can be largely modeled as

a combination of screen disparity range and offset. For dynamic scenes with lateral and/or depth motion visual discomfort can be largely described by screen disparity range, lateral motion and the change in screen disparity.

In short, empirical evidence shows that parallax distribution has a major influence on the perceived visual discomfort. Not only the distribution of the parallax in space is of importance, but especially the distribution in time has a major effect on ratings of visual discomfort.

2.3 Visual discomfort measures

While an extensive library of studies on visual discomfort exists, there is no standardized methodology of measuring visual discomfort. Objective measurement methods, that measure visual fatigue, often borrow from methods described in optometric research and thus use similar optometric instruments (Lambooij et al., 2009). For subjective measurement methods this makes less sense. While the International Telecommunications Union (ITU) provides some guidelines such as ITU-R BT.1438 (ITU, 2000) and ITU-R BT.500-11 (ITU, 2002), these are mainly directed on appreciation-oriented applications for stereoscopic displays (Lambooij et al., 2009) and focus on picture quality instead of visual discomfort. In light of this deficiency, researchers have often created customized measuring tools and scales. Both a continuous assessment (e.g., Yano et al., 2002; Nojiri et al., 2006; Lambooij et al., 2011) and questionnaires (e.g., Conlon, Lovegrove, Chekaluk, & Pattison, 1999; Sheedy, Hayes, & Engle, 2003; Kuze & Ukai, 2008; Hoffman et al., 2008) have been used in previous research. Most of these questionnaires list a series of potential symptoms that should be rated on severity. The chosen symptoms are very similar between studies and often trace back to the Simulator Sickness Questionnaire (Kennedy, Lane, Berbaum, & Lilienthal, 1993) and other similar questionnaires. Lambooij et al. (2009) suggest that any questionnaire evaluating stereoscopic content should at least incorporate all the items that Sheedy et al. (2003) used in their questionnaire, which are: tired eyes, uncomfortable vision, headache, ache in or

behind the eyes, eye irritation, pulling feeling of the eyes, blurred vision, dryness of the eyes, burning eyes, stress, neck pain, and watery eyes.

Another potential cause for differences across different studies is that not all tests are equally appropriate to evaluate the effect of stereoscopic viewing on visual discomfort (Lambooj et al., 2010). The researchers tested several objective, subjective, and performance indicators to evaluate visual discomfort and fatigue with 3D TV. Based on their research they suggest a combination of fusional range measurement and questionnaires for the evaluation of visual discomfort and fatigue related to 3D TV. In addition, they developed a simple measurement tool based on the ratio of the number of words read in 2D and 3D viewing conditions. This reading task is an application of the Wilkins Rate of Reading test (Wilkins, Jeanes, Pumfrey, & Laskier, 1996).

In this research we decided to look even further and borrow methods from another research field not unrelated to visual discomfort, namely that on visually induced motion sickness (VIMS) and postural imbalance. These methods are introduced in the next section.

2.4 Visually induced motion sickness and postural instability

Motion sickness is a response to real, perceived, or even anticipated movement in which cue conflicts can cause symptoms like dizziness, fatigue, and nausea (Kennedy, Drexler, & Kennedy, 2010). Motion sickness comes in various forms e.g. car sickness, sea sickness, air sickness, space sickness, simulation sickness and is commonly divided into three groups: motion sickness due to motion felt but not seen, motion sickness due to motion seen but not felt, and motion sickness due to both systems detecting motion that does not correspond. Visually induced motion sickness (VIMS) is a name given to those cases where motion sickness is caused by motion that is seen but not felt. Examples are simulation sickness caused by playing computer or video games (Merhi, Faugloire, Flanagan, & Stoffregen, 2007), motion sickness from virtual reality (Howart & Costello, 1997), and motion sickness from watching movies on

big screens (e.g. IMAX) or watching movies where the camera is moving considerably more than in most movies (Ujike, 2007).

Motion sickness is theorized to be induced due to sensory conflicts between sensory systems (Reason & Brand, 1975). In the case of VIMS this would encompass the visual and vestibular systems. An example is the disagreement between vergence and visual accommodation while viewing stereoscopic images. Takada, Matsuura, Takada, and Miyao (2011) analyzed the severity of motion sickness induced by viewing conventional 3D movies on a liquid crystal display (LCD) compared to that induced by viewing these movies on a head-mounted display (HMD). They measured body sway of the participants in a resting state and during exposure. In addition, participants filled in the simulator sickness questionnaire (SSQ) before and immediately after exposure. They found that for both display types the total locus length during exposure was significantly larger than that during the resting state, but for the additional indices only those for the HMD were significantly larger during exposure than during the resting state. Furthermore, they also found no significant differences on the SSQ scores. While this experiment failed to show increased postural instability for a LCD, it did show that viewing a 3D movie on a HMD can induce postural instability.

Several other researchers have shown similar results were postural instability increased when viewing motion stereoscopically versus viewing motion in 2D (e.g., Hoshino, Takashi, Ohmi, & Yoshizawa, 1997; Freeman, et al., 2000) and that there exists a positive correlation between visually induced motion sickness (VIMS) and postural instability (e.g., Cobb, 1999; Smart, Stoffregen, & Bardy, 2002). Researchers have theorized and shown in several cases that postural instability actually precedes motion sickness (e.g., Bonnet, Faugloire, Riley, Bardy, & Stoffregen, 2006; Merhi et al., 2007). However, some criticism and nuancements are given towards this postural instability theory (see Bos, 2011), citing Kennedy and Stanney (1996), they mention it is very likely that motion sickness and postural instability

are second order effects under control of a common center. Motion sickness is in essence a very extreme form of discomfort, which makes us wonder if postural instability can be used to measure visual discomfort on a wider spectrum.

2.5 Inducing visual discomfort

From the reviewed theory so far we can safely say that some people experience more discomfort when viewing images or films in 3D, than when the same content is viewed in 2D. In this section we explain how visual discomfort can be induced.

2.5.1 Angular disparity

The maximum amount of disparity in a stimulus should be considered carefully. An important division can be made for disparities that fall within the zone of comfort and those that are placed beyond the zone of comfort. In section 2.2.1 we acknowledged the one degree retinal disparity as the limits of the zone of comfort. Viewing stereoscopic content with disparities outside the zone of comfort are likely to induce discomfort to a significant part of the viewing audience. In literature, disparity is often defined in

$$\eta_A = \angle f - \angle a$$

Equation 1

$$\eta_B = \angle f - \angle b$$

Equation 2

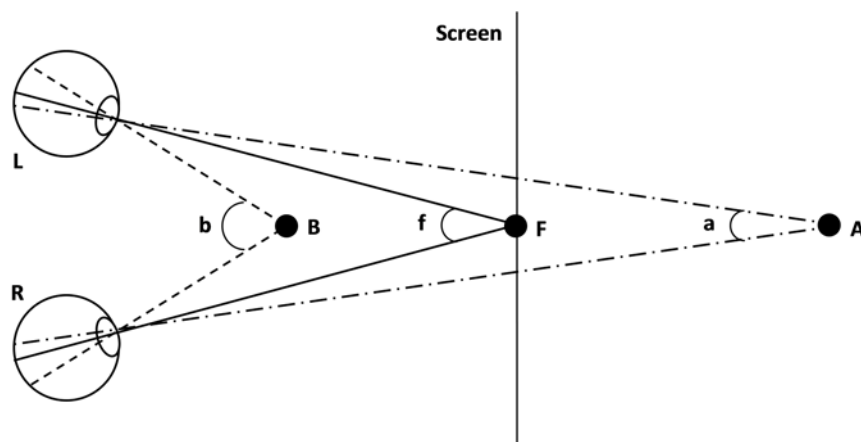


Figure 5. Angular disparity is defined relative to the current fixation point (adapted from Holliman, 2005).

angular disparity levels (e.g., Speranza et al., 2006; Lambooi et al., 2009). These can be calculated using Equation 1 and Equation 2. The symbol η is used for disparity, η_A and η_B are the binocular angular disparities for point A and point B. Positive values represent uncrossed disparity such as point A, negative values represent crossed disparity such as point B (see Figure 5).

2.5.2 Motion type

Motion in video sequences can be categorized in two groups, global motion and local motion. Global motion is closely related to camera movement while local motion is related to object motion. Especially global motion due to pitch and roll camera motion can be experienced as very sickening (Ujike & Watanabe, Effects of stereoscopic presentation on visually induced motion sickness, 2011). Several other motion types are possible with a camera such as: crab, pan, tilt, dolly, and boom. The majority of the past researches on visual discomfort and time-variant disparities focus on two directions of local motion, namely: planar motion and depth motion (e.g., Yano, 2004, Speranza et al., 2006; Li, Barkowsky, Wang, & Le Callet, 2011).

Lambooi et al. (2011) remark that while the effect of depth and lateral motion indeed play a part in inducing visual discomfort their specific contributions depend on the activity of the scene. Current research shows a large effect of depth motion on discomfort and only a small effect of lateral motion (e.g., Yano et al., 2002; Yano et al., 2004).

2.5.3 Motion velocity

The velocity of on-screen motion is likely to influence the amount of discomfort that a stimulus generates. Most of the studies on stereoscopic motion have been using existing stereoscopic movies, in which velocity is often not defined. Speranza et al. (2006) did create their own stimuli and used three velocities in their experiment: 130 cm/sec, 260 cm/sec, and 390 cm/sec and four disparity magnitude levels: 30, 60, 90 and 120 minutes of arc. If we transform the velocity in motion frequency for the slowest

and fastest velocity at a disparity of 1° we get respectively 1.01 Hz and 3.03 Hz. This is a clear difference with known research on VIMS. Researchers found that lateral (sway) motion are specifically known to be nauseogenic at a frequency of about 0.2 Hz (Golding, Phil, Mueller, & Gresty, 2001).

Motion on a TV or other electronic display is simulated by showing images with a small displacement in a stroboscopic fashion. This results in a perception of motion, known as apparent motion, even though no real motion is present. When objects move at high speeds on a display there might be a decrease in sharpness (Westerink & Teunissen, 1995) and motion may not be perceived as smooth. This latter effect is called disintegration and is a failure of the apparent motion. Computer-generated clips are especially prone to the disintegration effect because they have relatively little intrinsic motion blur (Westerink & Teunissen, 1996). Using the data from their study, Westerink and Teunissen (1996) were able to calculate the velocity (in degrees per second) at which 50% of the replications were judged to disintegrate ($v_{50\%}$) as a function of the width (in degree) of the motion window width (w), see Equation 3.

$$v_{50\%} = 17.7 + 2.3 \times w \quad \text{Equation 3}$$

2.6 Literature summery

From the reviewed theory we have learned that there are several visual discomfort determinants. Both (extreme) absolute disparity and changes in disparity over time seem to induce visual discomfort. According to the accommodation-vergence theory this is caused by conflicting depth cues which causes strain on the visual system. In our research we do not set out to find whether this theory is true but focus on the properties of a stereoscopic stimulus in terms of motion and depth to find whether we can pinpoint which aspects of a stimulus are detrimental to visual comfort. In addition, we saw that disparity changes over time were even found to induce visual discomfort inside the zone of comfort which tells us that the zone of comfort is not necessary a guarantee for a comfortable stimulus. Moreover, we saw there exist

large differences between people and their susceptibility to and the severity of visual discomfort. We want to see if we indeed can group persons based on the ratio of the number of words read on the WRRT between 2D and 3D viewing conditions.

Most studies employ subjective measures and few also include objective measures. Because objective measures of visual discomfort often rely on complex optometric machines we decided to try and use postural instability measures in addition to the subjective measures. While the postural instability measures are often used in research on VIMS we do not know whether these are equally well suited for visual discomfort. Our experiment will be an investigation to the usefulness of these tools. The next chapter (Chapter 3) will continue with a summation of the important parts of the literature and their limitations which we try to address with our research.

Chapter 3

Rationale of this research

In this chapter we will describe which what we can take from current research on visual discomfort, the limitation we see in current research, and how we propose to fix at least some of these limitations. We will give a general outline of our research, explaining several of the choices we made. The full description of the experiment will follow in Chapter 4 (Experiment).

3.1 Limitations of current research

In the previous chapter we gave an extensive review of the current literature on visual discomfort. We have seen that visual discomfort is a serious problem for a significant part of the 3D viewing audience. While the frequency and severity of visual discomfort differs between individuals, we now know there are several general determinants that can cause visual discomfort.

Stereoscopic content creators and many researchers believe that limiting the absolute disparity to the general acknowledged limit of one degree, will prevent most viewers from experiencing visual discomfort. While this may be true, we believe that, in line with the presented research in section 2.2.2, absolute disparity may not be the only important determinant for visual discomfort. We believe that the effect of time-varying disparities in combination with fast motion, may well be as detrimental as large absolute disparities. This belief is strengthened by the research of Cutting and Vishton (1995; see section 0), which shows that accommodation and vergence have relatively little weight as depth cues on the depth impression of a viewer at distances larger than one meter. For typical living room conditions, the viewing distance is (much) larger than 1 meter, whereas during computer usage, the viewing distance is typically

(much) less than 1 meter (Matsumoto, et al., 2011). These conditions are confirmed by the general viewing conditions for subjective assessments in home environment are defined in the ITU Recommendation BT.500-11 (ITU, 2002). It shows that the preferred viewing distance is larger than one meter for HDTVs larger than 15 inch. We feel that current research on time-variant disparities is promising, but it has yet to provide us with a definitive overview of which attributes of time-variant disparities and motion are inducing visual discomfort, thus aiding content creators and display manufacturers in creating products that do not induce visual discomfort or can be adjusted to reduce visual discomfort.

3.2 Scope of this research

We are interested in the discomfort determinants as well as in exploring possible new ways of measuring discomfort when viewing stereoscopic content with motion. We focus on two aspects: motion with time-invariant disparities and motion in depth (i.e. time-variant disparities), as we feel these aspects might play a large role in the perception of visual discomfort. In combination with the promising, albeit criticized, research on postural instability and visually induced motion sickness (see section 2.4) we are looking at related fields of research for tools and theories that may apply to our type of visual discomfort as well. A positive benefit of postural instability is that it allows for implementations with autonomous measurements, e.g., imbalance can possibly be captured with a camera in the TV or display.

3.3 Hypotheses

Based on the literature we composed four hypotheses that we want to test by means of our experiment. We expect that the inclusion of binocular disparity in a stimulus will generate more visual discomfort than its 2D counterpart. Our hypothesis is that motion with a large disparity will induce more discomfort than motion without disparity (*H1*). This hypothesis is well supported by literature, which was extensively reviewed in Chapter 2 (e.g., Lambooij et al., 2010; Ujike & Watanabe, 2011; Yang & Sheedy,

2011). We assume that there is also a difference in the amount of visual discomfort experienced when viewing stereoscopic planar motion versus depth motion, due to the increased stress depth motion generates on the visual system. In other words, we expect that depth motion will induce more discomfort than planar motion (*H2*). We know that stereoscopic content stresses the visual system, but that the visual system can compensate as long as the disparity stays within the fusional limits (see section 2.1.3). We believe that a single disparity level will be experienced as less stressful than a continuously changing disparity where the visual system constantly needs to change its compensation. Results supporting this theory were found by Yano et al. (2002, 2004). We also believe that fast motion will induce more discomfort than slow motion (*H3*). This hypothesis is supported by several studies, which showed that high motion velocity induced more discomfort than low velocity motion (e.g., Yano et al., 2002; Speranza et al., 2006). Yano and colleagues found that a viewer's limit of binocular fusion is reduced when the viewer is following a fast moving target, which results in double vision. Finally, our hypothesis that people with moderate binocular status will experience more discomfort than people with good binocular status (*H4*) is based on the results by Lambooi et al. (2010) on individual differences, which we try to replicate in our study.

3.4 Experimental parameters

We decided to investigate the effect of motion and time-(in)variant disparities with an experiment where we measure participants' visual discomfort directly after and postural stability during viewing sessions of stimuli at different disparities, with different types of motion, and with different velocities. We looked at other studies on visual discomfort for defining several of the experimental variables, in the very least we have to choose the disparity, the motion types, the velocities of the motion, and the viewing distance.

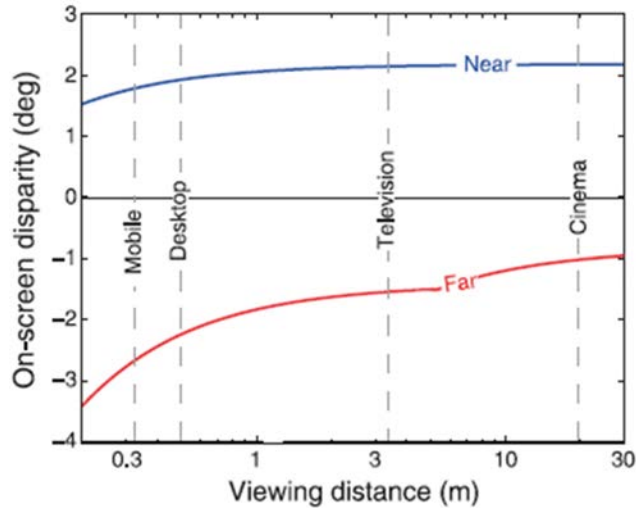


Figure 6. The zone of comfort plotted as disparity in degrees as a function of viewing distance in meters (taken from Shibata et al., 2011). The abscissa is plotted on a log scale. The break in the far boundary is a consequence of an adjustment due to the fact that most viewers cannot diverge the eyes more than 1° beyond parallel.

In our experiment we limit the maximum angular disparity at one degree. This is a conservative value of the zone of comfort but still larger than the disparity used in most 3D movies. The reason is twofold: first, we want to induce visual discomfort but do not want its effect to drown out possible effects of motion; second, we want to see how we can best measure the resulting discomfort, which requires participants to perceive discomfort. If we look at the limits of the zone of comfort given by Shibata et al. (2011; see Figure 6) we can conclude that with a viewing distance of 200 cm, an ecological valid viewing distance (Matsumoto, et al., 2011), we are well within the limits of the zone of comfort. Like the research we described in section 2.5.2, we narrow our research to local motion and thus decide to set the virtual camera, used to generate the stimuli, at a fixed position. In addition, we only use horizontal planar motion and depth motion. We feel these motion types have high ecological validity, based on current 3D Hollywood movies, and have been used in previous research on this topic (see section 2.5.2).

Chapter 4

Experiment

This chapter describes the experiment, of which the parameters have been introduced in section 3.4, to find answers to the proposed hypotheses (section 3.3). We start with a short description of the experiment design, followed by the stimuli, methods, participants, apparatus, measures, and the experiment procedure.

4.1 Experiment design

We used computer-generated stimuli that consisted out of a background and a foreground object individually placed at a certain distance. For the horizontal planar motion stimuli there were two independent variables: background-foreground (BG-FG) position and motion component. The BG-FG position levels consisted of their respective disparity level, which were: $\{-1.0^\circ, +1.0^\circ\}$, $\{-1.0^\circ, 0^\circ\}$, $\{0^\circ, +1.0^\circ\}$, $\{0^\circ, 0^\circ\}$, and $\{+1.0^\circ, +1.0^\circ\}$ where negative values represent crossed or near disparity and positive values represent uncrossed or far disparity (see Table 2). Motion component consisted out of two levels: foreground motion (FGM) or background motion (BGM). To see how velocity would affect planar motion we added one condition (BG-FG position: $\{-1.0^\circ, +1.0^\circ\}$, motion component: BGM) with a motion frequency of 0.8 Hz. All other horizontal planar motion conditions had a motion frequency of 0.6 Hz. The depth motion stimuli had two independent variables: motion path (with three levels: $\{+1.0^\circ, -1.0^\circ\}$, $\{0^\circ, +1.0^\circ\}$, $\{0^\circ, -1.0^\circ\}$) and motion frequency (with three levels: 0.4 Hz, 0.6 Hz, or 0.8 Hz; see Table 3). The motion frequency describes the time it takes for the moving object(s) to finish one entire motion along the set path and back to the starting position.

Table 2. Overview of the horizontal planar motion conditions in this research. Motion component is the component that moved, either background motion (BGM) or foreground motion (FGM). Motion direction is the axis on which the component moved, either x (horizontal planar motion) or z (depth motion). Background depth is the position of the background, either 0 deg. (SCREEN) or +1.0 deg. (UNCROS) disparity. Foreground depth is identical with the addition of -1.0 deg. (CROSSE). Motion frequency is the frequency of one full motion along the given path, which was equal in angular degrees.

Condition number	Motion component	Motion direction	Background depth	Foreground depth	Motion frequency (Hz)
1	BGM	X	SCREEN	SCREEN	0.6
2	BGM	X	SCREEN	CROSSE	0.6
3	BGM	X	UNCROS	SCREEN	0.6
4	BGM	X	UNCROS	CROSSE	0.6
5	BGM	X	UNCROS	UNCROS	0.6
6	BGM	X	UNCROS	CROSSE	0.8
7	FGM	X	SCREEN	SCREEN	0.6
8	FGM	X	SCREEN	CROSSE	0.6
9	FGM	X	UNCROS	SCREEN	0.6
10	FGM	X	UNCROS	CROSSE	0.6
11	FGM	X	UNCROS	UNCROS	0.6

Table 3. Overview of the depth motion conditions in this research. Motion component shows that only the foreground object was moved (FGM). Motion direction shows the axis on which the component moved, here z (depth motion). BG point depth and FG point depth shows the two endpoints of the linear motion path. Values can be either 0 deg. (SCREEN), +1.0 deg. (UNCROS), and -1.0 deg. (CROSSE). Motion frequency is the frequency of one full motion along the given path.

Condition number	Motion component	Motion direction	BG point depth	FG point depth	Motion frequency (Hz)
12	FGM	Z	SCREEN	CROSSE	0.4
13	FGM	Z	SCREEN	CROSSE	0.6
14	FGM	Z	SCREEN	CROSSE	0.8
15	FGM	Z	UNCROS	SCREEN	0.4
16	FGM	Z	UNCROS	SCREEN	0.6
17	FGM	Z	UNCROS	SCREEN	0.8
18	FGM	Z	UNCROS	CROSSE	0.4
19	FGM	Z	UNCROS	CROSSE	0.6
20	FGM	Z	UNCROS	CROSSE	0.8

To prevent participants from looking away from the screen during a stimulus we added a concentration task. Participants had to press a key as fast as possible during each stimulus at five random

intervals. Each interval was made visible by changing the color of (one of) the moving object for one second.

Randomization of the stimuli across participants was achieved by using a "Williams designs". A Williams design is a (generalized) Latin Square design that is also balanced for first order carryover effects. This gave our design carryover balance with very few participants, in our case with twenty conditions we got twenty different stimuli orders.

4.2 Participants

Participants were tested for normal, or corrected-to-normal (≥ 1), visual acuity and stereoscopic acuity (≤ 60 seconds of arc), as well as colorblindness. Visual acuity was measured using the Landolt-C test on the television screen using the standalone FrACT application (v3.6.3; Bach, 2010). For the properties of the television screen, see the apparatus section. Stereo acuity was tested using the Randot stereo test and colorblindness was tested using Ishihara plates. In total there were 29 participants of which four did not pass screening, two had a visual acuity below our threshold of 1 (.78 and .94) and two had a stereo acuity above our threshold of 60 seconds of arc (70 and 140 seconds of arc). The remaining 25 participants had an average visual acuity of 1.40 ($SD = .15$) and an average stereoscopic acuity of 26.20 ($SD = 8.81$).

Our sample contained 15 male and 10 female participants. They were between 19-58 years of age ($M = 25.28$, $SD = 8.82$). 6 participants wore glasses and 3 participants wore contact lenses for eye correction. The correction ranged from -5.00 to 0.25 for the left eye ($M = -2.06$, $SD = 1.58$) and -4.75 to 0.25 for the right ($M = -1.94$, $SD = 1.47$). One person had had eye surgery and did not wear any corrective devices.

None of the participants watched 3D content regularly. All participants indicated to watch 3D content once a year or less in cinemas (25), on TV (25), and on a mobile phone (25). All except one participant,

indicated the same for (handheld)computer (24). This participant said to watch 3D YouTube movies with an average frequency of once a week.

4.3 Apparatus

The TV used is a Samsung 46" C750 3D LCD TV, which is an active 3D TV (i.e. a time sequential display with a pair of liquid crystal shutter glasses) with a full-HD (2D) resolution (1920x1080 pixels). The TV was placed on eye height when seated, approximately 100 cm, at a viewing distance of 200 cm. At that viewing distance and height, measuring in the direction of the display, we measured an increase of about 40 lux when the display was on in a dark room. Whether a black or white screen was shown did not matter at this distance. The fully lighted room had an illumination level of 650 lux whether the screen was turned on or off. The dimmed ambient light setting had a illumination level of 9.5 lux when the screen was turned off and a illumination level of 40 when the screen was on. To measure the center of gravity of the participant during the experiment, a modified Wii Balance Board was attached to the chair and a magnetic tracker receiver was attached to the nape of the neck using a necklace with a counterweight. The modified balance board was placed in a larger wooden encasement, which leveled the seating area. The balance board registered weight shifts with four pressure sensors, software logged the balance front to back and right to left, the total pressure/weight on the board, and the polar values of the balance. The magnetic tracker used was Flock of Birds (FOB) DC magnetic position tracker that was able to collect the observers' six degree-of-freedom position data (i.e., x, y, z, azimuth, elevation, and roll). during the entire viewing of the stimuli. The FOB transmitter was placed on a height of approximately 100 cm. Both the balance board and the FOB tracker could be calibrated (e.g., resetting the initial value) using the same software responsible for the logging of each measurement device (both programs were custom developed by the TU/e). The programs were set to a sample rate of 100 Hz. A small table was placed in front of the participants, on which the questionnaires and a Bluetooth keyboard were placed (see Figure 7).

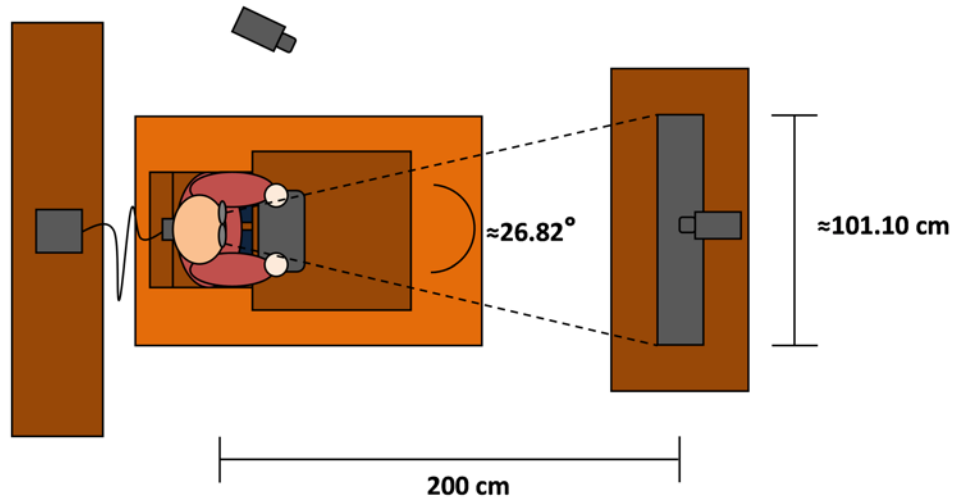


Figure 7. Top view of the experiment setting. The participant is seated on a chair with a backrest at 200 cm from the 46" TV screen, which gives a field of view of 26.82 deg. The chair stands on a (modified) Wii board, which contains four sensors positioned near the legs of the chair. The transmitter of the magnetic tracker is placed on a bookcase, which puts it on almost equal height as the sensor, which is placed in the nape of the neck.

Participants were recorded with a JVC Everio camera, which was mounted above the TV. A second camera recorded the screen itself. The video data was not used in any analyses. We only performed the recordings as reference for possible reviewing at a later stage. The cameras, the balance board, and the magnetic tracker were connected to one Dell PC. Due to technical problems the TV and the wireless keyboard were connected to a separate laptop. See Figure 8 for a schematic overview. This added an extra level of technical difficulty to the experiment where both machines needed to be synchronized if we wanted to compare stimuli playing time and the key presses on the keyboard with the postural stability data from the balance board and the FOB tracker. Due to time restrictions the difference between the system times of the PC and laptop was taken by averaging the time difference of 100 simultaneous key presses. This resulted in an average time difference of 544.36 ms between the clock on the Dell PC and the laptop where the Dell computer was running in front of the laptop. This of course is in no way an accurate measure, which means that timestamps for each measure (type) are PC/laptop dependent.

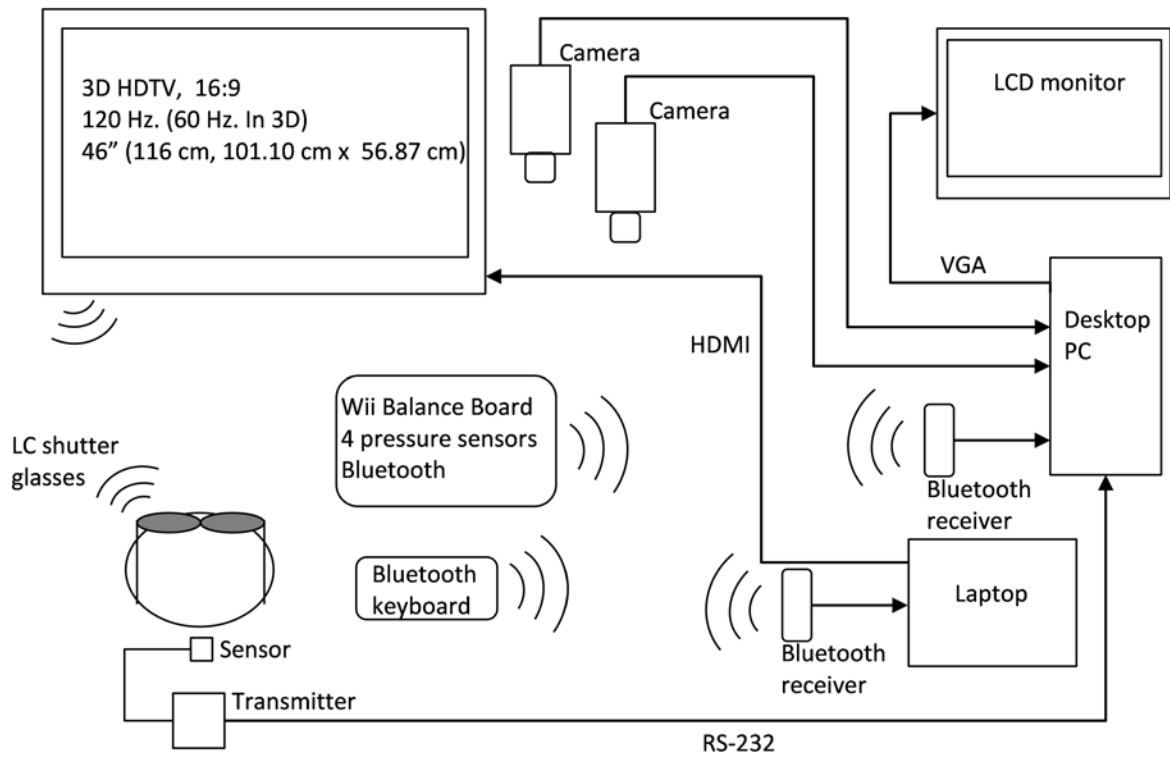


Figure 8. Apparatus of the experimental equipment. The 3D HDTV converts a 60 Hz top down movie clip into a time sequential signal. Stimuli are send from the laptop over HDMI. Keyboard presses are logged on the laptop. Data from the balance board and the magnetic tracker and the recordings from the cameras are logged on the desktop PC.

4.4 Stimuli

We differentiate between two types of stimuli based on the motion direction, which is either horizontal planar motion (translation of the object on the x-axis) or depth motion (translation of the object on the z-axis). These directions are chosen based on ecological validity, i.e. they occur often in stereoscopic movies. Stimuli are kept relatively simple so we can more easily pinpoint the source of discomfort than if we would present 3D Hollywood movies. We present the observers with a simple background, several background objects (only in the horizontal planar motion stimuli), and one foreground object.

All stimuli are rendered with the open source Persistence of Vision Raytracer (POV-Ray) ray tracing program (Persistence of Vision Raytracer Pty. Ltd.). For each clip of 30 seconds at 60 frames per second (FPS) we rendered 1800 left and 1800 right camera images at a resolution of 1920x1080 pixels. The stereo cameras were set to viewing distance of 200 cm and were placed in a toed-in configuration with a base distance of the stereo cameras was set to 6.5 cm, which is an often used average of the IPD in humans in several studies (e.g., Holliman, 2005; Chen, Fournier, Barkowsky, & Le Callet, 2010). Later we came to the conclusion that the average IPD of 6.3 given by Dodgson (2004) might have been a better representation but should not affect our results too much. The effect of this difference is that participants would have seen a larger disparity, i.e. in reality their eyes are closer together than at which the images are generated. This would suggest that the choice of 6.5 cm would give a higher possibility of inducing discomfort than if we would have chosen 6.3 cm.

Horizontal planar motion

For horizontal planar motion stimuli we manipulate foreground (FG) distance, background (BG) distance, and the moving component (either FGM or BGM). We define three depth levels: 0° , $+1.0^\circ$, and -1.0° , respectively 0 cm, 69.90 cm crossed, and 232.06 cm uncrossed from the screen or 200 cm, 130.10 cm, and 432.06 cm from the observer. To avoid framing effects we decided to not place the BG on -1.0° . This leads to ten different stimuli. A schematic representation of the five stimuli for foreground motion are shown in Figure 9. The eleventh stimulus is the stimulus with BG on $+1.0^\circ$, FG on -1.0° and motion frequency set to 0.8 Hz instead of 0.6 Hz. Where we initially thought on using sinusoidal motion such as is common in VIMS research, we decided to choose for uniform linear motion with immediate reversal, which makes the interpretation of the data much easier.

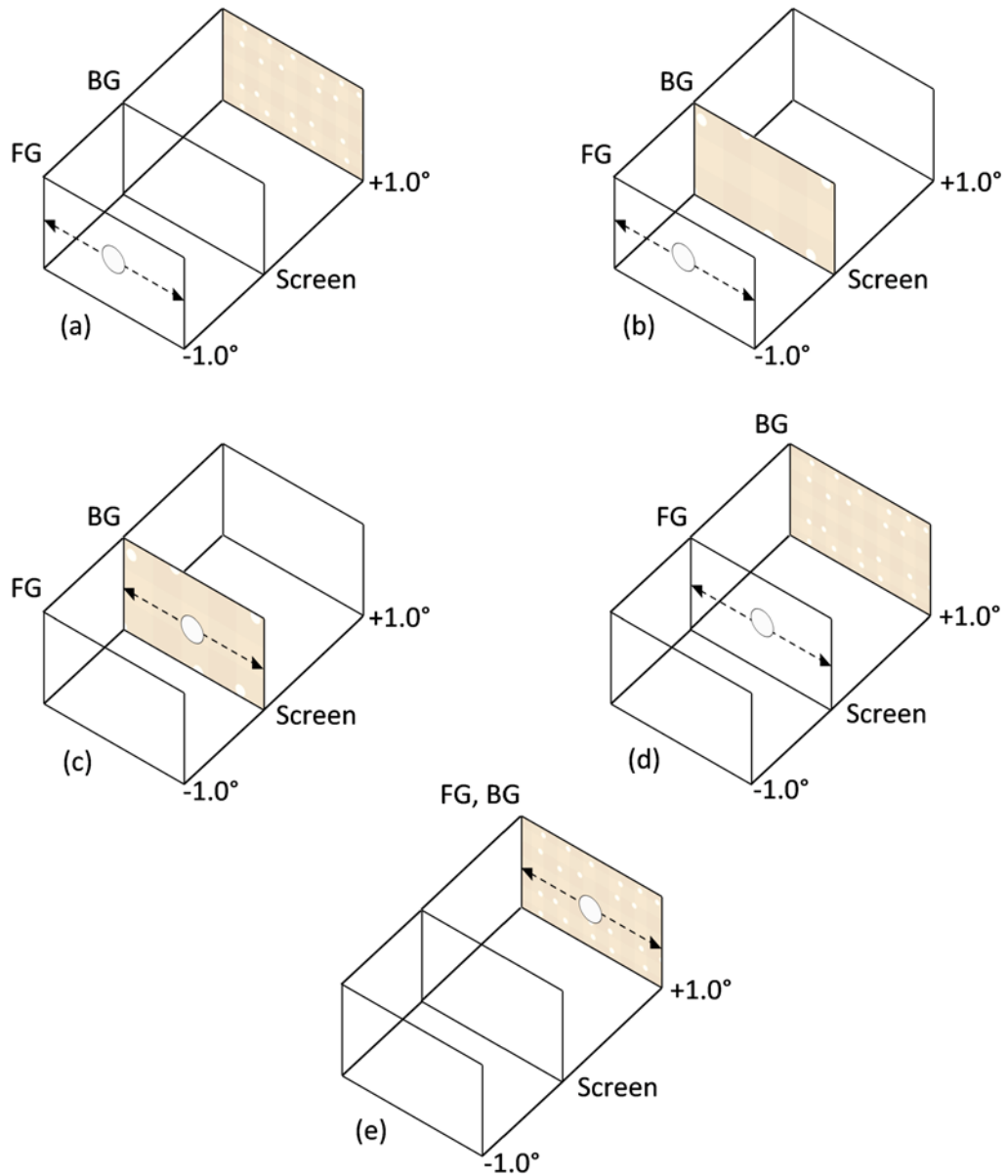


Figure 9. Schematic representation of the five horizontal planar foreground motion. The foreground object is placed on either 0 deg. or ± 1.0 deg. disparity while the background is placed on either 0 deg. or $+1.0$ deg. disparity to avoid framing effects. The five stimuli for horizontal planar background motion are equal with the only difference that the foreground object remains static and the background and the background objects move.

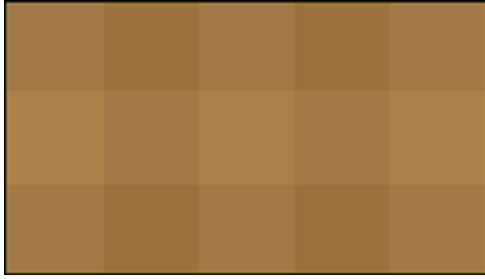


Figure 10. Enhanced image of the stimulus background pattern when placed on a depth of 0 deg. disparity. For clarity the brightness is adjusted to -40% and the contrast to +70%.

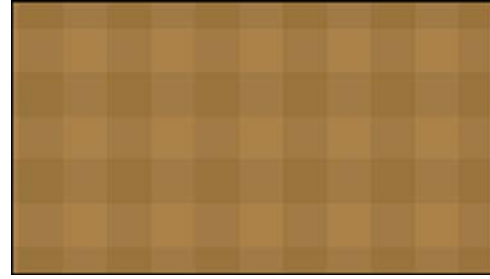


Figure 11. Enhanced image of the stimulus background pattern when placed on a depth of +1.0 deg. disparity. For clarity the brightness is adjusted to -40% and the contrast to +70%.

The background is made of a checkered pattern with a uniform background overlapped by horizontal and vertical semi-transparent bars of about 20 cm. This produces squares of three different colors with a low difference in contrast. The visual angle with a viewing distance of 200 cm of one block is $\approx 5.71^\circ$ on a depth of 0° disparity and $\approx 2.65^\circ$ on a depth of $+1.0^\circ$ disparity, see Figure 10 and Figure 11. We explicitly chose for the checkered pattern to visualize the background motion. The colors were chosen to give very little crosstalk in combination with the background and foreground object(s). The transitions between colors were of low contrast so that the viewing of the stimulus itself was as comfortable as possible. We chose to scale the background naturally when it was placed on different depth levels, this allows the observer to infer the depth at which the background is positioned from monocular cues such as: apparent size, linear perspective, and areal perspective besides the binocular disparity cue. We included light colored discs as background objects (see Figure 12 and Figure 13) to further visualize motion and give viewers a point of reference that can be tracked with the eyes. The foreground object is identical to the background objects, which consist of a disc with a width of 2° visual angle on screen level. This ensured us that the FG object was perceived in central vision (Berencsi, Ishihara, & Imanaka, 2005).

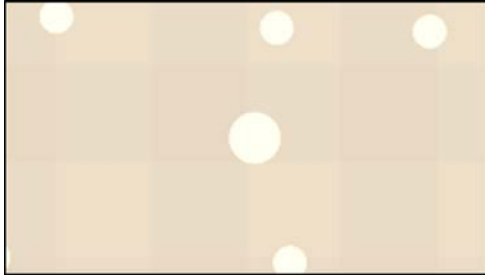


Figure 12. Stimulus with the background (consisting of the checkered wallpaper and the discs) placed on a depth of 0 deg. disparity and the foreground object on a depth of -1.0 deg. disparity.



Figure 13. Stimulus with the background (consisting of the checkered wallpaper and the discs) and the foreground object placed on a depth of +1.0 deg. disparity.

The path of motion should elicit the same vergence response in the eyes no matter at what depth the motion was shown. We therefore defined motion path in degrees of visual angle, which was set to 24° visual angle and was limited by the travel distance of the FG object on depth level of -1.0° that did not introduce framing effects. The motion frequency was set to 0.6 Hz (velocity = 28.8 deg./s) for all horizontal planar motion stimuli, with the exception of the eleventh stimulus which had motion with a

Table 4. Motion parameters at the three different depth levels for horizontal planar motion.

	Crossed (+1.0 deg.)	Screen (0 deg.)	Uncrossed (-1.0 deg.)
Path length (24 deg.)	55.21 cm	85.02 cm	183.68 cm
Velocity 0.6 Hz (28.8 deg./s)	66.25 cm/s	102.02 cm/s	220,42 cm/s
Velocity 0.8 Hz (38.4 deg./s)	-	-	293,89 cm/s

Table 5. Motion parameters for the three different motion types with depth motion.

	0-Crossed	Crossed-uncrossed	0-Uncrossed
Path length	69.90 cm	301.96 cm	232.06 cm
Velocity 0.4 Hz	55.92 cm/s	241.57 cm/s	185.65 cm/s
Velocity 0.6 Hz	83.88 cm/s	362.35 cm/s	278.47 cm/s
Velocity 0.8 Hz	111.84 cm/s	483.14 cm/s	371.30 cm/s

motion frequency of 0.8 Hz (velocity = 38.4 deg./s). Objects moving at these velocities should not be perceived as disintegrating because these are still far lower than $v_{50\%}$, which computes to 72.9 deg./s using Equation 3. The chosen velocities were defined for motion at screen depth. Because we wanted to keep velocity equal in terms of degrees visual angle we computed the speeds in cm/s for objects at each individual depth level. The resulting numbers can be found in Table 4.

Depth motion

For the depth motion stimuli we manipulate motion path between two disparity levels and motion speed. For the motion path there are three options: motion between -1° and $+1^\circ$, -1° and 0° , and 0° and $+1^\circ$, schematic drawings of these stimuli are shown in Figure 14. Speeds are defined as 0.2 Hz, 0.4 Hz, and 0.6 Hz, which sums up to nine stimuli total. See Table 5 for the parameters. Object properties are identical to those described earlier for horizontal planar motion with the addition of a ring. This ring is added as a reference at 0° disparity, which helps the observer to distinguish whether the FG object is moving in front or behind the screen.

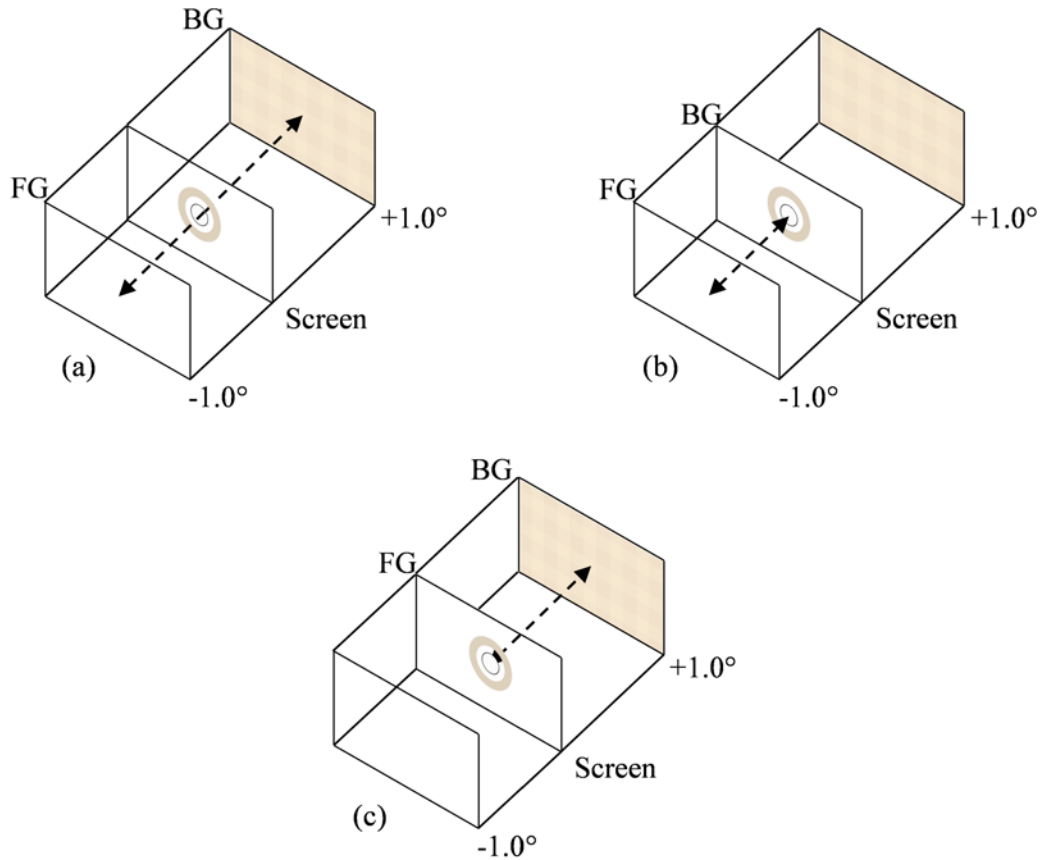


Figure 14. Schematic representation of the three motion types for depth motion. The foreground starts at 0 deg. disparity and moves between ± 1.0 deg. (a), -1.0 deg. and 0 deg. (b), or 0 deg. and $+1.0$ deg. (c). For all these stimuli the floating ring is placed on 0 deg. and the background on $+1.0$ deg. disparity. Speeds are varied across these three motion types to generate nine unique stimuli.

Concentration task

Participants were asked to follow the moving object(s) with their eyes. We added a concentration task to make sure participants kept their eyes on the moving object. At six pseudo-random moments during each stimulus one of the light colored circles would turn red for one second. The randomization algorithm excluded the first and last second of each stimulus and made sure there was at least one second between two consecutive signals. Participants were asked to press the spacebar on the keyboard the instant the color changed, which allowed us to get the participants' reaction time. We emphasized that we wanted

fast reactions without any errors. For the stimuli with foreground motion the FG object would change color, for the stimuli with BG motion one of the discs in the background would turn red. We made sure the discs in the background that could change color, did not leave the screen.

4.5 Measures

We aimed at three dependent variables: discomfort, defined as the calculated score on the 16-item discomfort questionnaire, concentration task reaction time, defined as the average time in which the spacebar was pressed after a disc turned red, and center of balance, defined as the calculated score based on the motion data from the balance board and the FOB tracker. In addition to these dependent variables we also measured various control variables (i.e., the WRRT, 3D viewing frequency, preference towards 3D, motion sickness susceptibility, and the frequency of visual discomfort symptoms when watching TV at home) in the pre-exposure questionnaire. Of these control measures we only discuss the WRRT and motion sickness susceptibility in this chapter, the other control measures are described in Appendix C.

Discomfort questionnaire

Before the first stimulus and after every stimulus participants filled in a discomfort questionnaire. Participants were asked to report the degree to which they experienced each of the sixteen symptoms (*tired eyes, uncomfortable vision, headache, difficulty concentrating, vertigo, ache in or behind the eyes, sleepiness, irritated eyes, “pulling” feeling of the eyes, blurred vision, dry eyes, difficulty focusing on an object, burning eyes, double vision, neck pain, and watery eyes*) at that moment. These symptoms were adapted from several questionnaires (e.g. Kennedy, Lane, Berbaum, & Lilienthal, 1993; Howart & Costello, 1997; Conlon et al., 1999; Sheedy et al., 2003). There were four possible answers for each symptom, reflecting the severity of the symptom (*none, slight, moderate, severe*).

Concentration task

From the concentration tasks, we recorded the reaction time and the number of errors for each of the six signals. Reaction time is defined as the time between the onset of the last visible red disk and the spacebar press, the number of errors is defined as the number of repetitive spacebar presses made after a correct press (but we also measure how many presses there were before the onset of the first showing).

Postural data

From the data from the balance board we calculated two balance statistics, the pressure difference between the front and back sensors (FB-balance, see Equation 4) and the pressure difference between the right and left sensors (RL-balance, see Equation 5). Scores between participants had different offsets from zero due to shifts in position during the experiment, nullifying the calibration at the beginning. We therefore decided to look at the variance as measure, which we calculated per participant per condition. We decided not to look at the FoB measures until after analysis of the balance board data, because the FoB tracker allows for more degrees of freedom which makes analysis more difficult.

$$FB\text{-balance} = (press_{front\ left} + press_{front\ right}) - (press_{back\ left} + press_{back\ right}) \quad \text{Equation 4}$$

$$RL\text{-balance} = (press_{front\ right} + press_{back\ right}) - (press_{front\ left} + press_{back\ left}) \quad \text{Equation 5}$$

WRRT

The Wilkins rate of reading task (Wilkins et al., 1996) consists of a reading task where a person has to read out loud, as rapidly as possible for 60 sec., a meaningless passage of seemingly random words. Each line consists of 15 words distributed randomly (e.g., “the is you to for see come look up dog and cat play

not my”). Because of the simple nature of the words even a poor reader can perform the task. Due to the randomization and the choice of the words, the text is independent of any syntactic and semantic constraints, and readers have to keep the text in focus as they do not know what word will come next.

Lambooij et al., (2010) developed a simple measurement tool using the WRRT consisting of the ratio of the number of words read between 2D and 3D viewing conditions. This measure was performed right after the screening. Unfortunately, only the reading speed in 3D was collected, which resulted in us being unable to use this measurement in our analysis.

Motion Sickness Susceptibility

Motion sickness susceptibility was evaluated by means of the standardized Motion Sickness Susceptibility Questionnaire Short-form (MSSQ-Short; Golding, 2006b). This short-form is one third of the length of the MSSQ-Long, respectively 18 and 54 items. The MSSQ (Golding, 1998; Golding, 2006a) rates (scale from 0-3 with a ‘not applicable’ choice, see Appendix F) how susceptible an individual is to motion sickness and what kinds of motion stimuli were most associated with motion sickness during childhood and over the past 10 years. Sickness was defined as feeling queasy, nauseated, or actually vomiting after exposure to a variety of motion stimuli (9) involving land, sea, and air travel, as well as playground equipment (swings and roundabouts) and funfair rides. Three different scores are computed to reflect motion sickness susceptibility: a childhood score (MSA; Equation 6), an adulthood score (MSB; Equation 7) and a MSSQ-short raw score (Equation 8).

$$MSA = \frac{\text{total sickness score child} \times 9}{(9 - \text{number of types not experienced as a child})} \quad \text{Equation 6}$$

$$MSB = \frac{\text{total sickness score adult} \times 9}{(9 - \text{number of types not experienced as an adult})} \quad \text{Equation 7}$$

$$MSSQ \text{ raw score} = MSA + MSB \quad \text{Equation 8}$$

4.6 Procedure

The experiment took place in a windowless room with a combination of TL-lighting and normal light bulbs. Ambient light was 650 lux, during the screening and pre-questionnaire. This was measured at the spot participants would view the stimuli, i.e., 200 cm from the TV, at a height of about 100 cm, and directed at the TV. Participants were asked to read and sign the informed consent, which informs them about the purpose of this study. They were then screened for visual acuity, visual stereopsis, and colorblindness. After the screening we turned off the TL-lighting, which left a dimmed setting of 9.5 lux, measured in a similar way as before. Participants were asked to sit in the chair in front of the TV. The chair had four legs and a backrest that slightly slanted backwards. When seated, participants took a Wilkins Rate of Reading Test and filled in the pre-exposure questionnaire. Preceding the experiment a training session was incorporated to familiarize the participants with the assessment, display and stimuli. The experiment leader then started the training session, which showed still images of the different stimuli and the concentration task. Upon completion of the training, participants were asked to fill in the first of the set of stimuli questionnaires, which would act as a baseline. The experiment leader then hung the necklace with the FOB receiver around the neck of the participant, calibrated the magnetic tracker and the balance board, and started the data logging. For the main measurements, the participant was instructed to sit in a comfortable way without trying to move during the experiment.

If the participant had no further questions the main trial was started and the experiment leader moved to an adjacent room from where he was able to follow the participant via the cameras and the program loggings. Participants viewed 20 stimuli which were separated with a pause of 1 minute, in which participants filled in the corresponding discomfort questionnaire for each stimulus. When the minute elapsed, the text on the screen changed instructing the participant to get ready for the next stimulus. The next stimulus was manually started by the participant by pressing a key on the keyboard. After the main trial the experiment leader reentered the room and asked the participant to fill in the post-exposure questionnaire. Finally, any questions from the participant were answered, and the participant was thanked for their participation and given the incentive. Figure 15 shows a schematic overview of the different stages in this experiment.

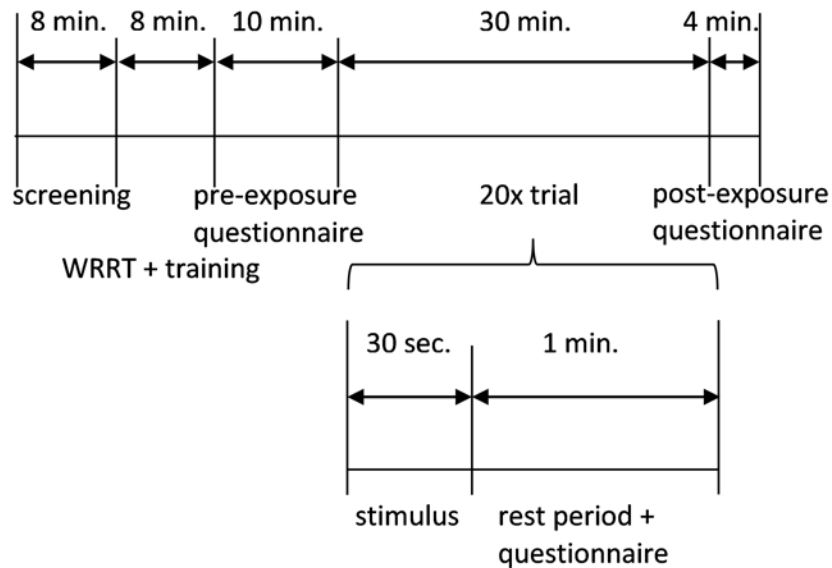


Figure 15. Time diagram of the procedure of the experiment.

Chapter 5

Results

In this section we describe the results of our experiments. Because the stimuli for the planar and depth motion are different we analyzed each set of stimuli separately. This section will first present the general results about the measures, followed by the results per measurement for the horizontal planar motion stimuli, concluding with the results from the depth motion stimuli. We are especially interested in the effect of velocity, disparity, motion component (in planar motion), motion direction, and individual differences on visual discomfort. Whether we perform parametric or non-parametric tests depends on the distribution of the data. We test all the distributions for normality using the z -scores of skewness and kurtosis. We compare these values to values that we For a distribution to be considered normal we compare its z -score with that would expect to get based on chance alone. At a significance of $p < .05$ we consider distributions with z -scores larger than 1.96 as non-normal (Field, 2005, p. 72). Z -scores are calculated by dividing the skewness or kurtosis by its standard error.

The structure of the results for the horizontal planar motion and depth motion analyses are the same. We start each subsection with the results of our analysis on the discomfort questionnaire followed by the results of the concentration task data, and concluding this section with the postural data.

5.1 Control measures

We used several control measures, which we described in section 4.5 and Appendix C. Here we quickly describe the descriptive statistics and any remarkable results of these control measures.

WRRT

The WRRT was performed on a stereoscopic screen only. The distribution of the number of words was normal (*skewness* = -0.36, *SE* = 0.46; *kurtosis* = -0.27, *SE* = 0.90), the distribution of the number of errors was only slightly positively skewed (*skewness* = 0.75, *SE* = 0.46; *kurtosis* = -0.07, *SE* = 0.90) meaning that several participants were able to read all 150 words or came very close. On average, participants read 95.92 words (*SD* = 39.92) and made 3.08 errors (*SD* = 2.40).

3D viewing frequency

The descriptive statistics of 3D viewing frequency were already discussed in section 4.2. In short, only a single participant viewed 3D content more often than six times per year.

Preference for viewing 3D

The preference of participants for viewing 3D (content) was measured by six questions (see Appendix C). To assess whether these items measured the same overall concept we performed a principal component analysis (PCA) that resulted in two scales. A ‘discomfort’ scale, composed of the items: “3D (movies) tires or hurts my eyes” and “3D (movies) make me feel nauseous or give me headaches”, with a Cronbach’s Alpha of 0.82 and mean inter-item covariances of 0.74. The second scale combined the items: “3D (movies) give a better overall viewing experience than 3D (movies)” and “I choose a 3D (movie) over a 2D (movie)”. This ‘3D preference’ scale had a Cronbach’s Alpha of 0.78 and mean inter-item covariances of 0.75. All items received a similar weight so that they give a meaningful scale, which allows for easier interpretation (McDonald, 1999). The distribution on the discomfort scale (*skewness* = 0.15, *SE* = 0.46; *kurtosis* = -1.06, *SE* = 0.90) and the distribution of the preference scale (*skewness* = 0.14, *SE* = 0.46; *kurtosis* = -1.18, *SE* = 0.90) were deemed normal. There seemed to be no clear preference in our sample, participants scored an average of 2.90 (*SD* = 0.94) on the summated discomfort scale and

3.16 ($SD = 1.02$) on the summated preference scale, where a score of 3.00 represents the center of the scales (*Neutral*).

Motion sickness susceptibility

The MSSQ-Short raw scores had a positively skewed distribution ($Mdn = 1.17$, $IQR = 0.67$, $skewness = 1.12$, $SE = 0.47$; $kurtosis = 0.67$, $SE = 0.92$). The average score ($M = 9.33$, $SD = 8.79$) was lower than the norms for the MSSQ-Short ($M = 12.4$, $SD = 9.4$, see Golding J. F., 2006b). Only 7 of the 25 participants exceeded the median (50th percentile) score of the norm, which means the motion sickness susceptibility of our sample is likely to be lower than that of the sample on which the norms were based. Looking at the results of the single item motion sickness susceptibility question at the start of the questionnaire (Appendix F) we found that most responses were in the “not at all” (44%) and “slightly” (36%) categories, with fewer in the “moderately” (16%) and “very much so” (4%). The correlation between the single item question and the MSSQ-Short was $r = 0.74$ ($p < .001$).

Discomfort at home

We performed a PCA to find any latent concepts in the 16 items. We only found one reliable concept: ‘physical eye discomfort’, which was composed of the items: *Ache in or behind the eyes*, *Burning eyes*, and *Irritated eyes*. This scale had a Cronbach’s alpha of 0.90 and inter-item covariances of 0.46. This composited measure was created by averaging the scores, ranging from 1 (*Never*) to 5 (*Always*), of the three sub-items. The resulting distribution was both positively skewed and leptokurtic ($skewness = 1.87$, $SE = 0.46$; $kurtosis = 3.15$, $SE = 0.90$) with a median score of 1.00 ($IQR = 0.67$). This means that the vast majority of the participants never, or not very often, experienced discomfort when watching TV at home. We can thus assume that there is no predisposition to discomfort from watching TV in our sample. This scale was found to correlate negatively with the discomfort scale extracted from the 3D preference

questions ($r = -0.48$, $p = .016$). This is a rather surprising finding, as it tells us that people experiencing discomfort with 3D content, experience close to no discomfort at home and vice versa. However, we have to keep in mind that both scales showed only very little absolute discomfort, so even though there might be a negative correlation, the actual level of discomfort is very low.

5.2 General results

This section describes results from the stimulus data, applicable to the whole dataset. We do this so we get comparable measures for both planar and depth motion. In this section we skip descriptive statistics for most of the measures as these are given in section 5.5.

Discomfort questionnaire

To filter out individual differences from the start of the experiment we computed the baseline corrected visual discomfort scores which are the scores after each stimulus minus the score before the first stimulus. To find any latent variables in the dataset a principal component analyses (PCA) was performed on the baseline corrected scores (see Appendix D). With 500 cases, the result of 25 participants times 20 repetitions, we should have enough data points for the PCA (a sample size of around 10-15 times the number of variables in the factor analysis is recommended; Field, 2005, p. 638; Hair, et al., 2006, p. 112). However, we have to keep in mind that all these data points come from the same 25 participants which could reduce the strength of the PCA.

From the PCA we extracted two factors, Fac1: '*Loss of visual focus*', consisting out of the items *Blurred vision*, *Difficulty Focusing on an object*, and *Double vision* (Cronbach's $\alpha = 0.70$, mean inter-item correlations = 0.48), and Fac2: '*Eye strain*', consisting out of the items *Tired eyes*, *Uncomfortable vision*, and *Irritated eyes* (Cronbach's $\alpha = 0.63$, mean inter-item correlations = 0.36).

Negative scores show that the participant experienced a decrease of discomfort from the baseline, while positive scores signal an increase of experienced discomfort compared to the baseline.

Concentration task

We used the mean task times per condition as our measure. We found several outliers, of which most occurred during the first viewed condition. Participants apparently did not know what to expect of the task or where they needed to focus, despite the training (see section 4.5), which caused them to respond severely slower than during the following conditions. We therefore removed the first condition from the measure.

The task errors were very low, which was expected as we prompted the participants to prevent mistakes. This resulted in an extremely positively skewed ($skewness = 6.45$, $SE = 0.11$) and leptokurtic distribution ($kurtosis = 60.50$, $SE = 0.22$), with a median of 0.00 ($IQR = 0.00$). Based on the frequencies of errors in several conditions, which was equally distributed, we decided to drop this measure from further analyses.

5.3 Horizontal planar motion

For horizontal planar motion we looked at conditions 1 through 11, excluding condition 6 which was added as extra (independent) condition and is analyzed in such way. For the descriptive statistics we only report distributions per measure, where we looked at the distributions per condition to validate whether we can use parametric tests.

5.3.1 Discomfort questionnaire

The factor 1 (*loss of visual focus*) distribution was positively skewed ($skewness = 0.96$, $SE = 0.16$) and leptokurtic ($kurtosis = 4.93$, $SE = 0.31$). A square root transformation made the factor 1 distribution far less skewed, though introduced a negative skew ($skewness = -0.75$, $SE = 0.16$) and increased kurtosis

(*kurtosis* = 5.81, *SE* = 0.31). The factor 2 (*eye strain*) distribution was slightly negatively skewed (*skewness* = -0.39, *SE* = 0.16) and leptokurtic (*kurtosis* = 2.14, *SE* = 0.31). Even though skewness is not very far from a normal, the leptokurtic distribution makes it difficult to use parametric tests. That is why we decided to perform non-parametric tests on the untransformed data for both factor 1 and 2. The factor 1 distributions were similar for BGM (*Mdn* = -0.12, *IQR* = 0.44) and FGM (*Mdn* = -0.14, *IQR* = 0.35). The factor 2 distribution for BGM had a median of 0.11 (*IQR* = 0.76) and the distribution for FGM had a median of -0.19 (*IQR* = 0.82). The descriptive statistics for the BG-FG positions are shown in Table 6. For the analysis of motion component we performed a Wilcoxon signed-rank test with Monte Carlo approximation (confidence level of 99% and sample size of 10000), for the analyses of BG-FG position we performed a Friedman's ANOVA with Monte Carlo approximation set to the same parameters as in the Wilcoxon test.

We found no significant difference on factor 1 (*loss of visual focus*) for FGM (*Mdn* = -0.14) versus BGM (*Mdn* = -0.12), $T = 100.50$, $p = .27$, $r = -.16$ and no difference between BG-FG position ($\chi^2(4) = 1.74$, $p = .75$). For the factor 2 score (*eye strain*) there was no significant difference between FGM and BGM, $T = 105.50$, $p = .34$, $r = -0.14$. We also did not find significant differences between the BG-FG

Table 6. Descriptive statistics for planar motion of the distributions for each BG-FG position condition for factor 1 and factor 2.

	BG-FG position	Median	Interquartile Range
Fac1	Screen-screen	-0.14	0.40
	Screen-crossed	-0.14	0.36
	uncrossed-screen	-0.14	0.46
	uncrossed-crossed	-0.14	0.36
	uncrossed- uncrossed	-0.14	0.62
Fac2	Screen-screen	-0.03	0.59
	Screen-crossed	0.06	0.72
	uncrossed-screen	-0.03	0.55
	uncrossed-crossed	0.09	0.95
	uncrossed- uncrossed	-0.24	1.21

position ($\chi^2(4) = 2.98, p = .56$).

Additionally, we tested if there was an effect of velocity on planar motion comparing condition 4 with condition 6, which was specially added for this purpose. The factor 1 distribution showed acceptable skewness ($skewness = 0.57, SE = 0.34$) but was also found to be leptokurtic ($kurtosis = 2.26, SE = 0.66$), which is why we performed the Wilcoxon signed-rank test. The median score for this distribution was -0.14 ($IQR = 0.56$). Results from the Wilcoxon signed-rank test showed there was no effect of velocity on *loss of visual focus* between 0.6 Hz ($Mdn = -0.14, IQR = 0.30$) and 0.8 Hz ($Mdn = -0.14, IQR = 0.60$), $T = 66.50, p = .26, r = -.16$. The Factor 2 distribution was deemed normally divided ($skewness = 0.33, SE = 0.34, kurtosis = 0.10, SE = 0.66$), with an average score of 0.19 ($SD = 1.07$). We performed a dependent t-Test to see whether there was a significant difference on *eye strain* between 0.6 Hz ($M = 0.10, SD = 0.94$) and 0.8 Hz ($M = 0.28, SD = 1.19$). Results showed that the difference was not significant ($t(24) = -1.07, p = .30, r = .21$).

5.3.2 Concentration task times

The task time distribution is positively skewed ($skewness = 1.01, SE = 0.16$) and leptokurtic ($kurtosis = 1.03, SE = 0.32$) with a median of 2099.83 ($IQR = 170.08$). Performing a log transformation made the distribution less positively skewed ($skewness = 0.53, SE = 0.16$) and flattened the distribution to an acceptable kurtosis ($kurtosis = 0.53, SE = 0.32$). Because positive skew remained, we performed non-parametric tests.

To see if there was a difference between FGM and BGM a Wilcoxon signed ranks test was performed. The results showed a significant large effect of motion component ($T = 3.00, p < .001, r = -.61$). This means that participants had a lower task time when stimuli presented foreground motion ($Mdn = 2048.37, IQR = 102.88$) than when stimuli presented background motion ($Mdn = 2178.33, IQR = 133.53$).

Table 7. Descriptive statistics for planar motion of the distributions for each BG-FG position condition for concentration task times.

	Median	IRQ
Screen-screen	2050.00	136.08
Screen-crossed	2071.83	98.92
uncrossed-screen	2160.08	161.89
uncrossed-crossed	2136.75	102.04
uncrossed- uncrossed	2128.25	149.83

For the analysis of the BG-FG depth position we performed a Friedman’s ANOVA and found a significant effect of BG-FG position ($\chi^2(4) = 29.31, p < 0.001$). Based on the medians (Table 7), we expect to find an effect of the background position which is why we performed post-hoc tests. We performed two Wilcoxon signed ranks tests with Bonferroni correction, which means we test using .025 as our critical level of significance. We tested the pairs Screen-screen – uncrossed-uncrossed and Screen-crossed – uncrossed-screen. Results indeed showed that the uncrossed-uncrossed condition resulted in significantly longer task times than the screen-screen condition ($T = 81.00, p < .013, r = -.31$). For the second pair we found that the uncrossed-screen condition resulted in significantly longer task times than the screen-crossed condition ($T = 38.00, p < .001, r = -.47$). What is interesting is that this difference might not be caused by the background position but due to the interaction effect between both independent variables.

Because it is difficult to identify interaction effects with non-parametric tests we performed a parametric test. While validity may be an issue here (z -score skewness = 3.31, z -score kurtosis = 1.66, $D(233) = 0.09, p < 0.001$), we think this might give us insight in how both independent variables interact. We performed a two-way ANOVA on the log transformed data, with the motion component and the BG-FG depth position as fixed factors and ‘Participant’ as random factor. Like with the non-parametric tests

we found a main effect of motion component ($F(1, 24.08) = 48.55, p < .001, r = 0.82$) and of BG-FG depth position on task time ($F(4, 96.82) = 8.73, p < .001, r = 0.51$). In addition, we also found a significant interaction effect between motion component and BG-FG depth position ($F(4, 79) = 8.33, p < .001, r = 0.54$), this effect can be clearly seen by looking at Figure 16.

We also looked at the difference between condition 4 and condition 6 which were identical except for

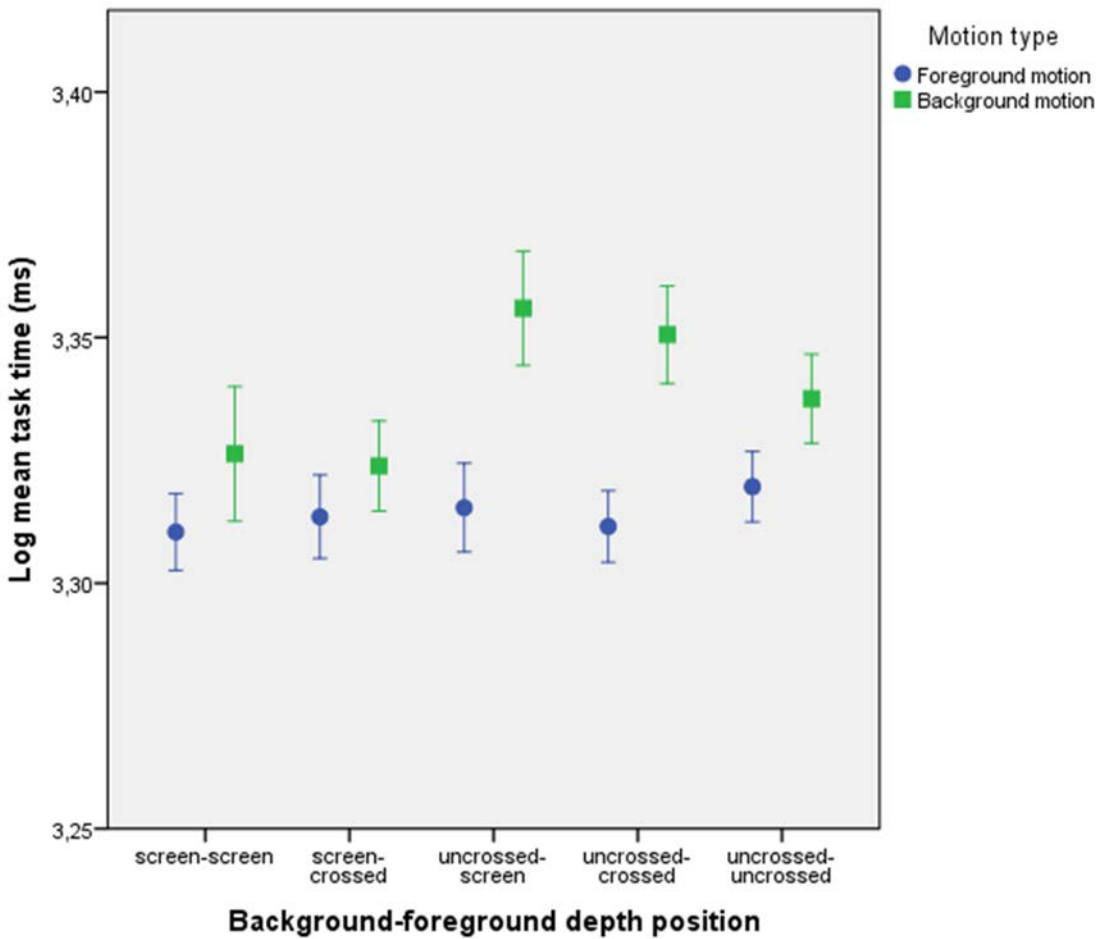


Figure 16. The log₁₀ mean task times for the foreground-background depth position and motion type combinations with 95% confidence intervals. With on the y-axis the log₁₀ transformed mean task reaction time in ms and on the x-axis the background-foreground depth position varying between the five defined combinations.

the velocity, respectively 0.6 Hz and 0.8 Hz. The distribution looked relatively normal (*skewness* = 0.53, *SE* = 0.67, *kurtosis* = 1.87, *SE* = 0.67), which was confirmed with a Kolmogorov-Smirnov test ($D(48) = .084$, $p > .05$). We performed a dependent t-Test but found no significant difference between the 0.6 Hz ($M = 2254.42$, $SD = 117.12$) and 0.8 Hz ($M = 2236.59$, $SD = 107.72$) conditions ($t(19) = 0.55$, $p = 0.59$, $r = .12$).

5.3.3 Postural data

We analyzed the variance of the balance front-back (FB) and right-left (RL) from the balance board data, which consisted out of the mean variance per condition per participant. The FB balance distribution was both positively skewed (*skewness* = 3.19, *SE* = 0.16) and leptokurtic (*kurtosis* = 11.77, *SE* = 0.31) with a median of 0.16 (*IQR* = 0.84). A log transformation removed almost all the positive skew (*skewness* = 0.25, *SE* = 0.16) and kurtosis (*kurtosis* = -0.95, *SE* = 0.31), which resulted in a slightly platykurtic distribution which still tested significantly non-normal on the Kolmogorov-Smirnov test ($D(248) = 0.71$, $p = .005$). The RL balance distribution had a similar distribution, i.e. it was positively skewed (*skewness* = 4.56, *SE* = 0.16) and leptokurtic (*kurtosis* = 24.30, *SE* = 0.31) with a median of 0.17 (*IQR* = 0.36). The log transformed data again improved the distribution, but left too much positive skew (*skewness* = 0.69, *SE* = 0.16, *kurtosis* = 0.30, *SE* = 0.31) to allow parametric tests.

Due to the deviation of normality for both distributions we decided to perform non-parametric tests on each distribution. To analyze differences between FGM and BGM we performed a Wilcoxon signed ranks test. We used Friedman's ANOVA to verify whether any differences between BG-FG depth position was significant.

For FB balance, we found no significant difference between FGM ($Mdn = 0.45$, $IQR = 1.04$) and BGM ($Mdn = 0.34$, $IQR = 0.97$; $T = 148.00$, $p = .71$, $r = -.06$), and no significant difference between BG-FG position ($\chi^2(4) = 3.14$, $p = .54$). For RL balance, we also found no significant difference between

Table 8. Descriptive statistics for planar motion of the distributions for each BG-FG position condition for the mean variance in the balance front-back and balance right-left.

		Median (kg)	Interquartile Range (kg)
Mean variance balance front-back	Screen-screen	0.24	1.16
	Screen-crossed	0.27	1.12
	uncrossed-screen	0.42	1.53
	uncrossed-crossed	0.14	0.86
	uncrossed- uncrossed	0.19	0.95
Mean variance balance right-left	Screen-screen	0.19	0.69
	Screen-crossed	0.15	0.30
	uncrossed-screen	0.25	0.48
	uncrossed-crossed	0.18	0.45
	uncrossed- uncrossed	0.15	0.49

FGM ($Mdn = 0.20$, $IQR = 0.53$) and BGM ($Mdn = 0.17$, $IQR = 0.38$; $T = 105.00$, $p = .12$, $r = -.22$), and no significant difference between BG-FG position ($\chi^2(4) = 4.54$, $p = .34$). Refer to Table 8 for the descriptive statistics per condition.

Also for this measure we tested whether velocity had any effect by comparing condition 4 (0.6 Hz) with condition 6 (0.8 Hz). The FB balance distribution was both positively skewed ($skewness = 2.73$, $SE = 0.34$) and leptokurtic ($kurtosis = 7.54$, $SE = 0.67$). We performed a log transformation to create an acceptable distribution ($skewness = 0.01$, $SE = 0.34$, $kurtosis = -1.18$, $SE = 0.67$). The RL balance distribution was initially very non-normal ($skewness = 12.71$, $SE = 0.34$, $kurtosis = 12.71$, $SE = 0.67$) but again a log transformation proved successful ($skewness = 0.64$, $SE = 0.34$, $kurtosis = -0.02$, $SE = 0.67$). We performed a dependent t-Test on both measures. We found that there was no significant difference on FB balance between the 0.6 Hz ($M = -0.62$, $SD = 0.79$) and 0.8 Hz ($M = -0.71$, $SD = 0.78$) conditions ($t(23) = 0.50$, $p = .62$, $r = .10$). Similarly, we found no significant difference on RL balance between the 0.6 Hz ($M = -0.65$, $SD = 0.70$) and 0.8 Hz ($M = -0.79$, $SD = 0.64$) conditions ($t(23) = 1.20$, $p = .24$, $r = .24$).

5.4 Depth motion

For horizontal planar motion we looked at conditions 12 through 20.

5.4.1 Discomfort questionnaire

For the conditions with depth motion, we saw again that the distributions were very leptokurtic and centered around zero. For factor 1 (*loss of visual focus*) this resulted in a positively skewed (*skewness* = 1.63, *SE* = 0.16) and leptokurtic (*kurtosis* = 5.53, *SE* = 0.32) distribution (*Mdn* = -0.06, *IQR* = 0.71). Performing a square root transformation removed most of the positive skew (*skewness* = 0.14, *SE* = 0.16) and helped lower the kurtosis (*kurtosis* = 2.57, *SE* = 1.04), though it still failed the Kolmogorov-Smirnov test ($D(224) = 0.21, p < .01$). Factor 2 (*eye strain*) showed a better distribution (*skewness* = -0.09, *SE* = 0.16, *kurtosis* = 1.25, *SE* = 0.32) but still deviated significantly from a normal distribution ($D(224) = 0.10, p < .01$). To analyze these non-normal distributions, we performed Friedman's ANOVA with Monte Carlo approximation (confidence level of 99% and sample size of 10000), for velocity and motion path. The descriptive statistics of the velocity distributions and the motion path distributions are given in Table 9 and Table 10.

The inferential statistics on factor 1 showed no significant effect of velocity ($\chi^2(2) = 0.89, p = .67$) and no effect of motion path ($\chi^2(2) = 1.34, p = .53$). Testing the factor 2 scores, we found no significant effect of velocity ($\chi^2(2) = 0.94, p = .64$) but we did find a marginal significant effect of motion path ($\chi^2(2) = 0.89, p = .50$). We performed Wilcoxon signed-rank tests on each combination of the three conditions to find out which conditions are significantly different from each other. To correct for the number of tests we do we used Bonferroni correction, meaning we use .0167 as our critical level of significance. We found no significant effect between uncrossed-screen and screen-crossed ($T = 70.00, p = .063, r = -.26$), between uncrossed-crossed and screen-crossed ($T = 108.00, p = .557, r = -.08$), and between uncrossed-

crossed and uncrossed–screen ($T = 50.00$, $p = .038$, $r = -.29$). The first and third test show small to medium sized effects.

Table 9. Descriptive statistics for depth motion of the distributions for each velocity condition for factor 1 and factor 2.

	Velocity (Hz)	Median	Interquartile Range
Fac1	0.4	-0.06	0.51
	0.6	-0.01	0.61
	0.8	0.02	0.51
Fac2	0.4	0.04	0.91
	0.6	0.06	1.39
	0.8	-0.08	1.24

Table 10. Descriptive statistics for depth motion of the distributions for each motion path condition for factor 1 and factor 2.

	Motion path	Median	Interquartile Range
Fac1	screen-crossed	-0.06	0.86
	uncrossed-screen	-0.06	0.72
	uncrossed-crossed	-0.06	0.54
Fac2	screen-crossed	0.14	1.31
	uncrossed-screen	-0.12	0.89
	uncrossed-crossed	0.24	1.12

5.4.2 Concentration task times

The task time distribution was found to be both positively skewed ($skewness = 2.17$, $SE = 0.17$) and leptokurtic ($kurtosis = 5.55$, $SE = 0.33$) with a median of 2146.17 ($IQR = 232.58$). The log transformed distribution still showed positive skew ($skewness = 1.76$, $SE = 0.17$) and high kurtosis ($kurtosis = 3.66$, $SE = 0.33$), which is why we performed Friedman’s ANOVA on the data to see if there is an effect of velocity and motion path.

We found a significant main effect of velocity ($\chi^2(2) = 44.72, p < .001$) between 0.4 Hz ($Mdn = 2407.41, IQR = 261.96$), 0.6 Hz ($Mdn = 2143.11, IQR = 93.89$), and 0.8 Hz ($Mdn = 2090.06, IQR = 108.28$). We performed three post-hoc tests, testing each combination of conditions, using the Wilcoxon signed ranks test with Bonferroni correction, which means we adjust our critical level of significance to .0167. Results showed that task times were significantly higher for the 0.4 Hz compared to the 0.6 Hz conditions ($T = 0.00, p < .001, r = -.62$), significantly higher for the 0.6 Hz compared to the 0.8 Hz conditions ($T = 27.00, p < .001, r = -.52$), and significantly higher for the 0.4 Hz compared to the 0.8 Hz conditions ($T = 0.00, p < .001, r = -.62$).

We also found a significant main effect of motion path ($\chi^2(2) = 42.56, p < .001$) between screen-crossed ($Mdn = 2051.17, IQR = 68.64$), uncrossed-screen ($Mdn = 2372.41, IQR = 213.69$), and uncrossed-crossed ($Mdn = 2216.22, IQR = 101.76$), showing that longer motion paths in depth possibly cause higher task times. We verified this theory by performing post-hoc tests on each combination of these conditions. We used the Wilcoxon signed ranks test with Bonferroni correction. The results showed that the task time was significantly higher for the uncrossed-screen condition compared to the screen-crossed condition ($T = 0.00, p < .001, r = -.62$) and also significantly higher for the uncrossed-crossed condition compared to the screen-crossed condition ($T = 1.00, p < .001, r = -.61$). Surprisingly, we found that task times were significantly higher for uncrossed-screen conditions than for uncrossed-crossed conditions ($T = 13.00, p < .001, r = -.57$), which contradicts our theory.

Because of the high skewness in the distribution we do not think it would be wise to pursue a similar path to find interaction effects as we did for horizontal planar motion. Therefore, we are limited to theory guided interaction effects. Based on Figure 17 it is difficult to spot any obvious interaction effects. There might be some kind of interaction effect based on 0.4 Hz scores per motion path condition. There seems

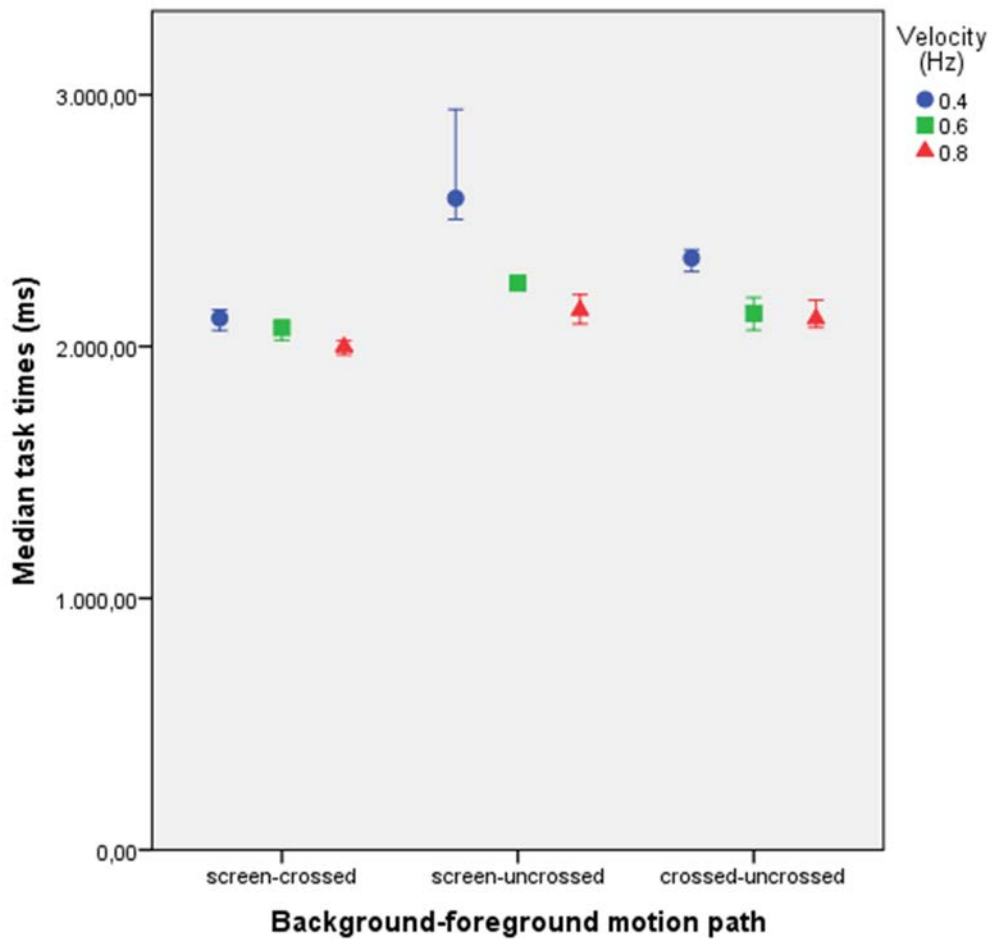


Figure 17. The median concentration task times for the background-foreground motion path depth and motion velocity combinations with 95% confidence intervals. With on the y-axis the median task reaction time in ms and on the x-axis the background-foreground motion path position varying between the three defined combinations.

to be a larger difference in task time between the 0.4 Hz condition and the other velocities which increases respectively for screen-crossed, crossed-uncrossed, and screen-uncrossed.

5.4.3 Postural data

As our measures for the postural data we took the mean variance of the balance front-back (FB) and right-left (RL) of the balance board data per condition per participant. The FB balance distribution was positively skewed ($skewness = 3.93$, $SE = 0.16$) and extremely leptokurtic ($kurtosis = 21.43$, $SE = 0.33$) with a median of 0.19 ($IQR = 0.92$). A log transformation helped improve the distribution ($skewness = 0.26$, $SE = 0.16$, $kurtosis = -0.90$, $SE = 0.33$), though it still failed the Kolmogorov-Smirnov test of normality ($D(222) = 0.06$, $p = .03$). The RL balance distribution also positively skewed ($skewness = 4.65$, $SE = 0.16$) and also extremely leptokurtic ($kurtosis = 28.21$, $SE = 0.33$). While the log transformation improved the distribution ($skewness = 0.53$, $SE = 0.16$, $kurtosis = -0.19$, $SE = 0.33$), positive skewness remained and the test of normality showed that the distribution deviated significantly from a normal distribution ($D(222) = 0.08$, $p = .002$). We performed Friedman's ANOVA on the untransformed data to validate whether there were significant differences between the conditions.

The results of the inferential statistics on FB balance showed no significant effect of velocity ($\chi^2(2) = 3.44$, $p = .18$) between 0.4 Hz ($Mdn = -0.06$, $IQR = 0.56$), 0.6 Hz ($Mdn = -0.06$, $IQR = 0.73$), and 0.8 Hz ($Mdn = -0.08$, $IQR = 0.87$). Additionally, we also found no significant effect of motion path ($\chi^2(2) = 1.68$, $p = .43$) between screen-crossed ($Mdn = -0.06$, $IQR = 0.91$), screen-uncrossed ($Mdn = -0.10$, $IQR = 0.80$), and crossed-uncrossed ($Mdn = -0.06$, $IQR = 0.51$). Similar results were found for RL balance, i.e. we found no significant difference between the 0.4 Hz ($Mdn = -0.18$, $IQR = 0.76$), 0.6 Hz ($Mdn = 0.21$, $IQR = 1.57$), and 0.8 Hz ($Mdn = -0.18$, $IQR = 1.22$) conditions ($\chi^2(2) = 2.96$, $p = .23$). Finally, balance was not significantly different between screen-crossed ($Mdn = 0.24$, $IQR = 1.62$), screen-uncrossed ($Mdn = -0.29$, $IQR = 1.10$), and crossed-uncrossed ($Mdn = 0.21$, $IQR = 1.13$) motion path conditions ($\chi^2(2) = 1.04$, $p = .60$).

5.5 Planar vs. depth motion

As a cross study test we were interested in the effect of motion component (i.e. planar motion vs. depth motion).

Discomfort questionnaire

For Fac1 we found a positively skewed (*skewness* = 1.44, *SE* = 0.11) and leptokurtic (*kurtosis* = 5.82, *SE* = 0.21) distribution. In general, participants did not differentiate much from their baseline score (*Mdn* = -0.14, *IQR* = 0.56). A square root transformation removed the positive skewness (*skewness* = -0.20, *SE* = 0.11) but could not help with the kurtosis (*kurtosis* = 4.63, *SE* = 0.22). A similar leptokurtic distribution (*kurtosis* = 1.55, *SE* = 0.22) was found for Fac2, although it was not skewed (*skewness* = -0.14, *SE* = 0.11). Again, participants did not differentiate much from their baseline score (*Mdn* = -0.18, *IQR* = 0.83). All tests of normality were significant, which is why we performed Wilcoxon signed ranks tests.

We found no difference between horizontal planar motion (*Mdn* = -0.09, *IQR* = 0.48) and depth motion (*Mdn* = -0.06, *IQR* = 0.39) conditions for Fac1 ($T = 139.00$, $p = .55$, $r = -.09$). The Fac2 results also showed no significant difference between horizontal planar motion (*Mdn* = -0.09, *IQR* = 0.74) and depth motion (*Mdn* = -0.01, *IQR* = 1.10) conditions ($T = 142.00$, $p = .82$, $r = -.03$).

Concentration task

The distribution of the task times without the first stimulus in the experiment had a median of 2138.83 (*IQR* = 206.71), was positively skewed distribution (*skewness* = 3.73, *SE* = 0.11) and had high kurtosis (*kurtosis* = 23.37, *SE* = 0.22). A log transformation could not help to create a normal distribution (*skewness* = 2.56, *SE* = 0.11, *kurtosis* = 11.03, *SE* = 0.22) which is why we performed a Wilcoxon signed ranks test on the untransformed data. Results showed a significant difference ($T = 0.00$, $p < .001$, $r = -.62$)

between depth motion ($Mdn = 2242.28$, $IQR = 146.23$) and horizontal planar motion ($Mdn = 2120.95$, $IQR = 85.74$).

Postural data

The distribution of the variance for the front-back balance was both positively skewed ($skewness = 3.71$, $SE = 0.11$) and leptokurtic ($kurtosis = 16.91$, $SE = 0.22$), with a median of 0.19 ($IQR = 0.87$). The distribution improved from a log transformation ($skewness = 0.23$, $SE = 0.11$, $kurtosis = -0.94$, $SE = 0.22$), though it still failed the Kolmogorov-Smirnov test of normality ($D(494) = 0.06$, $p < .001$). The distribution of the variance for the right-left balance was positively skewed ($skewness = 4.67$, $SE = 0.11$) and extremely leptokurtic ($kurtosis = 26.32$, $SE = 0.22$), with a median of 0.17 ($IQR = 0.36$). While a log transformation improved the distribution of the data ($skewness = 0.61$, $SE = 0.11$, $kurtosis = 0.06$, $SE = 0.22$) it still deviated too much from a normal distribution according to the Kolmogorov-Smirnov test of normality ($D(494) = 0.08$, $p < .001$).

Both distributions showed a very low variance for the majority of participants, however there are a few extreme values where the balance difference was 5 kg or more. Because both distributions were deviating from normality we performed Wilcoxon signed ranks tests on the untransformed data. The test on the front-back balance data indicated no significant difference ($T = 125.00$, $p < .33$, $r = -.14$) between the horizontal planar motion conditions ($Mdn = 0.48$, $IQR = 0.95$) and depth motion conditions ($Mdn = 0.43$, $IQR = 1.13$). The test on the right-left balance data also showed no significant difference ($T = 147.00$, $p < .69$, $r = -.06$) between the horizontal planar motion conditions ($Mdn = 0.22$, $IQR = 0.56$) and depth motion conditions ($Mdn = 0.25$, $IQR = 0.36$).

Chapter 6

Discussion

The first goal of this research was to see if we could find explicit causal relations between several motion and depth parameters of a stereoscopic movie clip and the amount of visual discomfort experienced. While we proposed several hypotheses in section 3.3, we feel we cannot safely accept or reject these based on our results. First and foremost because the hypotheses were aimed at measuring visual discomfort during exposure, while the subjective measure in our experiment measured post-effects instead. Based on previous studies, this was the measure we expected to yield results, especially in comparison to the other measures. The concentration task was something we added and, as far as we know, is not used as a measure in current visual discomfort literature. In addition, the postural measures were experimental and we did not know beforehand whether this would be able to detect differences. Though we will not use the hypotheses we set out to use, instead we will discuss the implications of our results on visual discomfort research in general. Moreover, we will discuss whether our second goal, determine whether we could use postural instability measures to measure and predict visual discomfort, was successful.

We found no significant effects of motion component, BG-FG depth position, velocity, BG-FG motion path, or between planar and depth motion on the two extracted factors from the discomfort questionnaire measure for either planar or depth motion. No effects on the postural measures were found either. However, clear effects of motion component and BG-FG depth position on task reaction times were found for horizontal planar motion in this study: BGM caused significantly higher response times than FGM, especially for conditions where the background was placed 1° behind the screen. Task times

were also significant during depth motion conditions. Results suggested that increasing velocity resulted in lower task times and motion behind the screen resulted in higher task times. We also found that depth motion resulted in significant higher task times than horizontal planar motion.

We propose two possible explanations of why no discomfort was measured with the subjective questionnaires. First, it could be that we did not induce visual discomfort and therefore did not measure it. We indeed found that the motion sickness susceptibility of our sample was much lower than the MSSQ-Short norm and we found no particular disposition for visual discomfort based on the results of the discomfort at home questions. However, participants did mention visual discomfort and trouble focusing on some of the stimuli, either in the open questions at the end of the questionnaire or during the debriefing. Of the stimuli types, planar background motion and depth motion were considered the most uncomfortable to watch due to many objects on the screen and repeated motion in and out the screen respectively. Overall, high velocity and large (crossed) disparity were said to be the most uncomfortable. These results correspond to the results found by Yano et al. (2002) and Speranza et al. (2006). Therefore we propose a second explanation. We argue that the high plasticity of the visual system caused symptoms to disappear almost immediately after the stimulus. We know from previous research that discomfort aftereffects can quickly diminish (Lambooy et al., 2009). While the stimuli we used were rather extreme in both disparity and velocity, we found that visual discomfort almost immediately disappeared after these short, 30 second, exposures. This finding is interesting, because it would mean that despite extreme disparities or velocities in depth, a person can quickly recover as long as the exposure was short. Of course it would be best to avoid exposure to these as visual discomfort is likely still experienced during exposure.

The task time measure led to several results. Though, task reaction times seem unrelated to visual discomfort, we argue there might be a correlation at a higher level. Based on our research we cannot

compare both measures because one measures exposure effects and the other post-effects. We can however propose a theory guided suggestion of how these measures would correlate. For instance, we could imagine that the visual system would need more time to process certain types of stimuli which results in a higher reaction time. Based on the results we found this means that BGM was more difficult to process than FGM, especially when the background was placed at 1° uncrossed disparity. Which makes sense because the entire background moved instead of one disk. This causes a significantly larger part of the field of view to change. In addition, more objects were visible when the background was placed at uncrossed disparity than in the conditions where the background was placed at crossed or screen disparity.

We also found that task times were significantly higher for low velocities than for high velocities. This seems contradicting at first but might can possibly be explained by the difference in relative disparity. Li et al. (2011) found that a subgroup of ten experts in 3-D perception, coding, quality assessment, and subjective experiments felt more visual discomfort with increasing velocity. But when relative disparity was high, visual discomfort was higher for low velocities than high velocities. The experts explained that when relative disparity is large it is difficult to fuse the foreground and background at the same time, which would lead to alternation of vergence between the front and back objects, which in turn made them feel uncomfortable. This is especially true for low velocities but was less of a problem for high velocities because high velocities made the object appear blurred, which increased their visual comfort. Even though we cannot relate task reaction time to visual discomfort we did find lower task reaction times for lower velocities. A possible explanation is the one given by Li et al. (2011) where low velocity makes the disparity between foreground and background more noticeable. However, this does not entirely fit with the results of depth position. While the shortest distance (screen-crossed) indeed had lower task times than the other two conditions we found that the third condition (uncrossed-screen) had significantly higher task times than the uncrossed-crossed condition. Based on the theory we would expect the condition with the longest path (uncrossed-crossed) to receive the highest task times A

different explanation why lower velocities had higher task times could be that the lower velocities are more nauseogenic. The lowest velocity condition had a motion frequency of 0.4 Hz and is closest of the three conditions to 0.2 Hz, which is the prime velocity for inducing motion sickness (Golding et al., 2001). The final result we found on task times was the difference between horizontal planar motion and depth motion, where depth motion had significantly higher task times than planar motion. Similar results on visual discomfort were explained based on the stress on the visual system due to the continuous changing demand (Yano et al. 2002, 2004). Again, we argue that this stress, which we could not measure, increased mental processing time which resulted in higher task times for depth motion compared to planar motion.

The fact that postural stability responses did not prove to be significant does not bode well for the possible application of postural responses as an objective measure. However, we cannot conclusively reject postural stability as a potential measure for visual discomfort. First, the postural response range in this study were quite low because of the seated position and the backrest of the chair. Second, the responses varied in their baseline due to body shifts, after which the tools were not recalibrated. This made interpretation much more difficult.

Chapter 7

Conclusions

With this research we set out to find how we could induce and measure discomfort, it appeared to be more difficult than initially anticipated. The subjective measure created to capture the construct of visual discomfort proved to be inconclusive. Arguably, because in our experiment it measured post-effects instead of exposure effects. Therefore, it is likely that we only measured residual effects from the conditions, which proved to be non-significant between conditions. We argue that no significant post-effects were measured due to a high plasticity of the visual system in combination with the short exposure.

We did find significant results on the task reaction time and discussed how certain stimuli might increase mental processing time leading up to higher reaction times. Motion in depth with low velocity showed higher task reaction times than depth motion with higher velocity. We suggest this might be explained by the fact that disparity differences between the foreground and background objects are easier to ignore at high velocities due to motion blur, whereas with low velocities the eyes are likely to move between the foreground object and the background depth levels.

Based on our results we advise content creators and display manufacturers to continue to prevent visual discomfort, although there does not seem to be much risk for enduring aftereffects, even for extreme disparity and velocity, as long as the exposure time is relatively short. However, it is not advised to use large disparities and/or fast motion in depth because viewers likely still experience visual discomfort during exposure.

Chapter 8

Recommendations and future work

We believe there are still unexplored areas in this field. While we found different results from what we expected, the original hypothesis still stand untested. Future research should limit their scope to a smaller, more specific part of stereoscopic motion. Emphasis should be put on finding a way to group participants on their predisposition to visual discomfort, for example with the WRRT 2D/3D ratio. In addition, we still believe that postural stability or center of gravity might be a valid measure to investigate in relation to visual discomfort. Though it might not work well in natural viewing conditions such as where people are seated. Furthermore, future studies should take care in measuring visual discomfort during the manipulation, although it would also be interesting to see whether the visual system shows similar plasticity when extreme stimuli are presented for longer durations. Concluding, we suggest that any experiment should be made less monotonous. This can be either done by limiting the duration of the experiment or by using less abstract and more interesting stimuli.

Summary

Now that three-dimensional televisions (3D TVs) become more common, there is also more attention to the possible risks of watching 3D TV. A well-known effect of watching 3D TV is that a significant number of people may experience visual discomfort when watching particular stereoscopic content. About one out of five persons have medium binocular status and consequently have a higher sensitivity to visual discomfort when watching stereoscopic content (Lambooj, Fortuin, IJsselsteijn, Evans, Heynderickx, 2010). On-screen motion is one of the potential causes of discomfort (Speranza, Tam, Renaud, & Hur, 2006; Ujike & Watanabe, 2011). However, it is not quite clear how different kinds of on-screen motion affect discomfort. We set out and investigated if and how the type of motion, the amount of (binocular) disparity in the images, and the binocular status of the viewer are of influence on the relation between motion and discomfort.

A controlled laboratory experiment with 25 participants was conducted to test if and how motion and disparity parameters affected visual discomfort. Participants watched 20 stimuli, which consisted of two classes of stimuli. We differentiated between stimuli with horizontal planar motion, and stimuli with depth motion. Both stimulus types used uniform linear motion. For the horizontal planar motion stimuli there were two independent variables: foreground-background (BG-FG) position and motion component. The BG-FG position levels consisted of their respective disparity level, which were: $\{-1.0^\circ, +1.0^\circ\}$, $\{-1.0^\circ, 0^\circ\}$, $\{0^\circ, +1.0^\circ\}$, $\{0^\circ, 0^\circ\}$, and $\{+1.0^\circ, +1.0^\circ\}$ where negative values represent crossed or near disparity and positive values represent uncrossed or far disparity. Motion component consisted out of two levels: foreground motion (FGM) or background motion (BGM). All horizontal planar motion conditions had a frequency of 0.6 Hz. The depth motion stimuli had two independent variables: motion path (with

three levels: $\{+1.0^\circ, -1.0^\circ\}$, $\{0^\circ, +1.0^\circ\}$, $\{0^\circ, -1.0^\circ\}$ and motion frequency (with three levels: 0.4 Hz, 0.6 Hz, or 0.8 Hz). In total there were 20 stimuli, each with a duration of 30 seconds.

A subjective measure was created, which was based on similar measures used in previous studies. Participants had to rate the severity of visual discomfort symptoms before the first stimulus and after each following stimulus. To make sure participants were viewing the stimulus we added a task where participants had to press a button when this was signaled on the screen. We were able to use the task reaction time as a second measure. As our final measures, we used postural data, specifically the mean variance for the balance front-back and the balance right-left, which was continuously captured during exposure using a Wii balance board. Participants had a 1 minute break between each stimulus condition, in which they could rest their eyes and fill in the questionnaire. Important to emphasize is that the questionnaire asked participants to rate the severity of discomfort symptoms they experienced after each stimulus. In short, we measured post-effects of our manipulation on the subjective measure.

Our results showed there was no significant main effect of either motion component or BG-FG depth position on the subjective measure or on our postural measures for planar motion. Similarly no significant main effect of velocity or motion path was found on the subjective measure or the postural measures. We also found no effect between planar and depth motion on these measures. The task time measure, however, proved to yield some interesting results. We found a significant main effect for each of the dependent variables. For planar motion we found that BGM resulted in higher task times than FGM and that this was especially true when the background was positioned at 1° behind the screen (uncrossed). For depth motion we found that lower velocities resulted in higher task times and that the crossed path (screen-crossed) resulted in significantly lower task times than the uncrossed path (uncrossed-screen) and that the uncrossed path had significantly higher task times than the full path (uncrossed-crossed).

We argue that the lack of results on the subjective measure can be caused by two likely theories. First, no visual discomfort was induced, or, what we think is more suitable, that the visual system proved to have high plasticity against these kind of stimuli for these relative short exposure times. The reason that no effects were measured on the postural measures is probably because the variance of postural balance was low overall. This is probably caused by our experimental setup with its rather natural viewing conditions (people were seated in a chair with backrest). In most postural balance experiments, participants are standing up. We argue that the results for the task times might be explained by the difference in mental processing between conditions. We think that BGM might induces a heavier load on the mental processing power compared to FGM because a larger part of the visual field is in motion and more objects could be seen in when the background was placed on uncrossed disparity than when it was placed at crossed or screen disparity. Similarly, we believe that depth motion takes longer to process due to the changing nature of the conflicting depth cues, compared to horizontal planar motion. The differences found in velocity might be explained by the relative difference between background and foreground disparities, which is easier to ignore for high velocities but causes possible delays in mental processing for lower velocities. While our data only partly supports this theory, i.e., the longest path length showed lower task times than the full path length, another theory could be that lower velocities are closer to 0.2 Hz which is the prime velocity for inducing motion sickness.

Based on these results we encourage stereoscopic content creators and display manufacturers to continue to prevent inducing visual discomfort with their products. Even though, the visual system seems highly robust against short exposures of extreme disparity and motion parallax, viewers are still likely to experience visual discomfort during the exposure.

Appendices

A. 3D techniques & TV types

There exist many different ways to create and present 3D images to a viewer. The most common way to reproduce a stereoscopic image with depth is to use two 2D-images taken from two slightly different viewpoints and present them separately to the viewer's eyes. These systems require a playback unit to generate the images and a display unit to separate the images and present one to the left eye and the other to the right eye.

Table 11 shows an overview of the most common 3D systems. Here we will only discuss two of the most popular systems currently sold to consumer markets, which are polarized filter systems, and field sequential systems. For a complete description of each system please refer to Pastoor and Wöpking (1997), Holliman (2005), and Urey, Chellappan, Erden, and Surman (2011). Polarized filter systems and field sequential systems both require a specific pair of glasses, which help separate the left and right

Table 11. 3D display systems and the image separation methods (adapted from: Kawai, 2002).

System	Separation technique
Head mounted display system	Two separate displays, one in front of each eye.
Anaglyph system	Left and right images are separated by difference in color. Glasses use color filters.
Polarized filter system	Left and right images are separated by the difference in polarization. Glasses use polarized filters.
Field sequential system	Left and right images are separated by time. Glasses use liquid crystal shutters.
Autostereoscopic system (three types: holographic, volumetric, and multiple image (Sexton & Surman, 1999))	Left and right images can only be seen by the correct eyes due to barriers (parallax barrier display) or lenses (lenticular display) in front of the display. No glasses are needed.

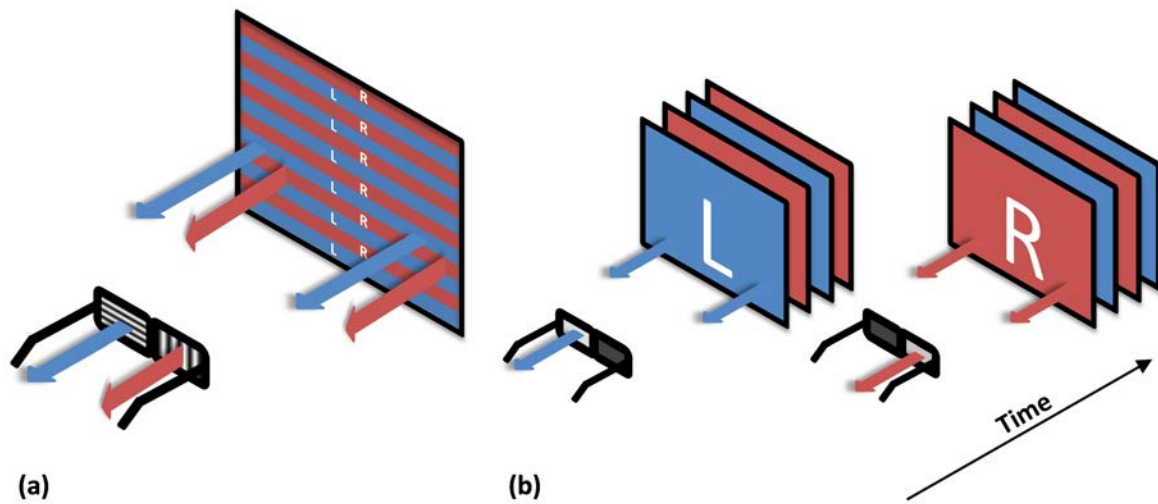


Figure 18. Schematic of a polarized filter 3DTV (a) and a field sequential 3DTV (b). In the polarized filter system a passive filter is used to separate the left and right view and guide each view to the correct eye. In the field sequential system an active filter is used, i.e. liquid crystal shutter glasses that alternates between transparent and opaque glasses with high frequency and synchronized with the TV.

image (see Figure 18). Polarized filter systems present the two 2D-images at the same time on the display but interlaced. On the screen a filter with alternating polarized stripes is placed so that the left and right view are displayed in a different polarization. The pair of glasses uses similar polarization filters but separates these so that one polarization direction can only pass through the left glass and the other polarization direction can only pass through the right glass. This allows for a spatial way of blocking a view from one of the eyes. Field sequential systems present the left and right images at different times on the display. The corresponding pair of glasses use a temporal way of blocking views from the wrong eye by making the glass in front of that eye opaque at the same time as the other eye's image is displayed. This works because the human visual system is capable of merging the constituents of a stereo pair across a time-lag of up to 50 ms (Pastoor & Wöpking, 1997).

B. Visual discomfort determinants (continued)

1. Binocular mismatches

Artificial stereoscopic images presented by 3D displays differ from natural vision in the fact that 3D displays do not present all the 3D information perceived by the visual system in natural conditions (Kawai, 2002). The mismatches between various 3D cues in human perception that stereoscopic systems create, leads to visual discomfort when viewing stereoscopic images (Onural et al., 2006). Binocular mismatches (or stereoscopic distortions) are binocular image imperfections that can come from different sources and different stages in the content generation process. Some examples are: bad alignment of the left and right camera, which introduces an image offset between the two images could cause stereoscopic disparities; optical differences between camera lenses could introduce shifts, magnification, and rotation errors; improper capture conditions, filters or errors in editing could introduce differences in luminance, color, contrast, or sharpness (Tam et al., 2011).

Lambooj et al., (2009) make a distinction between image generation-related distortions such as: keystone distortion depth-plane curvature, puppet theater effect, and shear distortion, and the display-related distortions such as: the picket fence effect, image flipping, and crosstalk. Most of these imperfections are well understood and can induce visual discomfort, especially when multiple distortions occur simultaneously (Woods, Docherty, & Koch, 1993). Kooi and Toet (2004) examined several of these binocular mismatches and found that almost all of these distortions induce visual discomfort if presented in a large enough quantity. However, visual discomfort was most strongly determined by vertical disparity, crosstalk, and blur (see Meesters et al, 2004; Woods et al., 1993 for an in-depth overview). Of these distortions, we consider crosstalk such a common distortion that we should give it at least some introduction. Crosstalk is a distortion which is caused by the imperfect separation of the left and right-eye views. This may cause the viewer to perceive ghosting (i.e., when a small portion of one eye's view is

perceptible in the other) and blurring. Research showed that higher crosstalk levels are more visible at larger camera base distances (i.e., larger disparities), but perceived depth remained constant between different levels (up to 15%) of crosstalk (Seuntiëns, Meesters, & IJsselsteijn, 2005). (Wang, et al. (2011) found similar results for the influence of disparity on crosstalk. They found that crosstalk visibility and acceptability thresholds are lower for increasing levels of contrast and disparity. With higher levels of contrast and disparity, less crosstalk is allowed.

2. *Depth inconsistencies*

Conflicting depth information resulting from errors in disparity can be referred to as depth inconsistencies (Tam et al., 2011). While typically stereoscopic depth is embedded in horizontal disparities between the left- and right-eye views, an alternative method is to use depth maps. A depth map is a matrix associated with a picture or video frame that stores the depth of each pixel. Stereoscopic content can be more efficiently transferred using the 2D signal plus the depth map (Fehn, 2004). Due to compression and/or transmission artifacts it is likely that depth inconsistencies are introduced. It is, however, not known in what way these errors might affect visual discomfort.

Another source of depth inconsistencies are 2D-to-3D conversion algorithms. These algorithms are being developed to create more stereoscopic content in relative short time. As these conversion algorithms rely on assumptions, estimations, and heuristic cues (Zhang & Tam, 2005) they will inherently introduce artifacts that include spatial and temporal inconsistencies. One of the most prominent artifacts is that of disocclusion. Disocclusion occurs when an occluded object becomes visible from a new viewpoint (Daly, Held, & Hoffman, 2011). There is no information of how the image should look at these areas, which makes it very difficult to create a perceptually flawless image. These types of depth inconsistencies were found to induce visual discomfort (Tam & Zhang, 2006). For a detailed review of the perceptual issues that arise from stereoscopic signal processing refer to Daly et al. (2011).

3. *Perceptual and cognitive inconsistencies*

Perceptual and cognitive inconsistencies might also influence visual comfort (Patterson & Silzars, 2009). These conflicts arise when there is a mismatch between our percept and our knowledge of the physical reality. Patterson and Silzars (2009) argued that the basis for this cue conflict and visual discomfort is to be found in the mental processes of human reasoning. They theorized that more discomfort is to be expected with greater engagement of the intuitive reasoning system, e.g. when a greater number of cues is involved, and/or the closer stereoscopic content matches the physical reality but still can be distinguished as inconsistent. While to our knowledge no empirical evidence exists to support this theory, it is reasonable to believe that, like physical cue conflicts, these mental cue conflicts can cause some discomfort. Further research should be conducted to show whether this mental strain can cause visual discomfort, and whether it is of similar scale as the other sources of visual discomfort.

C. Control measures

The following control measures are based on questions taken at the start of the experiment. A copy of these questions can be found in Appendix F.

3D viewing frequency

We asked participants how often they viewed 3D content in cinemas, on TV, on a computer, and on a mobile phone. For each of these categories participants could choose between five frequencies: *less than once a year, less than six times a year, every month, every week, or every day.*

Preference towards 3D (content)

To measure participants initial preference for 3D (movies) we asked them to evaluate seven statements on a five-point Likert scale (*Strongly agree, Agree, Neutral, Disagree, Strongly disagree*). The statements we used measured the possible positive effects of 3D (more immersion, higher level of naturalness, better viewing experience), the possible negative effects (distracts, tires or hurts the eyes, makes me feel nauseous or gives me headaches), and finally we asked whether they would choose (a) 3D (movie) over a 2D (movie).

Symptom experiences when watching TV at home

Finally we asked participants about possible discomfort when watching TV at home. We used 16 questions with the same 16 symptoms as in the discomfort questionnaire. The formulation was slightly adjusted, so it would ask participants how often they experience each symptom when watching TV at home. Answers were given on a five-point frequency scale: *Never, (Not very often) Infrequently, Sometimes, Fairly often, Always.*

D. PCA on the discomfort questionnaire items

A principal components analysis was carried out on the 16 discomfort variables to see whether the dataset could be reduced. The baseline corrected data (the values just before the experiment were subtracted from each value) from 20 measurements were taken into account (one after each stimulus). Missing value cases were excluded listwise. Coefficients with absolute values below .4 are suppressed. Extraction based on Eigenvalue greater than 1. We used an oblique rotation method (direct oblimin) due to the high expected correlations between the variables and the higher theoretical validity. We set the delta to 0 and max iterations to 25. The component correlation matrix (from the PCA) showed that the variables indeed correlated with each other.

From the first analysis with all 16 variables we decided to drop *vertigo* and “*pulling*” *feeling of the eyes* from the factor analysis based on the individual Kaiser-Meyer-Olkin measure of sampling adequacy (MSO) score. The MSO score represents the ratio of the squared correlation between variables to the squared partial correlation between variables and lies between 0 and 1, where a value of 1 indicates each variable is perfectly predicted without error by the other variables (Field, 2005, p. 640). The individual MSO score was 0.43 for *vertigo* 0.47 for *sleepiness*, and 0.37 for “*pulling*” *feeling of the eyes*, which are both under the 0.5, which is recommended by Kaiser (1974).

To come to a reliable factors we had to repeat the PCA. In repeated runs all individual MSO scores were larger than 0.5. In the repeated PCA we wanted to achieve the following goal: find the factors comprised of variables of which none cross-loads on another factor (in the pattern matrix) and none has a communality lower than 0.5.

The scree plot of the second run without *vertigo*, *sleepiness*, and “*pulling*” *feeling of the eyes* is shown in Figure 19. The plot shows quite clearly that factors after the second still explain a large part of the variation. Not all variables had a communality of above 0.5 so we dropped the variable with the lowest communality, *headache* (.45) and reran the analysis. In the new analysis *Ache in or behind the eyes* showed had a communality of .40 and was dropped from the analysis.

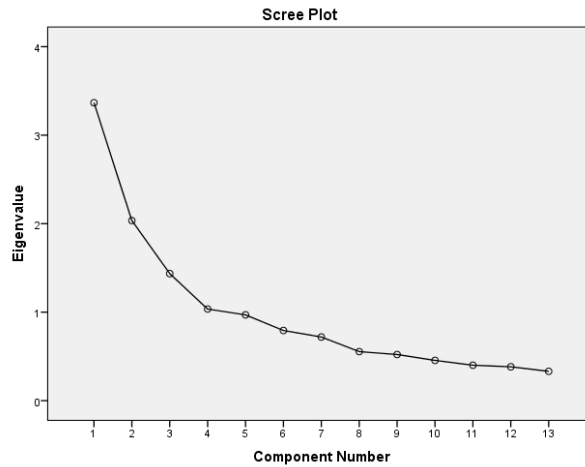


Figure 19. Scree plot of the principal component analysis on the baseline corrected discomfort scores from the discomfort questionnaire.

In the next analysis all communalities were above 0.5 and all variables together had an average communality of 0.66. These factors explained 66.09 % of the variance. There were cross-loadings (>.4) for *dry eyes*, *tired eyes*, *difficulty concentrating*, *blurred vision*, *burning eyes*, *neck pain*, *double vision*, and *watery eyes*. We removed these variables one by one and tested whether the other variables still passed our criteria. In the end we ended up with two factors (Figure 20), which explained 66.74 % of the variance.

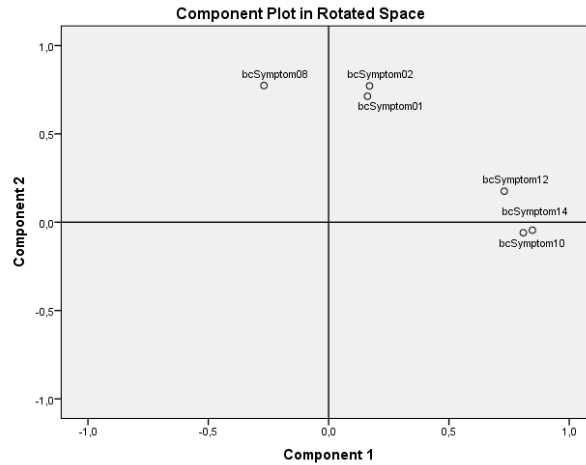


Figure 20. Component plot of the remaining discomfort items in rotated space.

The two factors were validated and were found to have Cronbach's alphas of above 0.6

Table 12. Factor validation of the two factors found with a principal component analysis on the baseline corrected discomfort scores from the discomfort questionnaires.

Factor	Items	Item names	Cronbach's α	Mean inter-item correlations
F1	10, 12, 14	Blurred vision, Difficulty Focusing on an object, Double vision	.701	.477
F2	1, 2, 8	Tired eyes, Uncomfortable vision, Irritated eyes	.631	.364

E. Participant instructions

3D motion

In this experiment we show you some short movie clips with different types of motion and ask you to pay close attention to the moving parts in the video clip. At random moments in time and at random positions on the screen, an object in the clip will be colored red. Your task is to press the spacebar on the keyboard when an object appears red. Try to react as fast as you can without making any mistakes. After each movie clip you are asked to fill in some questions.

Procedure

First, we would like to ask you to fill out several questions about yourself, your experiences with 3D, and activities where you may have experienced some kind of visual discomfort or motion sickness. After this, you will be asked to sit in front of the TV and put on the 3D glasses. We will then start with a short training session to familiarize you with the 3D TV, the stimuli and the task. For the main study you will get to see 20 stimuli of 30 seconds each. After each stimulus you are given a break of 1 minute in which you are asked to fill in a questionnaire. We will conclude the study with one final questionnaire on which you again need to indicate the symptom levels.

Please fill in questions 1 to 11 on the following pages. Try not to think too long before answering the questions, there are no wrong answers.

F. Questionnaires

Questionnaire

1. Please state your age.

_____ Years

2. Please state your gender.

	Male	Female
_____	<input type="radio"/>	<input type="radio"/>

3. Do you wear glasses or contact lenses for eye correction?

	Glasses	Contact lenses	No
_____	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

4. If you do, what is the correction power? (if you do not know by heart, please give an estimate)

	Left	Right
_____	_____	_____

5. Have you had eye surgery?

	Yes	No
_____	<input type="radio"/>	<input type="radio"/>

6. Do you regard yourself as susceptible to motion sickness (e.g. in cars, boats, funfair rides)?

	Not at all	Slightly	Moderately	Very much so
_____	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

The next questions will ask about your past experiences with 3D content.

7. On average, how often do you watch 3D content (e.g. in the cinema, on TV, on your (handheld)computer, or on your mobile phone)?

	Less than once a year	Less than six times a year	Every month	Every week	Every day
1. Cinema	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
2. TV	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
3. Computer	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
4. Mobile phone	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

In the next questions we ask you to evaluate several statements concerning 3D content. For the sake of clarity when we write 3D movies we mean any 3D content that you watch (e.g. in the cinema, on TV, on your (handheld) computer, or on your mobile phone).

8. Please evaluate the degree to which you agree with the statement below.

	Strongly agree	agree	neutral	disagree	Strongly disagree
1. 3D distracts from rather than adds to the viewing experience.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
2. 3D makes me feel more immersed (in a movie).	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
3. 3D (movies) tires or hurts my eyes.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
4. 3D makes a (movie) feel more natural.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
5. 3D (movies) give a better overall viewing experience than 2D (movies).	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
6. 3D (movies) make me feel nauseous or give me headaches.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
7. I choose a 3D (movie) over a 2D (movie).	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

The next two question blocks are designed to find out how susceptible to motion sickness you are, and what sorts of motion are most effective in causing that sickness. Sickness here means feeling queasy or nauseated or actually vomiting.

Your CHILDHOOD Experience Only (before 12 years of age), for each of the following types of transport or entertainment please indicate:

9. As a CHILD (before age 12), how often you felt sick or nauseated?

		Not applicable – never traveled	Never felt sick	Rarely felt sick	Sometimes felt sick	Frequently felt sick
1.	Cars	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
2.	Buses or Coaches	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
3.	Trains	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
4.	Aircraft	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
5.	Small Boats	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
6.	Ships, e.g. Channel Ferries	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
7.	Swings in playgrounds	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
8.	Roundabouts in playgrounds	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
9.	Big Dippers, Funfair Rides	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Your Experience over the LAST 10 YEARS (approximately), for each of the following types of transport or entertainment please indicate:

10. Over the LAST 10 YEARS, how often you felt sick or nauseated?

		Not applicable – never traveled	Never felt sick	Rarely felt sick	Sometimes felt sick	Frequently felt sick
1.	Cars	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
2.	Buses or Coaches	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
3.	Trains	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
4.	Aircraft	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
5.	Small Boats	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
6.	Ships, e.g. Channel Ferries	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
7.	Swings in playgrounds	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
8.	Roundabouts in playgrounds	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
9.	Big Dippers, Funfair Rides	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

11. Please report how often you experience the symptoms below when watching TV at home.

	Never	(Not very often) Infrequently	Sometimes	Fairly often	Always
1. Do your eyes feel tired when watching TV?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
2. Do your eyes feel uncomfortable when watching TV?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
3. Do you have headaches when watching TV?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
4. Do you lose concentration when watching TV?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
5. Do you experience vertigo when watching TV?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
6. Do you experience ache in or behind the eyes when watching TV?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
7. Do you feel sleepy when watching TV?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
8. Do your eyes feel irritated when watching TV?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
9. Do you feel a “pulling” feeling around your eyes when watching TV?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
10. Do you experience blurred vision when watching TV?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
11. Do your eyes feel dry when watching TV?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
12. Do you have difficulty focusing on an object when watching TV?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
13. Do you experience burning eyes when watching TV?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
14. Do you experience double vision when watching TV?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
15. Does your neck hurt when watching TV?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
16. Do your eyes get watery when watching TV?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

These next questions are used to get a measure of how you feel at **this moment**.

12. Report the degree to which you experience each of the symptoms below, at this moment.

	None	Slight	Moderate	Severe
1. Tired eyes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
2. Uncomfortable vision	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
3. Headache	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
4. Difficulty concentrating	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
5. Vertigo	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
6. Ache in or behind the eyes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
7. Sleepiness	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
8. Irritated eyes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
9. "Pulling" feeling of the eyes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
10. Blurred vision	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
11. Dry eyes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
12. Difficulty focusing on an object	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
13. Burning eyes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
14. Double vision	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
15. Neck pain	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
16. Watery eyes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

**End of the pre-trial questionnaire.
Start the trial by following the instructions on the TV.**

The questions on this page were repeated after every stimulus.

Stimulus 20.

These next questions are used to get a measure of how you feel at **this moment**.

32. Report the degree to which you experience each of the symptoms below, at this moment.

	None	Slight	Moderate	Severe
1. Tired eyes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
2. Uncomfortable vision	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
3. Headache	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
4. Difficulty concentrating	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
5. Vertigo	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
6. Ache in or behind the eyes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
7. Sleepiness	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
8. Irritated eyes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
9. "Pulling" feeling of the eyes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
10. Blurred vision	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
11. Dry eyes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
12. Difficulty focusing on an object	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
13. Burning eyes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
14. Double vision	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
15. Neck pain	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
16. Watery eyes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

End of the trial.

Please fill in the post questionnaire on the next page.

You can answer the next questions in Dutch if you like.

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