

Human factors in the perception of stereoscopic images

by

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ABSTRACT

Research into stereoscopic displays is largely divided into how stereo 3D content looks, a field concerned with distortion, and how such content feels to the viewer, that is, comfort. However, seldom are these measures presented simultaneously. Both comfortable displays with unacceptable 3D and uncomfortable displays with great 3D are undesirable. These two scenarios can render conclusions based on research into these measures both moot and impractical. Furthermore, there is a consensus that more disparity correlates directly with greater viewer discomfort. These experiments, and the dissertation thereof, challenge this notion and argue for a more nuanced argument related to acquisition factors such as interaxial distance (IA) and post processing in the form of horizontal image translation (HIT). Indeed, this research seeks to measure tolerance limits for viewing comfort and perceptual distortions across different camera separations.

In the experiments, HIT and IA were altered together. Following Banks et al. (2009), our stimuli were simple stereoscopic hinges, and we measured the perceived angle as a function of camera separation. We compared the predictions based on a ray-tracing model with the perceived 3D shape obtained psychophysically. Participants were asked to judge the angles of 250 hinges at different camera separations (IA and HIT remained linked across a 20 to 100mm range, but the angles ranged between 50° and 130°). In turn, comfort data was obtained using a five-point Likert scale for each trial. Stimuli were presented in orthoscopic conditions with screen and observer field of view (FOV) matched at 45°.

The 3D hinge and experimental parameters were run across three distinct series of experiments. The first series involved replicating a typical laboratory scenario where screen position was unchanged (Experiment I), the other presenting scenarios representative of real-world applications for a

single viewer (Experiments II, III, and IV), and the last presenting real-world applications for multiple viewers (Experiment V). While the laboratory scenario revealed greatest viewer comfort occurred when a virtual hinge was placed on the screen plane, the single-viewer experiment revealed into-the-screen stereo stimuli was judged flatter while out-of-screen content was perceived more veridically. The multi-viewer scenario revealed a marked decline in comfort for off-axis viewing, but no commensurate effect on distortion; importantly, hinge angles were judged as being the same regardless of off-axis viewing for angles of up to 45°.

More specifically, the main results are as follows. 1) Increased viewing distance enhances viewer comfort for stereoscopic perception. 2) The amount of disparity present was not correlated with comfort. Comfort is not correlated with angular distortion. 3) Distortion is affected by hinge placement on-screen. There is only a significant effect on comfort when the Camera Separation is at 60mm. 4) A perceptual bias between into the depth orientation of the screen stimuli, in to the screen stimuli were judged as flatter than out of the screen stimuli. 5) Perceived distortion not being affected by oblique viewing. Oblique viewing does not affect perceived comfort.

In conclusion, the laboratory experiment highlights the limitations of extrapolating a controlled empirical stimulus into a less controlled “real world” environment. The typical usage scenarios consistently reveal no correlation between the amount of screen disparity (parallax) in the stimulus and the comfort rating. The final usage scenario reveals a perceptual constancy in off-axis viewer conditions for angles of up to 45°, which, as reported, is not reflected by a typical ray-tracing model. Stereoscopic presentation with non-orthoscopic HIT may give comfortable 3D. However, there is good reason to believe that this 3D is not being perceived veridically. Comfortable 3D is often incorrectly converged due to the differences

between distances specified by disparity and monocular cues. This conflict between monocular and stereo cues in the presentation of S3D content leads to loss of veridicality i.e. a perception of flatness. Therefore, correct HIT is recommended as the starting point for creating realistic and comfortable 3D, and this factor is shown by data to be far more important than limiting screen disparity (i.e. parallax).

Based on these findings, this study proposes a predictive model of stereoscopic space for 3D content generators who require flexibility in acquisition parameters. This is important as there is no data for viewing conditions where the acquisition parameters are changed.

Keywords: 3D, stereoscopic, comfort, distortion, orthoscopic, synopter, interaxial, vergence, IA, HIT

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CHAPTER 1 - INTRODUCTION

1.1 Thesis Outline

Chapter 1 introduces fundamental aspects related to stereoscopy, including principles of human binocular vision, and reviews literature pertinent to acquisition parameters, horizontal image translation (HIT), viewing comfort, and 3D stereography technology. It concludes with the presentation and justification of the current work, including a review of gaps in the research and a statement of the study hypothesis.

Chapter 2 provides a methodological overview of the procedural choices and logic underlying stimulus generation and the experimental setup.

Chapter 3 describes an experiment designed to investigate the effect of viewing distance on perception distortion and comfort of a 3D hinge, i.e., Experiment I. The chapter also includes a report of results following a pilot experiment examining the impact of texture selection on viewer perception.

Chapter 4 describes Experiments II and III, which investigated perceived distortion and comfort of 3D hinges presented in positive parallax.

Chapter 5 describes Experiment IV, which investigated perceived distortion and comfort of 3D hinges presented in negative parallax.

Chapter 6 describes an experiment involving multiple viewer positions (Experiment V) on distortion and viewer comfort.

Chapter 7 delivers an evaluation of the interpretation of the experiments' findings from a psychophysical perspective. This evaluation ties together the main outcomes of the empirical studies described previously and evaluates the performance of the modelling techniques employed. In addition, the chapter provides a discussion of the respective limitations of each experiment and the implications of this study's findings for future research.

Chapter 8 concludes the thesis with a discussion of the study's contributions derived from its findings.

1.2 Historical Aspects of Stereoscopy

Although virtual reality appears to be a fairly recent development, the principles that make it possible are not new and, in fact, were the subject of ancient investigation. A key principle that makes virtual reality possible is human vision's ability to perceive depth. Artificial applications such as VR headsets and 3D filming mimic the mechanics of this form of 3D vision from two eyes, referred to as stereopsis. Although studies into these mechanics are long and storied, several stand out from among the numerous contributions made by scientists over the past centuries.

Between 1492 and 1513, Leonardo da Vinci observed that the eyes see subtly different images (Brooks, 2017; Da Vinci, 1835). An analysis of a recently rediscovered copy of the *Mona Lisa* produced by an apprentice found that Leonardo had an understanding of these subtle differences and was capable of reproducing them to mimic human vision (Carbon & Hesslinger, 2013). These painting techniques were based on even earlier observations, some dating as far back as the fourth century BCE (Brewster & Bache, 1854; Høg, 2008; Zajonc, 1995).

Progressing from da Vinci's observations on binocular vision (i.e., seeing with two eyes), several other scientists made notable additions that further developed the understanding of human vision. For instance, Sir Isaac Newton's analysis of human colour vision (Newton, 1704) inspired further research into our capability to, despite having only two eyes that may rival each other, fuse subtly different images to produce a single vision (Porta, 1593 as cited by Howard, 2012, and Wade, 1996; Wade & Ono, 2012).

However, these and other notable scholars were unable to make empirically conclusive arguments on human binocular vision's ability to perceive depth when observing the external environment. Their failure to make these cornerstone arguments was primarily due to the unavailability of empirical findings as opposed to observational findings, a fact that several scholars readily conceded (Crone, 1992; Le Clerc, 1679; Smith, 1996). In other words, there were no reliable instruments available to authoritatively link the presence of two eyes with 3D or depth perception (Smith, 1996), thereby making it impossible to re-create 3D vision in real-world applications.

It would take the public demonstration of the stereoscope device by Sir Charles Wheatstone in 1838 (Blundell, 2011; Wheatstone, 1838; Zone, 2014) for the scientific community to begin investigating this link in earnest (Crone, 1992; Wade & Ono, 2012). Through this device,

depicted in Figure 1-1, Wheatstone proved empirically that (1) a human's two eyes perceive objects in subtly different ways, (2) humans experience single vision despite these subtle differences, and (3) there is a relationship between viewing distance and 3D or depth perception (Wheatstone, 1838; Wade & Ono, 2012). In addition, Wheatstone demonstrated that presenting a pair of subtly dissimilar images through this device mimicked actual human vision. This device and the image pairs, called stereograms or stereocards, led to the creation of a booming VR-like industry in the late nineteenth century.

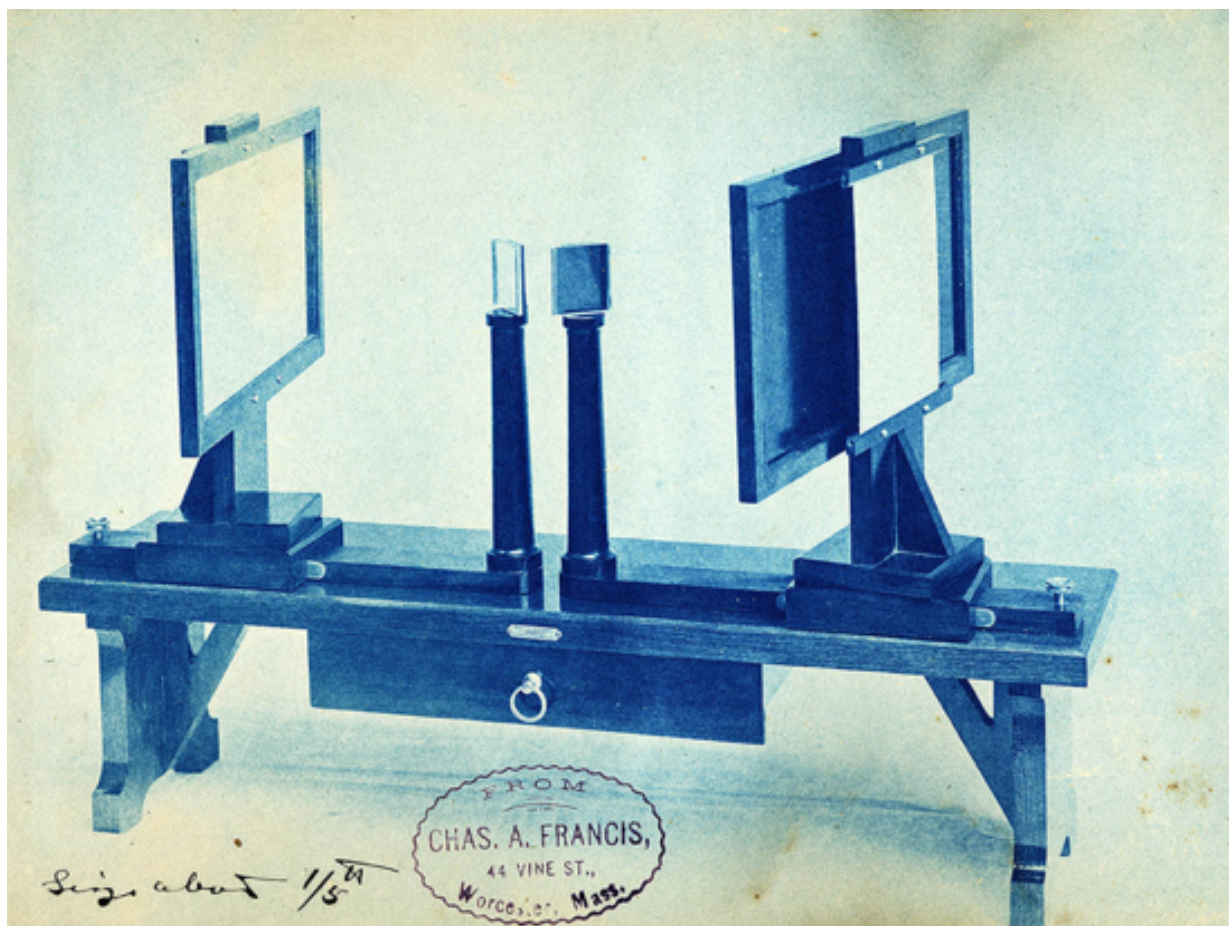


Figure 1-1. The Sanford model of Wheatstone's mirror stereoscope made by the departmental mechanic Chas A. Francis at Clark University's psychological laboratory, USA (ca. 1895) (adapted from Evans, 2003).

Before the emergence of this VR-like industry, however, the cumbersome stereoscope design depicted above required improvement. In 1840, David Brewster introduced a handheld device that used prisms instead of large mirrors (Brewster, 1845; 1856; Spiro, 2006a; West, 1996). To use this device, stereograms were inserted at the floor of a viewing box, and viewing these produced a form of surreal immersive experience. In the figure below, the observation pieces "R" and "L" were separated by a distance similar to that between the human eyes, and observed stereo cards were inserted at the floor of the device.

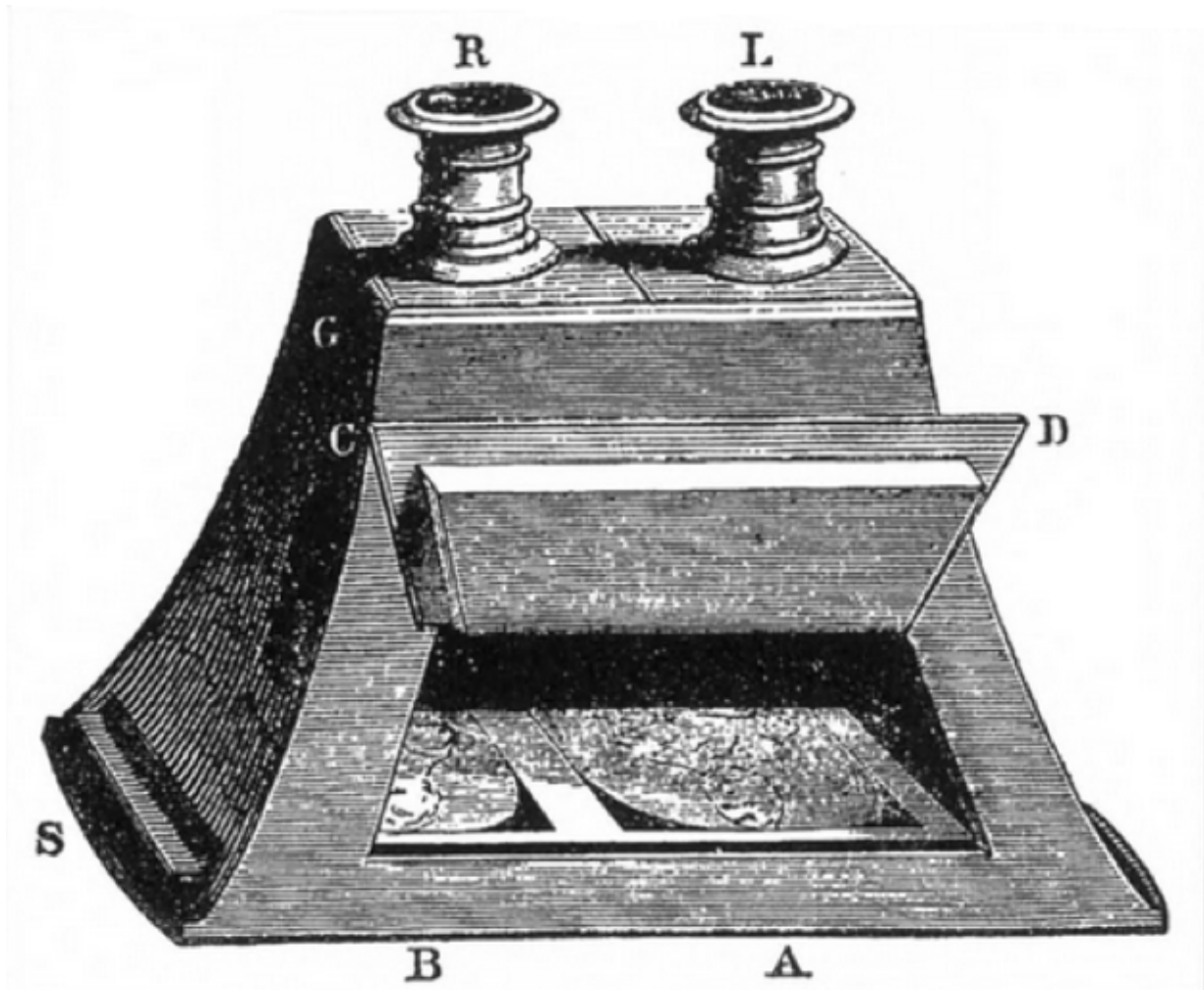


Figure 1-2. Brewster's refracting or lenticular stereoscope (1851) (adapted from West, 1996; Brewster, 1856 as cited by Zone, 2014).

Twenty years later, Oliver Wendell Holmes introduced an even more improved stereoscopic viewer with several advantages over its predecessors. Firstly, Holmes' viewer made extensive use of wood to make it affordable and further miniaturised the two prismatic lenses to increase the ergonomic factor. Lastly, the viewer had three slots at the far end of its wooden stand such that the viewer could change focal power during use (West, 1996).



Figure 1-3. The Holmes' handheld stereoscope (1869) (left panel) and the Holmes-styled stereoscope (right panel) (adapted from Holmes, 1869, as cited by Silverman, 1993).

Unsurprisingly, these improvements made the device an immense commercial success. In the three months following its introduction, which followed the debut of the photographic process by about one year, about 250,000 stereoscopes were sold in England, France, and the United States (West, 1996). From 1854 to 1856, ten years after the introduction of Brewster's viewer, the London Stereoscopic Company mass-produced and sold over 500,000 stereographs in England alone (Spiro, 2006a; 2006b). Between 1854 to 1920, about 300 million stereo cards or stereographs were sold, with one major American stereographic company, Underwood & Underwood, publishing 25,000 cards a day between the 1880s and the 1920s (Staples, 2002) and 300,000 stereoscopes per annum by 1901 (Spiro, 2006a). Underwood & Underwood found particular success in a "boxed set" of 100 cards that depicted scenes from virtual tours of such foreign countries as Egypt, Japan, and India (Breasted, 1905; Brown, n.d.; DeLeskie, 2000; Spiro, 2006a)

In addition, Wheatstone's stereoscope inspired several subsequent applications, including the Kaiserpanorama (c. 1890), Tru-View (1931), the View-Master system (1939), and the Stereo Realist (1947) (Huhtamo, 1997; King, 2013; Luhmann, 2004; Silverman, 1993; Spiro, 2006a; 2006b).

This unparalleled commercial success and its derivative inventions forced the device onto the scientific community and even more so after the invention of the wet-plate photography technique (West, 1996). As a testament to the resilience of its introduction, Wheatstone's demonstration that 3D perception can be elicited by presenting pictorial images continues to find application today as in CRT or LCD displays (Holliman, 2006). Also, Brewster's lenticular stereoscope exists today, in principle, as head-mounted displays (Holliman, 2006).

In the years that followed, the empirical technique pioneered by Wheatstone also found multiple applications in the psychological laboratory, where important research was undertaken to investigate the issues of visual perception and cognition (Wade & Heller, 1997; Wade & Ono, 2012). Notable among these applications was the development of random dot stereograms and autostereograms, images with repetitive patterns that are designed to create the illusion of 3D immersion from a 2D image (Bergua & Skrandies, 2000; DeFelipe & Jones, 1992; Howard & Rogers, 1995; Julesz, 1960; Wade & Ono, 2012) as depicted in Figure 1-4 and Figure 1-5.



Figure 1-4. A classic three-panel random-dot stereogram as presented by Julesz (adapted from Tyler, 2005).

When viewed monocularly (with one eye), the random-dot stereogram above conveys no distinct visual data about its disparity structure, essentially being observed as randomly scattered dots. However, when observed binocularly (with both eyes), the viewer perceives stereoscopic (3D) information, with certain patterns appearing along different depth planes on the previously perceptually uniform background, such that squares protrude and recede in a three-dimensional space (Bhola, 2006; Tyler, 2005).

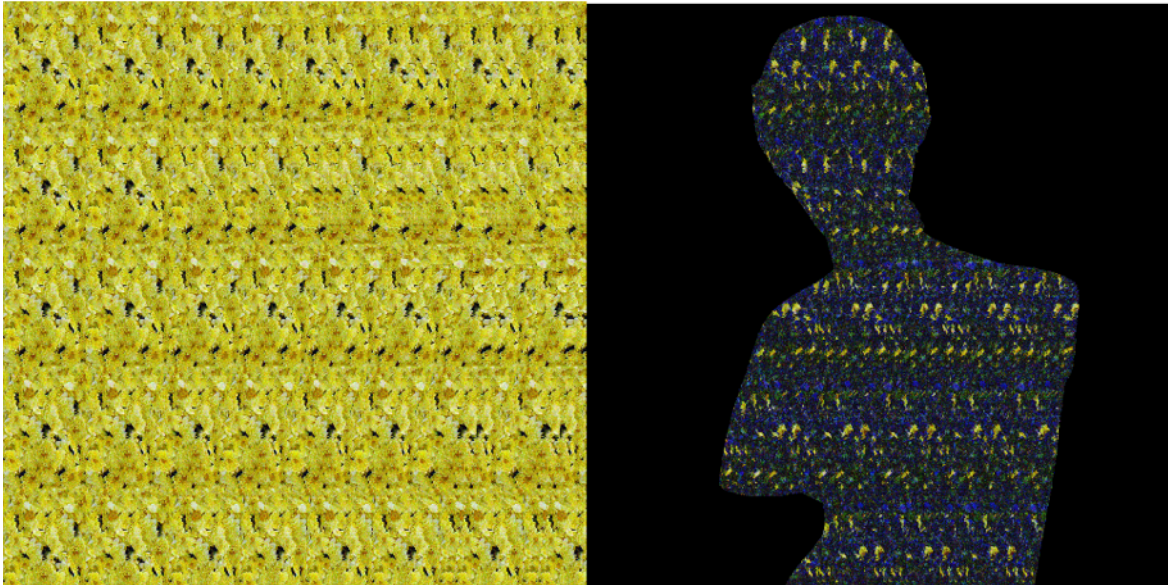


Figure 1-5. Autostereogram or Magic Eye (left panel) and its hidden pattern (right panel) (adapted from Contreras, 2016).

However, appreciating this 3D perception would occur only if the observer used artificial aids such as the stereoscope. The autostereogram represented above is essentially a single-image 2D stereogram that elicits stereopsis (i.e., "seeing in 3D") without the use of optical equipment, that is, with the naked eye (the "auto" part). Although initially a trademark, the term "magic eye" has come to generically refer to such colour random-dot autostereograms (Ione, 2005). Tsuda, Yue, and Nishita (2008) - Figure 1-5. These computer-generated images, not unlike stereograms, contain hidden patterns that emerge only with use of the proper viewing technique.

The use of these repetitive patterns enabled vision science researchers to arrive at a more precise understanding of the human visual system's production of 3D vision and, in turn, facilitated the arrival of more familiar applications such as 3D films and the red-green anaglyph glasses used in viewing stereo content today (Wade & Heller, 1997).

On a related note, while Frederick Varley had demonstrated a two-lens stereoscopic (3D) camera in 1890 (Coe, 1969) and Henri René Bünzli had publicly projected a pseudo-3D film a decade later (Bordwell, 2010; Bünzli, 1900; Jacobson, 2015; Sauer, 2010), another twenty-two years would be required for 3D filming and projection to be proven commercially viable. As with the stereograms in the nineteenth century, the cinematic novelty of 3D films was met with a feverish audience appetite. The year 1952 saw the very first full-length colour stereoscopic film and, between then and 1955, the "Golden Era" of stereoscopic 3D (S3D) cinematography, dozens of S3D films and commercials were released. Fifty films in this format were released between 1953

and 1954 (Balio, 2009; Tricart, 2016) and, in 1952 alone, United Artists bought up to ten million Polaroid glasses to forestall any future spectacle shortages (Balio, 2009; Lev, 2003).

However, this feverish uptake was short-lived. Viewers complained of eye strain due to poorly synchronised projection of the left and right eye views of the film reels (Fernando, Worrall & Ekmekciođlu, 2013; Zone, 2005). Other complaints included colour and cue mismatches and out-of-focus scenes (Balio, 2009; Daily News, 1953; Fernando, Worrall & Ekmekciođlu, 2013). S3D cinematography would not recover sufficiently from these complaints until the turn of the twenty-first century.



Figure 1-6. Movie audience wearing Polaroid 3D glasses during Nov 1952 premier of *Bwana Devil* in Hollywood, Los Angeles (adapted from *Life*, 1952).

1.3 Uptake and Popularity

Since this earlier period, numerous advances have been made in the field of stereoscopic displays, including miniaturization of displays. Decades of advances in vision science have also alleviated the challenges of collecting, analysing, and projecting 3D data. These advances have led to delivery of more immersive experiences and, hence, a rising demand for stereoscopic content (Gleicher, 2008; Ogawa, 2013), particularly since 2003.

Indeed, as of 2015, almost forty television channels were dedicated to 3D content (Malik, 2015). By 2004, 54% of IMAX theatres worldwide could exhibit 3D films and documentaries, an increase from 50% the previous year. The share of IMAX 3D theatres would increase to 70% in 2008, 76% in 2009, and 82% by 2010 following the debut of *Avatar* (IMAX Corporation, 2004/2005/2009/2010/2011). Interestingly, by 2010, there was a backlog of over 220 3D theatres awaiting construction or completion, with industry stakeholders buoyed by the surprise commercial success of the year's superlative blockbuster, *Avatar* (IMAX Corporation, 2011).

Arguably, *Avatar* solidified the enthusiasm around 3D uptake (Grasnick, 2013; Kroeker, 2010; Yun, 2010), building from the box-office successes of such previous 3D films as *The Polar Express* (released in 2003), *Chicken Little* (November 2005), and *Beowulf* (November 2007) (Desowitz, 2005; Mendiburu, 2012; Zone, 2012). Prior to *Avatar's* screening in late 2010, there was no comparable, mass-market 3D success story (Robey, 2009). From its December 2009 debut through to March 2010, 34% of IMAX Corporation's entire 2010 box office revenue would be from this single movie (IMAX Corporation, 2011). Indeed, about 82% of *Avatar's* box-office revenue came exclusively from 3D screenings (Brevet, 2010; Cunningham, 2016). Furthermore, 7% and 28.3% of Cineplex's total 2010 theatrical revenue was from screening *Avatar* and an assortment of other 3D films, respectively (Cineplex Entertainment, 2011).

Avatar, the defining movie and commercial tipping point of the era of great reboot of stereoscopic cinema, represented a significant, albeit iterative, leap in developing and utilizing innovations that had somewhat mitigated the viewer issues that had dogged and stymied S3D content (Spöhrer, 2016). This stereo renaissance has led to a dramatic increase in 3D-equipped theatres, launch of 3D-only cable channels, development of 3D TVs and mobile phone interfaces, success of 3D video games and their consoles, and a general increase in interest in its techniques from cinematographers and researchers alike. An equally important effect of this renaissance has been the resurgent mainstream popularity of stereo head-mounted displays (HMDs) that provide cinematic and holographic virtual reality (VR) experiences (Spöhrer, 2016). The net effect of this reboot could be quantified in 2011 when almost 50 3D films were exhibited in North American theatres. See MPAA (2013) and Schechter, Moran and Di Ianni (2015) for a full analysis of box office trends and projections.

However, as during the Golden Era in the mid-twentieth century, the medium has experienced a decline as studios and producers have often oversold the stereoscopic format and over-priced 3D tickets (Tricart, 2016), with viewers reporting unrelenting eye fatigue and discomfort. Without

a doubt, the mainstream post-2003 resurgence of 3D content now faces strong headwinds. For instance, between 2010 and 2011, revenue from 3D box office films declined by almost 20% despite doubling in the 2009-2010 period (Schechter, 2015; Solimini, 2013). Also, 3D TV purchases as a share of all TV purchases in the United States decreased from 23% in 2013 to 8% in 2016 (Katzmaier, 2017). Unsurprisingly, conventional wisdom has been that the success of S3D imagery largely depends on users finding viewing S3D images as comfortable, if not more so, than traditional 2D images.

Despite these setbacks, stereographic techniques are finding increasing applications across different sectors. A key platform for deploying S3D technology is the virtual reality (VR) head-mounted display (HMD).

Figure 1-7 shows assumptions for three scenarios of HMD shipments—accelerated uptake, base case, and delayed uptake—across different industry applications. In total, the VR market may reach an annual turnover of US\$182bn by 2025, a market size similar to that of the tablet hardware and TV industry combined (Bellini et al., 2016).

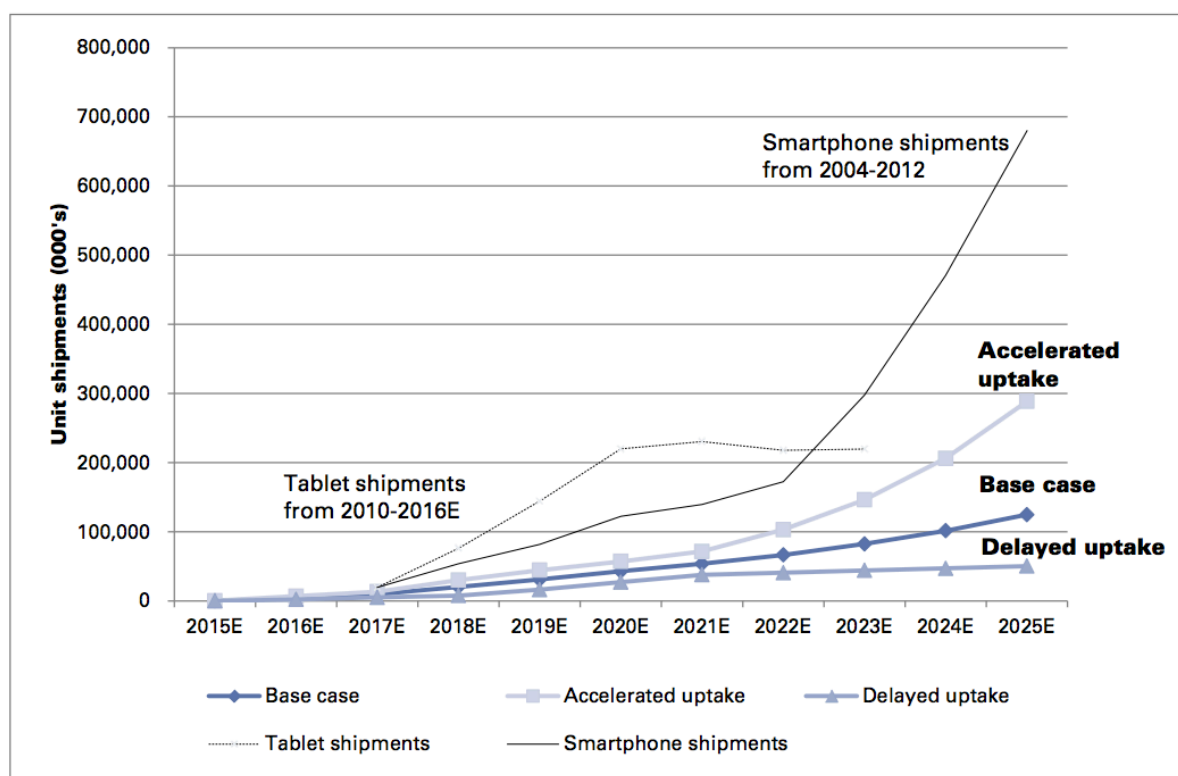


Figure 1-7. Shipment assumptions for VR devices up to 2025 compared to ramps for smartphone and tablet shipment data. The assumptions show that VR uptake may rival and possibly outpace the historical trend of tablet adoption (adapted from Bellini et al., 2016).

1.4 Issues of Viewer Discomfort

So-called stereo cameras are used to acquire a 3D image. These cameras simulate human binocular vision by using two separate cameras to capture images of the same object from slightly different perspectives. Just as with human eyes, each of these cameras captures a slightly different image from a fixed viewpoint. Once acquired, the images are then presented on a display such that the left camera's image is shown to the left eye and the right camera's image is shown to the right eye. The extent or degree of separation between the left and right images is referred to as parallax.

While this acquisition of 3D content attempts to perfectly mimic the mechanics of human vision, stereo cameras do not always capture 3D images that are realistic. Perfect mimicry is attempted when setting the horizontal distance between these two cameras in what is referred to as camera separation or, in applied contexts, interaxial distance (IA). Stereographers set this separation as closest to the anatomical distance between human eyes, that is, the interpupillary distance (IPD), and the typical IPD is taken as 60 mm (Spottiswoode & Spottiswoode, 1953). Images acquired in this manner are considered orthostereoscopic, meaning that the acquired image is a true-to-scale 3D reproduction of the filmed object.

However, stereographers also use this distance creatively, exceeding or falling short of the interpupillary distance. Images acquired in this way make real-life objects appear gigantic (*gigantism*) or small (*dwarfism*). These effects have an impact on human factors, making S3D content less comfortable, especially with regard to dwarfism.

That said, once acquired, 3D images are then presented to viewers through several display technologies that either rely on special headgear or glasses (*stereoscopic*) or do not require the viewer to wear any of this gear (*autostereoscopic*). Regardless of the display technology utilised, the display surface is flat, and this flatness does not correspond to how humans perceive the natural environment, that is, as inherently three-dimensional. In the natural environment, the eye can accommodate smoothly across different *actual* distances to achieve focus. The flatness of the 3D display device, however, introduces inconsistencies in the image such that, while the subtly different images are acquired by two side-by-side cameras that function similarly to human vision, the static distance to the viewer's eyes causes them to fail to achieve accommodation. This conflict is a critically important factor in eliciting viewer discomfort.

Due to these inconsistencies, stereoscopic 3D (S3D) content is often associated with several viewer complaints with the viewing experience for 3D content contributing to nausea, eye strain, and general discomfort (Bellini et al., 2009; Banks, Kim & Shibata, 2003; Nakamura, Tanaka, & Takaki, 2013; Shibata, Kim, Hoffman, & Banks, 2011a; Yang & Sheedy, 2011). These measures are important issues in viewer comfort and can be divided into objective and subjective aspects.

Objective aspects of viewer comfort, which constitute what is referred to as visual discomfort, are associated with image issues, and it is attributable to 3D content that has poor resolution, jitteriness, flickering, and unnatural image motion (Kim, Park & Oh, 2011). Other causes of this type of discomfort include inappropriate head orientation and the imperfect separation of the two eyes' images so one eye's image is viewable by the other (Banks, Read, Allison, & Watt, 2012).

On the other hand, subjective aspects precipitate visual fatigue symptoms. Blehm, Vishnu, Khattak, Mitra, and Yee, (2005) and Gowrisankaran and Sheedy (2015) provide a category of computer vision syndrome (CVS) symptoms that correlate with symptoms experienced during prolonged watching of S3D content. These adverse effects, akin to visually induced motion sickness, include headaches, eye tiredness, nausea, dizziness, convulsion, confusion, and double or blurred vision (Naqvi, Badruddin, Malik, Hazabbah, & Abdullah, 2013; Shibata et al., 2011a).

Table 1-1. The rank of self-reported 3D viewing symptoms from most severe (1) to least severe (8) based on three scenarios (adapted from Scrogan, Press, & Yang, 2013).

Severity of 3D viewing symptoms	When watching a live S3D movie	When viewing/playing a 3D game	When watching animated S3D images
1	Double vision	Nausea	Disorientation
2	Nausea	Dizziness	Difficulty concentrating
3	Dizziness	Headache	Dizziness
4	Blurred vision	Difficulty thinking	Difficulty thinking
5	Pain inside eyes	Double vision	Headache
6	Pulled eyes	Neck aches	Neck aches
7	Eye sore	Blurred vision	Difficulty visually focusing
8	Neck aches	Pain inside eyes	Pulled eyes

Table 1-1 shows a colour-coded categorization of the severity of viewer symptoms summarised across three different scenarios: watching a live-action S3D film, playing a S3D game, and watching animated S3D images. As the table shows, self-reported symptoms related to motion sickness has a higher frequency than those related to degraded visual perception.

These symptoms can be quantified through standardised measurement methods such as the Simulator Sickness Questionnaire (Kennedy, Lane, Berbaum, & Lilienthal, 1993), Visual Discomfort Scale (Conlon, Lovegrove, Chekaluk, & Pattison, 1999), various fatigue monitoring technologies (FMT) (Kim et al., 2011; Kim & Lee, 2011; Zhang et al., 2013; Sommer & Golz, 2010; Wang, Yang, Hu & Wang, 2016), and other 3D-specific Quality of Experience (QoE) metrics (Campisi, Le Callet & Marini, 2007; ITU-R, 2015; Meesters, IJsselsteijn & Seuntiëns, 2004; Moorthy & Bovik, 2013;). The ability to determine and predict any of these aspects of viewer comfort is important in the design of ophthalmologic and stereo display systems (Shibata et al., 2011a).

Importantly, the forced decoupling of accommodation and vergence eye movements are believed to cause the negative issues associated with viewer discomfort (Hoffman, Girshick, Akeley & Banks, 2008; Howarth, 2011; Kim, Shibata, Hoffman & Banks, 2011; Lambooi, Fortuin, Heynderickx & IJsselsteijn, 2009; Love et al., 2009; Shibata et al., 2011a; Ukai & Howarth, 2008; Vienne, Blondé, Doyen & Mamassian, 2011; Wann & Mon-Williams, 2002). A detailed examination of this forced decoupling is provided in Section 1.6.3 CHAPTER 1: Vergence-Accommodation Conflict.

1.5 Issues in 3D Stereography

1.5.1 The Geometry of Stereography

The basic principle underlying the stereoscopic technique is to capture subtly different points of view of the same image and leave it to the viewer to naturally determine the image's depth. Each of the two stereo cameras shoots different footage that mirrors the perspective of each eye. This footage from each of the two cameras forms a stereo pair that the viewer's brain can then fuse into a single image.

This configuration of two cameras capturing footage of the same object is an attempt to replicate the function of human vision using two eyes. This is not the full extent of the replication, however. In a process called 'converging the cameras', the two stereo cameras must also capture

footage from the same point of view while at different lines of sight, thereby mimicking the eyes' rotation, which depends on head movements about a shared pivot point.

Best practice dictates that these matched stereo cameras also be spaced at approximately the typical inter-pupillary distance. By adjusting IA, dynamically adjusting the amount of depth or 3D information in a scene is possible; increasing IA, for instance, increases the amount of depth or 3D captured (Reeve & Flock, 2010). This relationship between IA and amount of depth is crucial in recreating an immersive experience. Film post-production processing cannot match the amount of depth that a high amount of IA makes possible. The amount of an image's depth in front of the display screen (i.e., negative parallax) as a percentage of that behind the display (i.e., positive parallax) is referred to as the depth or disparity budget (see Figure 1-8). The total desired amount of parallax (usually in percentage of screen width) is specified by a film's director and stereographer. High IAs elicit high depth budgets that, in turn, are both unfixable during post-production and unfusable by viewers, leading to discomfort. The depth budget, a technical choice, is distinct from the parallax range, the result of this choice. Parallax range is the amount of disparity contained in a scene, were it measured with a disparity-mapping tool.

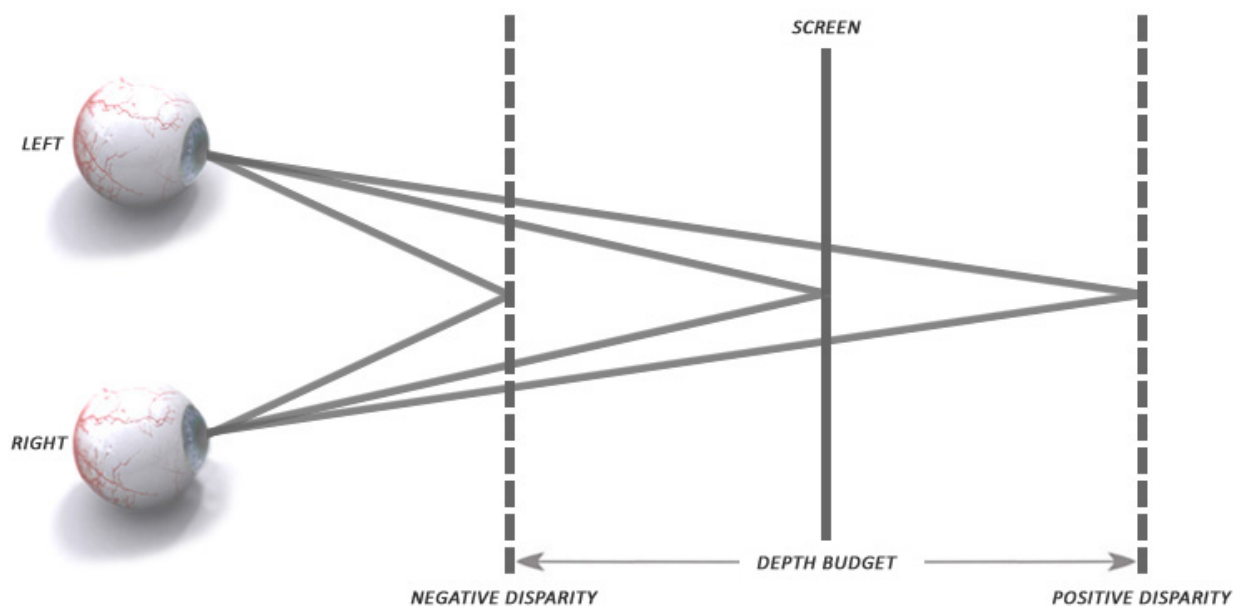


Figure 1-8. Representation of the depth budget: the amount of 3D depth between the nearest and furthest items presented on a 3D display. The nearest object is at negative disparity while the furthest is at positive disparity.

The acquired images are then simultaneously projected to the respective eyes, and the degree of their separation is known, in applied terms, as horizontal parallax. Zero parallax occurs when

the eyes converge at exactly the same point as during natural viewing. In applied scenarios, zero parallax means that S3D images are projected on the display screen.

Positive parallax, on the other hand, occurs when an acquired S3D image is projected behind the screen, leading to a perception that the image is *into the screen*. This is achieved by shifting the left eye's view further left relative to that of the right perspective. In this manner, the eyes' convergence point is calibrated to fall behind the display. In contrast, negative parallax causes the S3D image to be perceived as being outside the monitor or *in front of the screen* and is achieved by shifting the corresponding views towards each other, i.e., the left eye's view is shifted towards the right. In this way, the convergence point is designed to fall in front of the display. See Figure 1-8.

In Figure 1-9, note that the left and right eyes converge at different points in "space" according to the depth presented, but always accommodate on the display's surface.

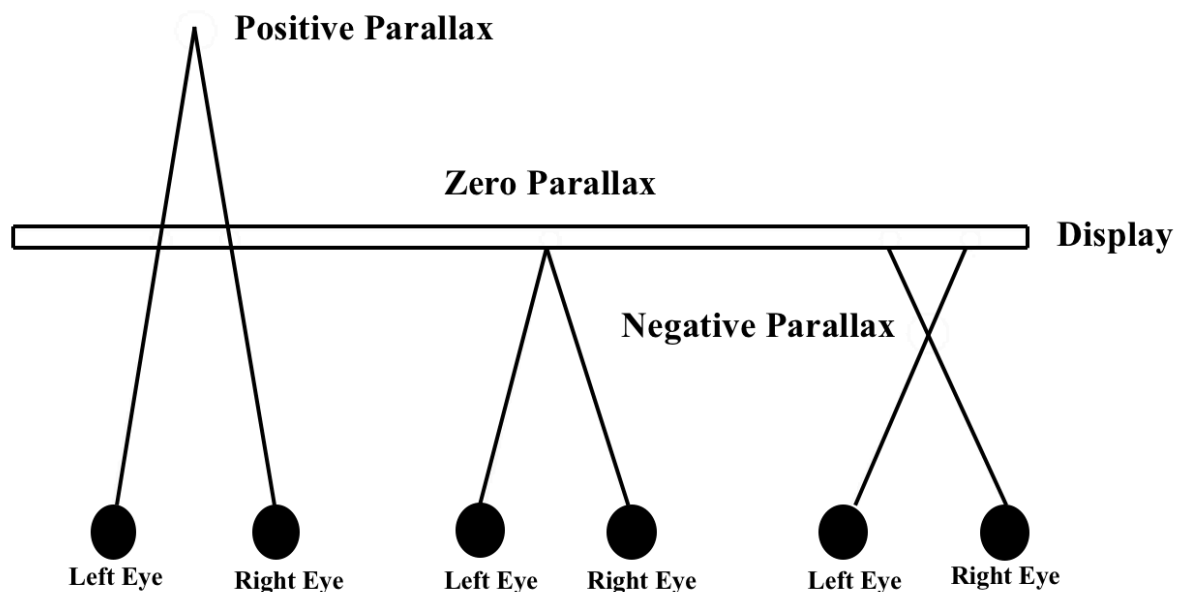


Figure 1-9. The three different forms of screen parallax or disparity as perceived by the viewer: positive, zero, and negative parallax.

The principles explored in the preceding paragraphs can be codified into three steps: 1) stereoscopic image acquisition, 2) stereoscopic 3D presentation, and 3) viewer visual interpretation and fusion (Held & Banks, 2008). These steps serve as the basis behind

categorizing the various misperceptions arising out of stereoscopic content. Geometric misperceptions occur as a result of an incongruous selection of acquisition and presentation parameters, while perceptual misperceptions are inherent to the viewer's visual system. This section further explores the former approach, including attendant parameters, and the latter approach (i.e., the perceptual model) is in itself underlined by human factors and elicits misperceptions such as the vergence-accommodation conflict (see Section 1.6.3: Vergence-Accommodation Conflict) (Held & Banks, 2008). The geometric model, as already noted, depends on image acquisition and presentation or viewing, and the mathematics characterizing these two steps is covered exhaustively elsewhere (Woods, Docherty, & Koch, 1993; Held & Banks, 2008). However, a foundational introduction to these two initial steps is provided below.

1.5.2 Issues in Image Acquisition

Several techniques are used to ensure that the two stereo cameras converge on an object, including positioning the stereo cameras so that they are parallel to each other, toeing in, and using off-axis offset.

1.5.2.1 The parallel camera configuration

The parallel setup has the optical axes of the stereo cameras overlapping at infinity with the cameras looking straight ahead into space. In this scenario, images at infinity are projected onto the screen display, and all other images, regardless of their distance from the two cameras during acquisition, are presented in front of the display. As defined above, this condition delivers negative parallax where S3D images fall in front of the screen. However, this setup also means that no images can be displayed behind the screen, thereby eliminating positive parallax. This distortion of parallax is undesirable and constitutes a significant stereographic violation.

Since parallel stereo camera rigs cannot compensate for parallax, the stereographer must crop and correct camera convergence to ensure that the correct images are presented at the right parallax. According to Speranza, Stelmach, Tam, and Glabb (2002), the parallel condition is least comfortable, with viewers self-reporting greatest comfort when the stereo cameras are slightly converged.

Post-processing involves ensuring that the closest images are presented at the display surface so as to introduce positive parallax. This correction often leads to loss of image quality, including

loss of wide aspect ratio, image compression, and size distortion effects. Images closest to the parallel cameras suffer most during post-processing due to marked losses in frames and aspect ratios. (For a fuller discussion, refer to the sub-section below.)

1.5.2.2 The toed-in camera configuration

A solution would be to shift the parallel camera lenses sideways at an inward angle, away from the non-intersecting optical axes as depicted in Figure 1-10 below.

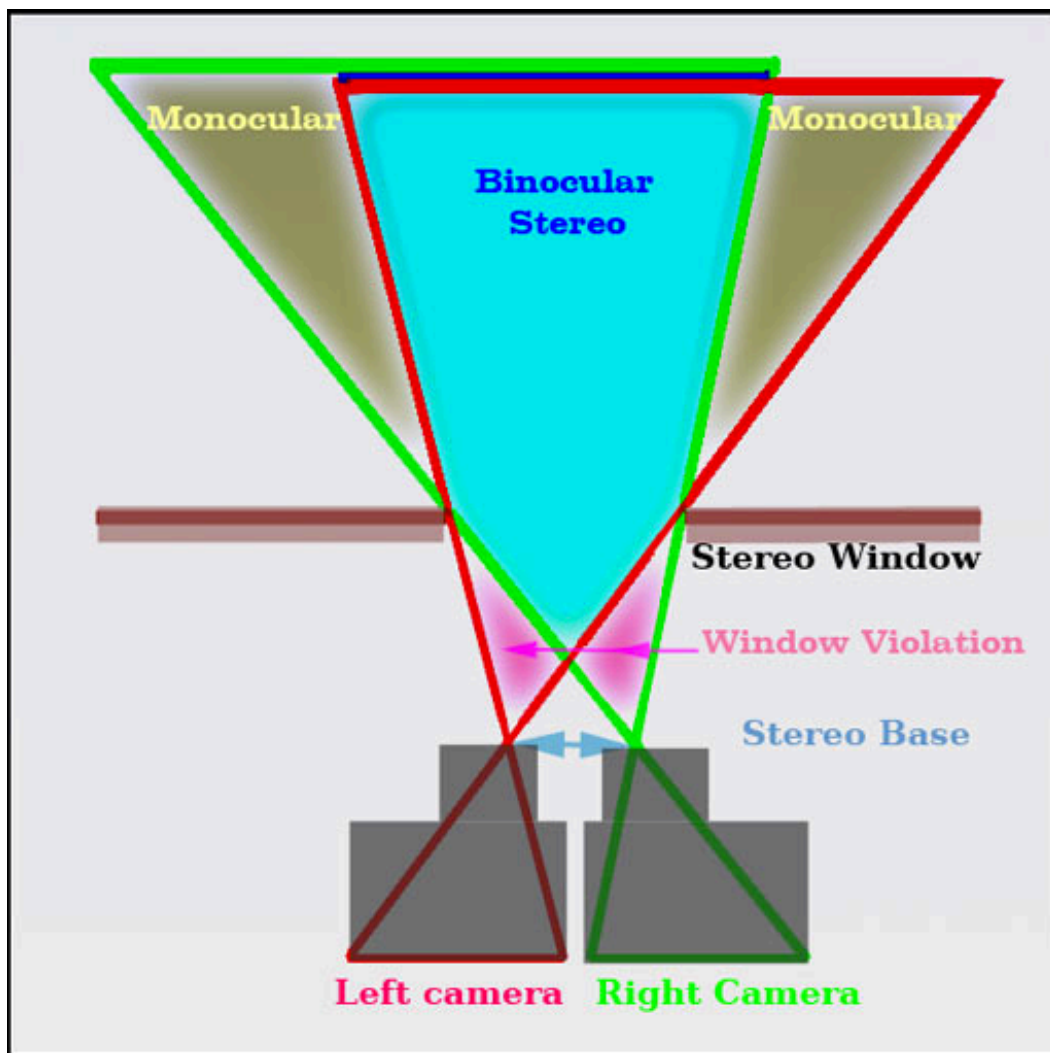


Figure 1-10. A parallel stereo camera rig with the camera sensors off-set sideways from the respective optical axes. The area of binocular stereo is behind the point where the optical axes of the two stereo cameras converge (adapted from Wattie, 2012).

In the figure, the area designated “binocular stereo” represents the stereo picture, whereas the “window violation” areas encompass images seen by only one camera. These latter areas are resolved by lowering the depth budget. The off-set depicted can be accomplished in one of two ways.

First, using the shift function of a tilt-shift lens, stereographers can physically shift the lens horizontally relative to the image without sacrificing field of view, i.e., parallel camera frustum shift. The second technique involves software-mediated offset. Whereas the physical offset can result in skewed fields of view, i.e., skewed frustum, software-mediated offsets often sacrifice the field of view and demand focal length changes due to implications of post-production cropping. The perils of cropping underlie the industry recommendation for over framing, that is, avoiding filling the frame during zooming to allow for extra frame space for later cropping necessary to preserve the intended aspect ratio. However, horizontal sensor shift in the camera removes the need for over-framing (Wattie, 2012).

This horizontal shift, which leads to the retention of image pixels and of the aspect ratio, does not cause keystone distortion (described later). Due to these advantages, shifting the camera's image sensors outwards (as opposed to during post-processing) is the preferred method for converging parallel stereo rigs.

Unlike the parallel configuration, the toed-in setup involves tilting both cameras inwards. In this way, the optical axes of the two stereo cameras intersect mid-way through a stereo picture, resulting in an image whose shifted image frames are presented without converging.

When projected, the S3D images have both negative and positive parallax, with images appearing in front of, on, and behind the display screen, depending on their physical positions.

However, the toed-in configuration elicits keystone distortion (Held & Banks, 2008; Woods et al., 1993) as depicted in Figure 1-11. Indeed, objects viewed by only one of the two cameras are not part of the stereo picture, thereby avoiding stereo window violation. The keystone distortion problem entails vertical disparities that cause the heights of the left and right S3D images to not be identical. This vertical misalignment occurs when the left edge of the left image and the right edge of the opposite image are magnified, i.e., there is dissimilar magnification of the corners of each side of the respective S3D images. These vertical disparities, increasing from the centre to the periphery of the image and increasing as toeing-in increases, may have a negative impact on viewer comfort (O'Kane & Hibbard, 2007).

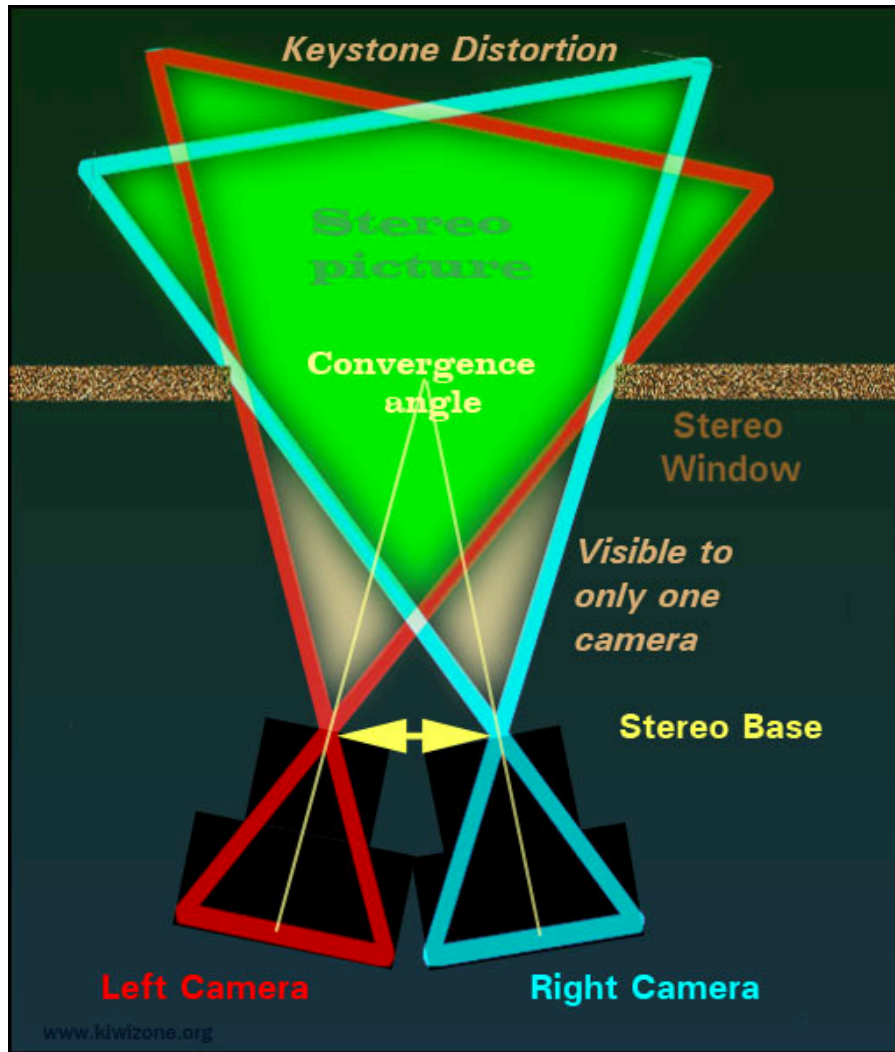


Figure 1-11. A toed-in rig with both cameras tilted towards the same stereo picture in the foreground which is represented here by the area designated as the stereo picture (adapted from Wattie, 2012).

This toed-in setup is considered expedient since correcting for camera convergence errors in the parallel configuration requires the use of custom optics and extensive post-processing to superimpose foreground images to the screen display. Toeing in, on the other hand, can be accomplished using digital cameras. (Applied issues concerning filing using the toed-in configuration are presented in Section 1.6.4: Vergence-Accommodation Conflict: Applied Principles.)

Nonetheless, in both cases, correction of the camera convergence is essential: toed-in requires correction to eliminate keystone distortion (i.e., keystone correction) in which the image is rotated about the Y-axis. Keystone correction is also required during use of the parallel setup, to introduce the full range of image parallax (i.e., HIT) across the left and right images.

1.5.2.3 Horizontal image translation (HIT)

Correction of camera convergence errors is achieved through the application of HIT, the horizontal translation of the two stereo images relative to their initial separation (IA).

HIT adjusts the point at which stereo images appear in relation to the display surface, that is, the convergence point. This convergence point is added wherever desired by the stereographer. Scene points can then be positioned in space as desired: in the foreground, on the screen plane, or into infinity. As illustrated in Figure 1-12 below, alteration of the depth position is achieved by adjusting the horizontal distance between the respective images in the stereo pair. In this regard, “convergence” refers to the process of realigning horizontally separated stereo images with respect to each other.

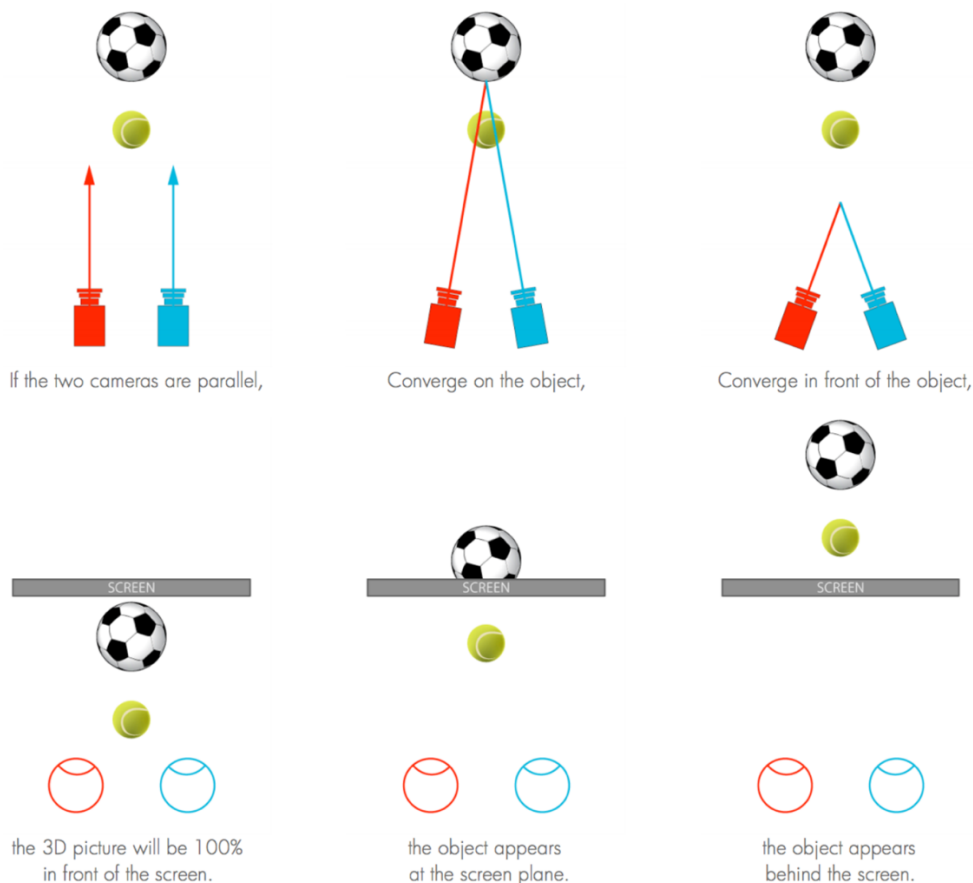


Figure 1-12. By toeing-in stereo cameras, end-users adjust an object’s position vis-a-vis the display. In this case, the cameras’ optical axes are physically converged as desired by the stereographer, in front of, behind or on the object. In post-production, adjusting the convergence point is achieved by algorithmically shifting the horizontal distance of respective images such that they appear where in space desired (adapted from Reeve & Flock, 2010).

Indeed, HIT denotes the distance between the horizon points of the left and right stereo images, i.e., the furthest points visible in the images. Depth for these horizon points is typically evoked

when one object in the depth plane occludes another object such that the latter object's depth profile on the display surface appears discontinuous owing to the perceived obstruction, a phenomenon referred to as texture accretion. The object with a visibly contiguous depth boundary, therefore, is perceived to be physically closer and larger. Therefore, due to texture accretion, the nearest horizon contains the most depth. To enhance or eliminate this accretion, HIT involves horizontally shifting the stereo views in opposite directions until the desired parallax is achieved. In this way, distant objects (background) that the stereographer does not want to bring to visual attention appear widely separated and on the screen plane (i.e., have zero parallax), and the nearest in-focus images (foreground) “pop out” of the screen *in front* of everything else (i.e., negative parallax), superimposed on the background. Stated otherwise, HIT involves adjusting the depth profile (i.e., distance) of the parallel left and right S3D images by moving them along the horizontal axis, thereby enabling the stereographer to superimpose the closest objects and allowing for natural depth continuity.

Without HIT, it would be impossible to achieve perfect depth position for points relative to the focal or accommodation point, which, naturally, has zero parallax (Broberg, 2011). In point of fact, a viewer's eyes should accommodate at the screen surface regardless of parallax presented. All in all, applying HIT is necessary to make the depth volume balanced, or “sweetened”, to achieve the desired stereo window, and to establish a zero-parallax setting.

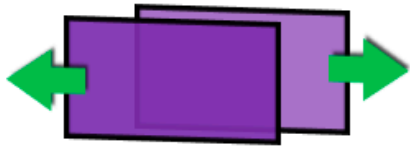
CGI ACQUISITION



-
1. **Generate duplicate images**
no HIT, no IA
[HIT 0mm & IA 0mm]



-
2. **Move the images apart**
HIT established, no IA
[HIT 60mm & IA 0mm]



-
3. **Choose IA in software**
HIT unchanged, IA established
[HIT 60mm & IA 60mm]



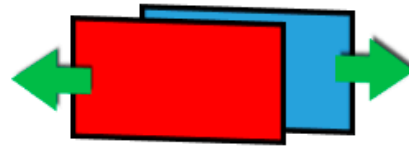
CAMERA ACQUISITION



-
1. **Capture left & right images**
HIT established, IA established
[HIT 30mm & IA 30mm]



-
2. **Move the cameras apart,**
HIT changes, IA changes
[HIT 60mm & IA 60mm]



-
3. **Converge physical cameras**
HIT changes, IA unchanged
[HIT 30mm & IA 60mm]



Figure 1-13 Dependencies of HIT and IA for computer-generated and camera capture

HIT is the mainstay of stereographic post-production and 3D storytelling. It is crucial in minimising geometric distortions; by assigning comfortable parallax values for presentation on

a parallel stereoscopic display, HIT can minimise vergence-accommodation conflicts, thereby alleviating visual discomfort and fatigue (Holliman, 2006; Valentic, 2011).

In computer generated 3D imagery (CGI), two images are generated algorithmically as if taken by a camera with the specified IA. HIT refers to the separation of the two generated images when displayed to the viewer. Thus, IA and HIT can both be independently manipulated (please see Figure 4-20, Figure 4-21 and Figure 4-22), unlike in the case of physical cameras, where only HIT can be manipulated in post-processing.

The correspondence between the two cases is that when a physical camera is used, it creates an implicit baseline for the HIT (as defined for CGI) equal to the IA (see Figure 1-13).

In this thesis, where a numerical value for HIT is used or implied, it references the value for CGI, namely the separation of the images displayed to the viewer.

1.5.2.4 Off-axis stereo rigs

Another technique for acquiring S3D images involves the use of off-axis stereo rigs. This configuration, utilising the best of both worlds, consists of two parallel stereo cameras but with converging fields of view as shown in Figure 1-14. The parallel component eliminates keystoneing. On the other hand, offsetting the image plane such that the two matched cameras converge at the foreground object (akin to toeing-in) provides the stereographer the ability to assign zero parallax. In this manner, the acquired image exists in the theatre space without inducing non-intuitive vertical disparities. This setup is the correct way to deliver inherently comfortable stereo pairs.

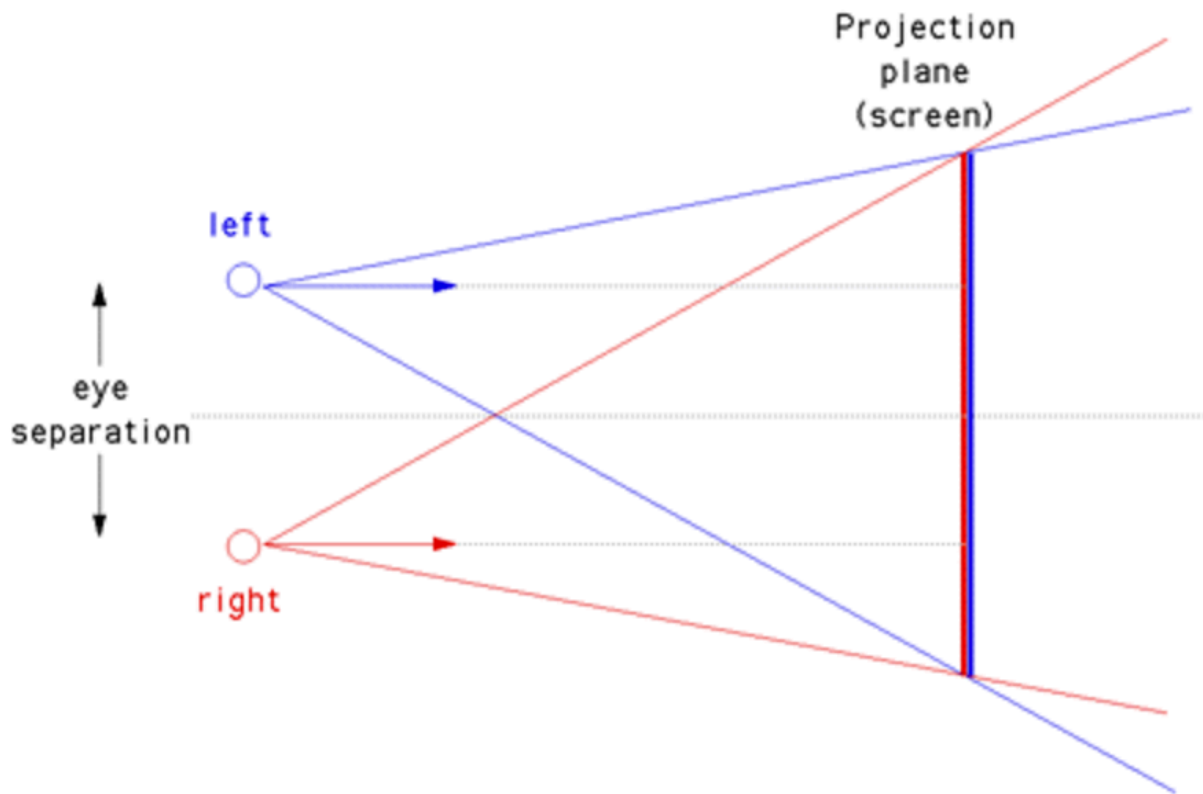


Figure 1-14. Off-axis stereo camera configuration showing the parallel cameras with frustum converging inward (adapted from Bourke, 1999).

1.5.3 Issues in Stereoscopic Projection and Viewing

Acquiring stereoscopic content is only part of the equation. Viewer comfort is also affected by how this content is then displayed. Here, too, technical conditions determine presentation of S3D content so as to least affect human factors and recreate immersion.

Display technologies are broadly categorised into stereoscopic and autostereoscopic. The former denotes technologies reliant on wearing special headgear or glasses while the latter denotes display technology not reliant on the viewer wearing any such special gear. Although authors have proposed expanded topologies for categorising 3D display technology, a consensual adherence to the framework separating stereoscopic and autostereoscopic technologies continues to find relevance (Pastoor & Wöpking, 1997; Blundell, 2011). Definitive topologies are provided by a host of researchers in the field (Cakmakci & Rolland, 2006; Cobb, 2006; Holliman, 2006; Kress & Starner, 2013), and a complete replication will not be pursued here.

Optical devices required to aid vision in viewing S3D content descend, in principle, from Wheatstone's and Brewster's stereoscopes (Holliman, 2006). These devices exist as anaglyph, passive polarisation, and active shutter glasses.

Anaglyphic devices operate by superimposing two images into a single, colour-coded image. Each coloured image (red for the left image and blue for the right) corresponds to a respective eye, and the chromatic filters on these glasses separate the images based on the colour channels. The anaglyphic technique is the most familiar to 3D viewers due to its usage over extant single-channel infrastructure such as film and TV media, although it supports a lower range of resolution and full colour information. These filters come in a variety of types including various combinations of red/cyan, blue/yellow, and green/magenta filters (Woods & Harris, 2010). An example of a multiple colour-multiplexed approach is deployed in Dolby 3D cinemas (Jorke, 2007; Jorke & Fritz, 2003; Jorke, Simon & Fritz, 2008; Richards & Gomes, 2011).

Passive 3D glasses, on the other hand, use passive polarization. By utilizing this technique, a single display can present a stereo image but with the images superimposed or overlapping. Each of the left-right images, though superimposed, is polarised for successive frames, after which the filters on the 3D glasses restrict the perception of the overlapping image such that only the right eye receives the encoded image captured by the right stereo camera and vice versa. This form of polarised encoding is cost effective to deploy and includes familiar devices such as the disposable RealD glasses (Lipton, 1996). Schuck and Sharp (2012) provide an exhaustive exploration and demonstration of various polarizing display systems.

Active shutter glasses represent another category of viewing devices used to elicit immersion when viewing S3D content. These glasses work in tandem with the vertical refresh rate of the display screen, rapidly alternating the presentation of the corresponding image from one eye to the other. To achieve these rapid alternations without interfering with normal vision (i.e., avoiding flickering), active shutter glasses and all equipment up the content pipeline must support high refresh rates.

Regardless, circularly polarised S3D displays, when used with linear polarization glasses, are susceptible to intolerable distortions even with a tiny amount of horizontal head tilt, that is, oblique or off-axis viewing (Law et al., 2013; Yang, 2014; Yeh & Gu, 2010). A 10% change in the geometric incidence showed onset of intolerable image deterioration in the form of crosstalk (described later) (Hong, Jang, Lee, Lim, & Shin, 2010). Woods and Tan (2002) and Woods

(2010) show that shutter leakage, at 0.1% even at 100% opacity, is accentuated with every change in angulation.

In real-world viewing, the impractical implication is that the viewer must remain in one position without even the subtlest of movements. Head tracking has been proposed as a solution (De la Barré & Jurk, 2011), but this technology introduces image lag and complexity into the S3D content pipeline.

Autostereoscopic displays allow viewers to consume 3D content without using any shutter or filter glasses. Displays requiring aided viewing often have a fixed image plane, and the viewer has to hold a single position or risk experiencing cross-talk. However, unlike those that demand aided-viewing, free-viewing displays enable group viewing of stereo content. Auto-stereoscopic technologies enable far greater viewer mobility, do not require optical devices, and support a larger number of viewers. Reviewing the different nomenclatures of these devices is worthwhile, as they reflect on the presentation techniques used to deliver comfortable S3D content.

Blundell (2011) proposes classifying autostereoscopic technology into two subclasses. The first denotes displays that do not provide any naturalistic support for oculomotor cues (i.e., accommodation and convergence). The second class includes displays that provide support for both motion parallax and oculomotor cues. These displays, which provide disparity and convergence cues and allow for the viewer to physically change viewing positions, thus support motion parallax, where parallax is defined as the relative movement of objects across the retina such that near objects are perceived to move. Importantly, autostereoscopic displays faster than farther objects to create relative motion and cue for visual depth. As a motion-based cue, movement enables the fast and reliable perception of depth (An, Ramesh, Lee, & Chung, 2011).

The first class discussed above includes virtual reality (VR), augmented reality (AR), and multiplex displays while the latter comprises volumetric, varifocal or multiscopic, and holographic displays. Holliman (2006) provides an alternative topology, denoting autostereoscopic displays that operate with a pixelated LCD such as parallax barriers, lenticular apparatus, and holographic systems and their application in two view twin-LCD and single-LCD systems.

On the other hand, Pimenta and Santos (2012) propose classifying autostereoscopic displays depending on the number of views or viewing angles supported by the display. According to

their viewpoint, multiscopic displays deliver multiple views without the need for optical devices through two main directional multiplexing techniques: parallax barriers and lenticular displays. When displaying a 3D image, these multi-directional displays have a single rotating screen or multiple static screens that present scene points to a finite range of segmented viewing angles akin to a cylindrical hologram. Pimenta and Santos (2012) also make note of the newer and superior technique of directional multiplexing, anisotropic diffusers. These techniques, nonetheless, do not support continuous-motion parallax, thereby causing optical distortions and limiting the realism and available viewing angles.

Support for motion-based cues is doubly important in the design of multiplanar S3D displays. Indeed, autostereoscopic 3D displays, especially those utilizing multi-view displays and lenticulated designs such as those enumerated above, enable overlapping motion parallax whenever an observer translocates between adjacent viewing zones (Reichelt, 2010). This multi-view design therefore ensures that the viewer(s) enjoys uninterrupted horizontal motion parallax across different viewing positions. Motion parallax thus underlies the ability to deploy stereoscopic displays in viewing scenarios where stereo glasses are unnecessary. In other words, the ability to evoke the sensation of uninterrupted motion parallax across a multiview planar surface has enabled the development of autostereoscopic stereo 3D displays.

Examples, principles, and applications of autostereoscopic displays can be found in the extant literature (Holliman, Dodgson, Favalora & Pockett, 2011; Hong et al., 2010; Miyazaki, Shiba, Sotsuka & Matsushita, 2006; Ni et al., 2006; Onural et al., 2006; Ranieri et al., 2012; Tay et al., 2008; Urey, Chellappan, Erden & Surman, 2011). In particular, Pastoor and Wöpking (1997) are notable for their exhaustive discussion of the different approaches to multiplexing and polarization and their applications to displays (although recent developments have introduced novel ways of displaying stereo content).

Ultimately, these multiplanar or multiview displays are an acknowledgement that real-world stereoscopic viewing demands the presentation of different parameters to every viewer at each viewing angle. While these presentation technologies attack this problem from one side, several acquisition techniques have been developed to solve the issue of distortion for multiviewing.

A prevalent technique is capturing content at a low disparity, i.e., a fraction of the typical human interocular distance. DOPs are well known for shooting with as little as 8 mm of disparity (compared to a typical human eye distance of 52-75 mm), thereby producing a very small amount

of resultant parallax. The disparity cue is thus perceived as being active but is not processed (Siegel & Nagata, 1999). However, while the distortive effects may be reduced, they are not eliminated, and, regardless of the presentation disparity, two viewers, one seated in the bottom left and the other in the top right of the cinema, experience significantly different perceptions of the same scene.

Another solution to the configurational problem of multiple viewers is for all viewers to use a synoptic device that removes all disparity, convergence cues, and accommodation information from the presented scene to present parity (Arnoldussen, Goossens & Van Den Berg, 2013; Harper & Lotto, 2001; Wijntjes, Füzzy, Verheij, Deetman, & Pont, 2016), allowing for independent manipulation of the point of convergence. In this way, there are no on-screen disparities to be distorted and no contextual disparities since the viewer's entire visual field is receiving monoscopic information.

This solution also works in 3DTV environments where a TV's surrounding context (e.g., bezel, wall behind, on-screen reflections) can interfere with a viewer's standard viewing (Black, Patel, Latto & Lawson, 2006; Wijntjes et al., 2016). Another technique used to vary the viewer's convergence point while ensuring no accommodative load is presenting the screen through an aperture in a blackout such that the screen's bezel and contextual information are not available to the viewer. These techniques are based on the difficulty of systematically varying the convergence point of stimuli while maintaining all other factors as apparently equivalent (Banks et al., 2009; Knill, 2007). This is evident because, while stereoacuity screening assumes that the observer is viewing a 3D target in optimal surroundings (Tidbury, Black & O'Connor, 2015), normative data indicate substantial inter-individual differences in the eyes' natural fixation point.

A cross-section of professionals that generate stereoscopic content insist on so-called orthostereoscopic viewing (explored later) conditions that attempt to replicate reality as closely as possible (Harper & Latto, 2001; Spottiswoode & Spottiswoode, 1953). While a useful starting point, it is important to closely define what reproducing natural human vision entails.

With respect to viewing cinema, there are two accepted ways of doing this. The first is by adjusting the IA setting of the left/right cameras to most closely reflect that of the 'normal' viewer. However, this method has the downside of being based, at best, on the average of a normally distributed measure. Thus, a capture IA of 62 mm is only truly orthostereoscopic for an individual exhibiting that eye distance. Generative content lacks this constraint; however, for

an eye distance at the edges of the normal distribution of eye distance, there can be up to a 13 mm or 25% disparity between the capture setting and the viewer's eyes. The second accepted way of reproducing normal human vision is to use lenses with a field of view that reflect or exceed the stereoscopic fusion area of a human.

1.5.4 Issues of Viewer Discomfort from Industry and Applied Perspectives

Watching stereoscopic 3D content can elicit symptoms of discomfort, some resembling motion sickness—dizziness, nausea, and vomiting—and others visual discomfort and fatigue. These viewer-comfort issues, or lack thereof, have stymied mass market adoption of 3D technology. Revenue from 3D films has decreased from the 2009-2010 peak years (Schechter, 2015; Solimini, 2013), a seeming failure that has extended to other verticals. For instance, 3D TV purchases in the American market have declined (Katzmaier, 2017) as major original equipment manufacturers (OEMs) shattered the production of 3D TVs (Katzmaier, 2017). Initial ambitions to establish 3D as an industry standard in the video games market have been scaled back across different platforms of current-generation home consoles (Carnoy, 2013; Orland, 2012; Phillips, 2013; Zachara & Zagal, 2009). By late 2017, the Nintendo Switch, Nintendo's fastest-selling game console, did not support 3D media despite pre-launch indications to the contrary (Dempsey, 2017; Sarkar, 2016), and Nintendo abandoned its earlier autostereoscopic 3D console (Nintendo 3DS) in favour of improving its previous 2D display console (Kuchera, 2017; Walton, 2017).

1.5.5 Industry Standards for Stereoscopic Production

Nonetheless, despite the acquisition technique employed by several detailed above, image distortion still occurs, especially where a sound grasp of the geometry of stereography is lacking. Industry standards and rules of thumb, which codify this geometry, are intended for use by stereographers to produce comfortable S3D content.

Arguably, best practice in stereographic production rotates around the intention to mirror and elicit the intuitive occurrence of binocular fusion and stereopsis in a normal observer. Therefore, stereographers prefer using low parallax values that are suited to senso-cortical fusion. For instance, into-the-screen (positive) parallax is limited to a 2% depth budget of the screen width when a 47" 3D TV is viewed at a distance of 2.7 metres. This parallax limit is intended to position the point of convergence at no more than a small distance from the focal accommodation at the planar display; ideally, this distance is ± 0.3 prism diopters, but the 2% limit yields 0.7 prism diopters (Charman & Whitefoot, 1977; ITU-R, 2000; Marcos, Moreno & Navarro, 1999).

On the other hand, negative parallax should not exceed 1% (Coppin, 2011; ITU-R, 2015), with total parallax within the nominal range of 3%.

These depth-budget limits are typically expressed as a percentage of the horizontal size of the display screen or of the frame's width. Other approaches to defining comfortable limits have been proposed, notably delimiting parallax based on the viewer's depth of field and retinal disparity. However, all approaches converge to comparable limits based on comfort, that is, 1% negative parallax and between 2% and 3% positive parallax (Coppin, 2011; ITU-R, 2015; Lambooj et al., 2009). Research further confirms this convergence to the zone of comfort for viewing stereoscopic content (Chen, Fournier, Barkowsky & Le Callet, 2011; Hibbard, Haines & Hornsey, 2017; Shibata et al., 2011a; Tam et al., 2011; Voronov, Vatolin, Sumin, Napadovsky, & Borisov, 2013).

However, these guidelines can be exceeded to satisfy justified editorial needs, with positive screen parallax (into screen) not exceeding 4% and negative screen parallax (out of screen) not exceeding a 2.5% depth budget (Coppin, 2011; Tricart, 2016; Vatolin et al., 2013; Voronov et al., 2013).

Comfort guidelines also affect selection of IA during content acquisition. The general rule of thumb, typically referred to as the 3% rule, stipulates that the starting point for IA should be $1/30^{\text{th}}$ of the distance from the stereo cameras to the closest object (i.e., the foreground). This equates to a 2.5-cm IA for every 1 metre of the scene (Mendiburu, 2012). Due to screen-size magnification (i.e., large screens amplify the presented depth), this rule is sometimes adjusted on a shot-by-shot basis, leading to several derivative rules, including the $1/60^{\text{th}}$ rule and $1/100^{\text{th}}$ rule (Bickerstaff, 2012; Mendiburu, 2012; Voronov et al., 2013). These derivative rules are necessary because the 3% rule is ideal for small screen sizes (about 65 inches wide) displaying images acquired by parallel stereo cameras where the background was set at infinity (Dashwood, 2011).

Nonetheless, research into human factors providing direct support for any of these rules of thumb is scant, although the literature does contain demonstrations of algorithm-based selection of acquisition parameters (Froner & Holliman, 2005; Holliman, 2004; Jones, Lee, Holliman, & Ezra, 2001; Oskam, Hornung, Bowles, Mitchell, & Gross, 2011). Williams and Parrish (1990), however, deserve special mention; their investigation into human factors yielded a recommendation to set viewing between -25% and +60% of the viewer-to-screen distance, with the far space limited to 60% of the head-screen distance. However, their recommendation aligns

with, and can therefore be generalised into, the 1% rule presented earlier. Their scene-scaling technique, however, appears to have marginal practical benefit (Holliman, 2005).

1.6 Principles of Human Binocular Vision

1.6.1 The Range of Stereoscopic Fusion

Although 5% to 12% of the global human population is stereoblind, that is, incapable of perceiving stereoscopic depth, binocular vision is a familiar and pervasive visual feature (Pettigrew, 1986) during which the fields of vision (FOV) of two eyes overlap to create a wide binocular field (Heesy, 2009). This visual-field overlap is aided, in part, by orbital convergence, the unique and largely isometric human orbital morphology that ensures the orbits are front-facing. Consequently, binocular vision ensures that the visual objects or images localised by each individual eye differently will be perceived as one through a process of singleness of vision or fusion. In the absence of fusion, it would be impossible for the human visual system (HVS) to accurately interpret depth and, therefore, achieve stereopsis, i.e., the perception of depth (Bhola, 2006).

Normal binocularity—the ability for the two eyes to focus on an object and deliver a fusible stereoscopic image—involves two levels of processing. The first is motor fusion whereby our eyes move (i.e., in vergence of eye movements) to the best matching point between the two received images in order to align them against each other (Fincham & Walton 1957; Fong et al., 2015; Hoffman et al., 2008; Love et al., 2009; Schor & Ciuffreda, 1983; Shibata et al., 2011b; Vienne et al., 2011). Once motor fusion has been achieved, sensory fusion can occur as the brain processes the limited range of parallax values without needing further eye adjustments (Custurdis et al., 2011).

At this point, sensory fusion depends on the ability to fuse the monocularly distinct retinal images to create the perception of depth. Normally, binocularity is characterised by oculomotor and cortico-sensory fusion resulting in singular vision, stereopsis, an enlarged and overlapping field of vision (FOV), and effective compensation for visual blind spots. This fusion is a neural process that occurs in two distinct stages.

The first stage of sensory fusion involves local pattern matching of the different neural signals sent from the left and right retinae. This process is immediate, precise, and effortless. In addition, this local feature extraction establishes stereoscopic correspondence and provides the geometric

information then utilised to generate an accurate estimate of retinal disparity (Parker, Harris, Cumming & Sumnall, 1996; Ramachandran & Rogers-Ramachandran, 2009).

Importantly, this process is dependent on the quality of the image falling on the retinal fovea (i.e., binocular foveation) since the neuronally dense fovea has the highest spatial resolution (Bhola, 2006; Blake & Wilson, 2011). Binocular foveation facilitates visual direction and attainment of the retinomotor zero point, at which there are negative incentives for ocular movement (Bhola, 2006).

The mechanism through which binocular foveation is achieved depends on attaining a shared subjective visual direction between the retinal elements, or “retinal points”, of both eyes. As the eyes focus on an image, its projection into each eye stimulates retinal elements that, in turn, stimulate the eye’s neural architecture. While normal human eyes have numerous disparate retinal elements, only several stimulating points share a common visual direction that falls in an area known as the “horopter”, or the horizon of vision (Bhola, 2006). Essentially, the horopter is a geometric concept defining the range of stimulating points across which fusion is achieved. These points or elements constitute the very essence of normal retinal correspondence (NRC) and make possible the law of sensory binocular correspondence: once the retinomotor zero point is perceived, the two foveae correspond to create binocular foveation and, eventually, binocular fusion and singleness of vision. Retinal elements that fall outside this horoptic curve would, conceptually, lead to physiological diplopia, or “double vision”, and thereby violate the law of sensory correspondence (Bhola, 2006). However, the visual system suppresses the phenomenon of diplopia through the non-foveal and extra-horoptic neural network forming Panum’s fusional area. Hence, stimuli occurring in disparate retinal elements located in Panum’s fusion area do not create binocular rivalry but, instead, lead to the cortical synthesis of stereoscopic vision. Objects whose visual axes are in front of or behind this fusional area are physiologically diplopic.

The haplopic method defines the corresponding retinal elements and, consequently, the boundaries of haplopia or single binocular vision. In Figure 1-15, Panum's fusional area (which forms the outer extremity of the horoptic curve) is between the inner and outer limits as marked out by the solid curves, forming a fusional volume that broadens towards peripheral vision (Ogle, 1950). The dashed curve between these two limits represents the horopter. Objects within this range project images to corresponding retinal points, locations with zero disparity, and are therefore perceived as a single image.

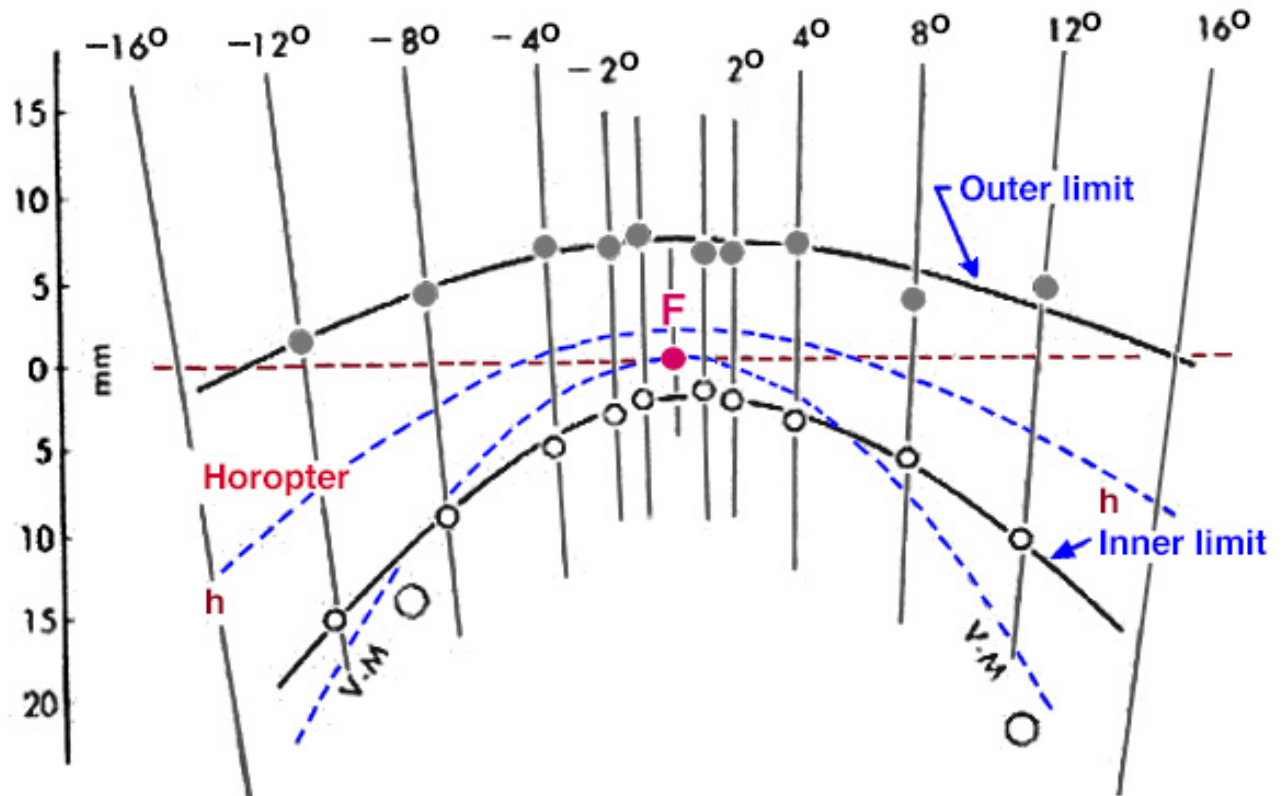


Figure 1-15. Determining the horopteric curve and Panum's fusional area using the haplopic method at a 40-cm viewing distance (adapted from Ogle, 1950).

Objects that fall in the zone of single binocular vision, i.e., outside the horopter but within Panum's fusional area, elicit stereoscopic or 3D vision, whereas those falling outside both the horopteric curve and Panum's area are perceived as diplopic. Physiological diplopia has important connotations for the stereoscopy practitioner due to its attribution to vergence errors, which, in turn, are closely associated with IA and, consequently, viewer discomfort during consumption of S3D content (Blake & Wilson, 2011).

There is no universally constant critical fusional limit, as this depends on a multitude of interacting factors including, for instance, the proximity of objects to another's visual field (Burt & Julesz, 1980) and luminance (Schor, Heckmann & Tyler, 1989). However, despite Burt and Julesz's (1980) objections, other researchers contend that there is a fixed fusional area, regardless of stimuli interactions. These include Krol and van de Grind (1982) and Yeshurun and Schwartz (1999); the latter assert that the fusional area has a lower bound, a double-sided magnitude of between 8 and 16 arcmin (foveal), scaling linearly toward the periphery. Qin, Takamatsu, and Nakashima (2004) used a 3D display to measure Panum's area and provide expanded insights with regard to nasalward and temporalward fusional ranges. Even so, numerous

phenomenological issues surround its specification (Thompson, Fleming, Creem-Regehr & Stefanucci, 2011); stated briefly, the complexity of the principles underlying these differences are beyond the scope of this study.

That the horopter exists points to the difficulty in perceiving the entire visual space. For example, strabismic disorders impair sensory fusion as the cyclopean visual system is incapable of fusing dissimilar images. To avoid such perceptual distortions in natural viewing, inhibitory mechanisms in the form of constant suppression diminish stereoscopic performance (Abd-Manan, Jenkins & Kaye, 2003). However, in the normal observer, the neuromotor processes that enable binocular fusion across various ranges and the stereoscopic effect occur intuitively. For instance, a reader instinctively moves across a page to place the content in foveal focus. So instinctive and effortless is the process that the reader is not surprised when binocularity works, but, rather, only when it does not.

The second stage of fusion is a higher-order cortical process during which triangulation of this neural input leads to recovery of a figure's depth profile (Parker, Smith & Krug, 2016). However, as demonstrated above, local pattern matching is an ultimate limiting factor in determining the range of fusion. Nonetheless, working together, these processes create a unitary visual precept of the external environment, i.e., singleness of vision or fusion (Bhola, 2006).

1.6.2 Disparity Distribution with Viewing Distances

The human visual system (HVS) extracts the third dimension from a variety of depth cues, whose understanding is important from both psychophysical and applied perspectives. During human binocular vision or simulated 3D, these cues eliminate or reduce cue conflict, unreliability, and stimuli disappearance (Kooi & Toet, 2004). In the HVS, these cues, the primary ones involved in depth perception, result from horizontal or vertical disparities (Blake & Wilson, 2011; Vishwanath, 2014). In 3D applications, depth can also be introduced artificially through the stereoscopic technique, which mimics the mechanics of actual vision, that is, acquiring subtly different images of the same object (Vishwanath, 2014; Wheatstone, 1838).

These depth cues are classified as either monocular (i.e., vision with one eye) or binocular (i.e., vision with two eyes). Monocular cues include texture, motion parallax cues, defocus blur, volume perception, and the monocular oculomotor cues of convergence and accommodation. Pertinent binocular cues include binocular disparity or parallax, the correspondence problem

phenomenon, and vergence control. While a brief discussion of this and other cues is provided below, Goldstein (2013) is recommended for an exhaustive review of the field and its principles.

Ultimately, these cues are necessary for determining both depth and distance between objects. Regarding the latter, it is important to note that the stereoscopic range does not extend infinitely. Different cues have different contributions to the perception of depth at various distances. Figure 1-16, plotted for a typical inter-pupillary distance of 62.5 mm, summarises previous investigations into the distribution of sensitivity to disparity and distance.

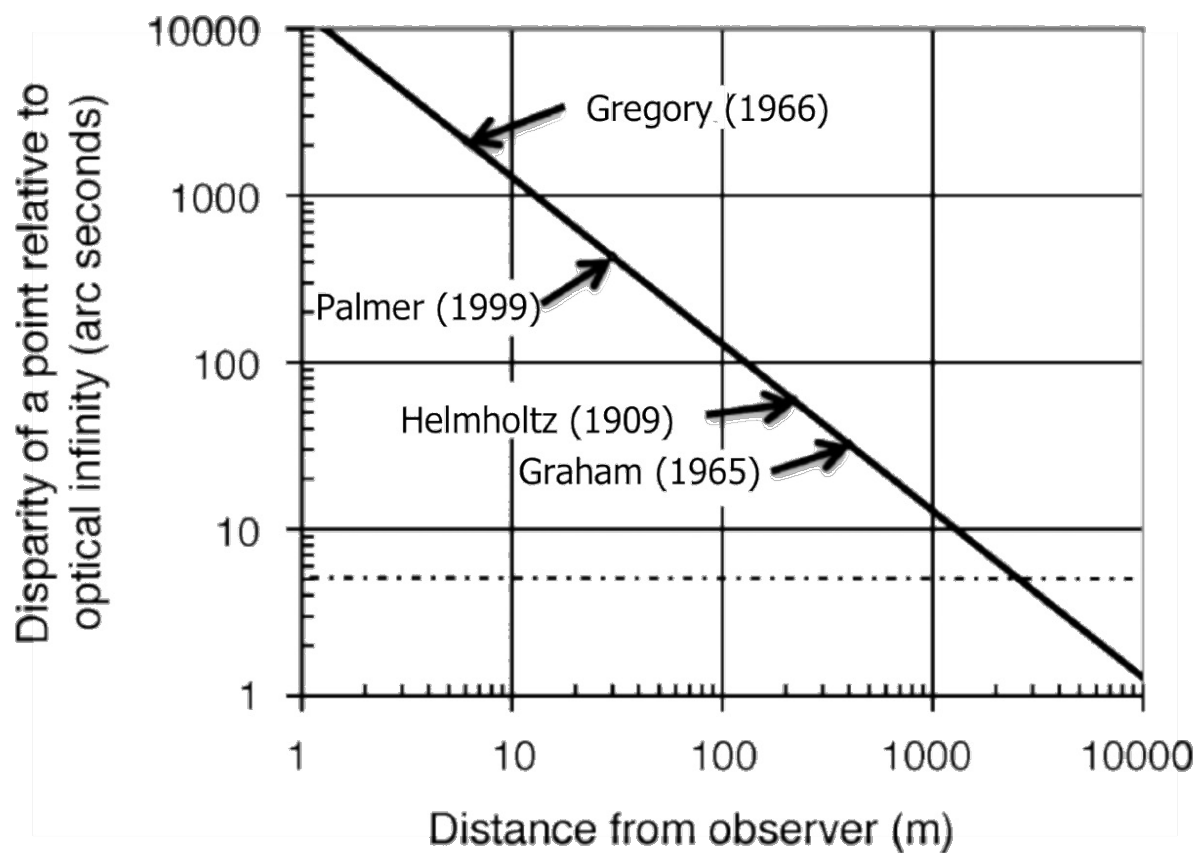


Figure 1-16. Disparity of an object at various given distances relative to an infinite point. Seminal works in the field are denoted within the hypotenused figure (modified from Allison, Gillam & Vecellio, 2009).

Gregory (1966) (arrow in Figure 1-16) shows that binocular disparity is greatest for distances not greater than about six meters, while Palmer (1999) estimates that stereopsis is useful for distances of less than thirty (30) metres, i.e., the near interaction space. On the other hand, Helmholtz (1909) estimates that stereoscopic depth can be recovered for objects at a maximum optical distance of ≤ 240 metres, although this estimate was made without an accurate—and modern—appreciation of stereoacuity. Graham's (1965) estimate is one of the more reasonable but, incidentally, is premised on poor observer stereo acuity. Allison, Gillam, and Vecellio (2009)

estimate that the maximal optical range of stereopsis for an observer/viewer with good stereoacuity (i.e., 5.0 arcsec or 20/20 vision) is at distances of greater than one kilometre. This estimate is represented by the dotted line near the base of Figure 1-16. Allison, Gillam, and Vecellio (2009) report that binocular vision provides the most striking advantage at a range of between 4.5 and 9 metres when scene smoothness is being discerned. A later study confirmed the gains in depth from binocular vision at large viewing distances, advantageous at the 20 m-40 m range, operational for experimental distances of up to 164m, and scaling for even larger distances (Palmisano et al., 2010). These latter findings show that the range of motor convergence is larger than originally thought and that viewers can distinguish between a distant object and the horizon with their eye muscles alone.

While the human visual system has been shown to be responsive to binocular vision (i.e., vision from two eyes) to reproduce three-dimensional information, the HVS can also preserve depth perception during monoscopic vision. Doing so requires reliance on monocular cues such as accommodation, convergence, motion parallax, volume perception, and defocus blur. Due to their orthographic feature, monocular cues are essentially local visual factors, that is, properties that are local to the image and are otherwise insufficient for the extraction of stereo information (Saxena, Schulte & Ng, 2007).

Visual artists are especially competent at evoking depth perception through the use of these monocular cues (Reichelt, 2010). Saxena et al. (2007) demonstrate that local cues are useful in stereo depth estimation and, therefore, are pertinent in stereographic applications. Indeed, monocular cues are critical in stereo 3D displays that are, by design, intended for use over relatively shorter viewing distances due to their lower discriminability thresholds (Reichelt, 2010). Figure 1-17 below summarises the extent of these thresholds.

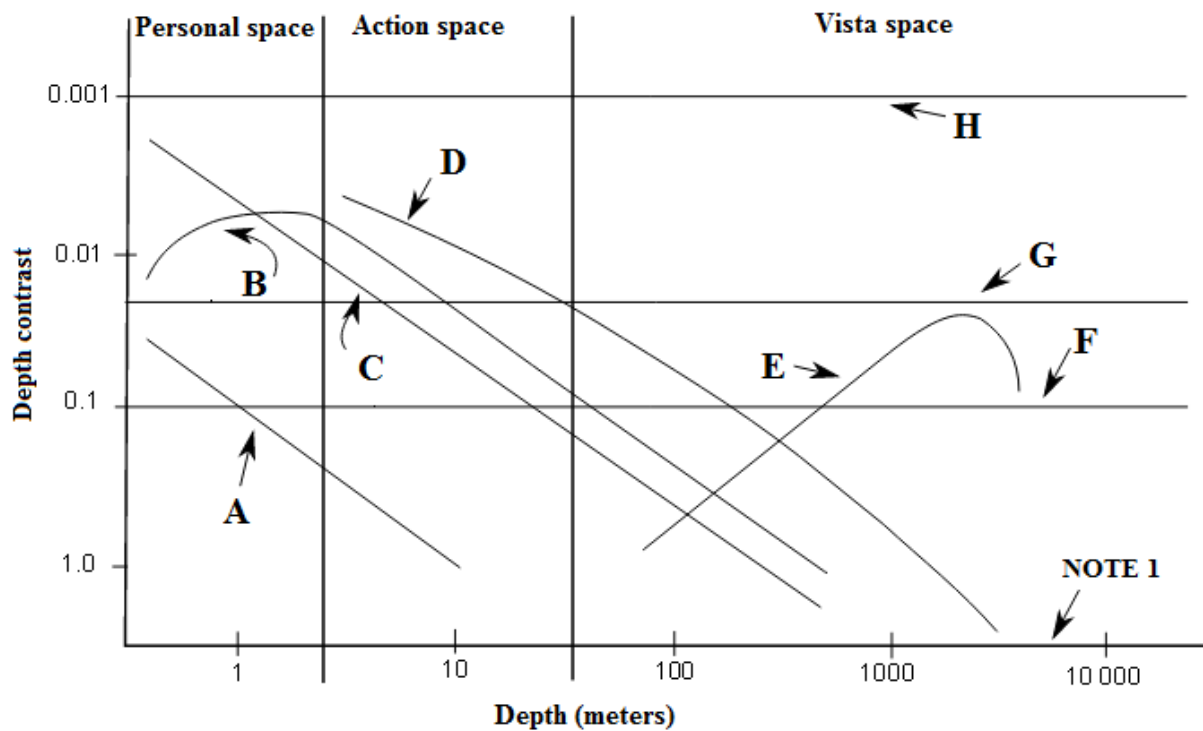


Figure 1-17. An idealised graphical summary of the contribution of nine depth cues (denoted with the alphabets “A” through to “H”) in the depth discrimination for an observer across a visualisation distance, from 0.5 m to 5,000 m (modified from Nagata, 1991; Cutting & Vishton, 1995).

NOTE 1 in Figure 1-17 above refers to the visual horizon, whereas *A* through *H* represent different monocular cues: convergence and accommodation (*A*), motion perspective (*B*), binocular disparities (*C*), height in visual field (*D*), aerial perspective (*E*), relative density (*F*), relative size (*G*), and occlusion (*H*). Note their different thresholds and points of utility.

For instance, the closely related mechanisms of convergence and accommodation are available only in the personal space, although accommodative capacity occurs equally for near-field and far-field objects, albeit with unaltered efficacy. The personal space is generally considered to be within about 20 metres. Occlusion, on the other hand, operates independent of distance, is immediately deployable, and has the highest discriminability thresholds (Nagata, 1991; Cutting & Vishton, 1995). A significant exposition of these concepts and the historical contexts behind their investigation can also be found in the timeless overview provided by Poggio and Poggio (1984).

Watt et al. (2005) present clear evidence of a relationship between viewing distance and depth perception. The study concluded that longer viewing distances allow more comfortable stereoscopic viewing. Hoffman et al. (2008) also concluded that longer distances minimise the

vergence-accommodation conflict, a key culprit in eliciting visual discomfort. Other researchers concurred that viewing distance has an impact on visual discomfort (Hoffman et al., 2008; Kim, Kane & Banks, 2014; Vienne, Blondé & Doyen, 2012; Vienne, Mamassian, Doyen & Blonde, 2012).

This section partially informs the first hypothesis, H₁.

1.6.3 Vergence-Accommodation Conflict

Accommodation refers to the process of obtaining image clarity through changes in focal length or optical power of the eyes' crystalline lenses. This process establishes object fixation, and, once obtained, reflexive action then ensures continual retinal focus on the object (Bhola, 2006). As such, it is a type of focus cue that provides information on the fixed distance of an image (Watt et al., 2005).

This mechanism is both instinctive and deliberate and enables vision across differing distances. For instance, as an observer focuses on a maximally distant object, the ciliary body adjusts the lenticular architecture to allow greater retinal focus (Froner, 2011). Then, as the viewing distance changes from a relatively far point to a relatively closer one, the ciliary body intuitively tensions the lens zonules (suspensory ligaments of the crystalline lens). While a detailed exposition has been provided on the relationship between disparity distribution and viewing distance, Keating (1988) observes that changes in retinal fixation are negligible beyond six metres (i.e., far point), maximal at 25 cm (i.e., the near point), and closer still for younger eyes. Bhola (2006) demonstrates that accommodation is a weakly effective cue to depth, often deployable in distances of less than two metres. Furthermore, accommodation, in itself, is naturally inaccurate, often leading to transient retinal defocus (Reichelt, 2010). Regardless, these operative distances are in keeping with the general dimensions of personal space as defined by Nagata (1991) and Cutting and Vishton (1995).

It stands to reason that, since ocular accommodation is an important human factor, an ideal stereo 3D display must competently induce it. Palmisano (2010) further argues that, since S3D displays cannot be reasonably scaled to take advantage of the far stronger depth cues available at greater viewing distances (see Figure 1-17), cues such as accommodation and convergence (described later) present opportunities to scale retinal disparity and, therefore, depth perception at near

observation distances. Froner (2011) concurs, noting that, since the typical viewing distance for a home S3D display is within a two-metre threshold, accommodation is an effective cue that signals distances and recreates veridical information.

On the other hand, convergence is the simultaneous adduction of both eyes when focusing on near objects to maintain single binocular vision (Bhola, 2006; Hughes, 1991). The eyes can, therefore, be said to move towards each other in closely coordinated movements with the accommodative mechanism through the accommodation-convergence reflex. As the eyes move inward, the sensation resulting from the tensioning of the ciliary body and crystalline lens confirms that the observed object is nearer or nearing the viewer. Where accommodation extrapolates information from changes in the lens's focal power to ensure retinal foveation, vergence extrapolates the same information from eye movements (Fong et al., 2015).

As with accommodation, convergence is especially useful in the design of S3D display systems since the mechanism is considered part of the ocular near triad, implying that it is essentially effective at closer distances and occasionally effective at distances no greater than ten metres (Bhola, 2006; Reichelt, 2010). Additionally, convergence closely interacts with accommodation as defined in the AC/A (relationship of accommodative convergence to accommodation) and CA/C (relationship of convergent accommodation to convergence movement) ratios, which denote the relationship between the two terms and their effect on one another and which are clinically relevant in vision correction. Exhaustive discussions of these relationships are also provided by Horwood and Riddell (2012), Lambooj et al. (2009), and Reichelt (2010), among other significant studies (Emoto, Niida & Okano, 2005; Fukushima, Torii, Ukai, Wolffsohn, & Gilmartin, 2009; Ripps, Chin, Siegel & Breinin, 1962; Shibata et al., 2005).

In Figure 1-18's scenario, the viewer is fixated (through vergence eye movements) and focused (through accommodation) on an angular point of real-life hinge. Panel (A) shows the viewer focused on the hinge while panel (C) displays the appearance of the stimulus during accommodation. The vergence distance, the visualisation distance to the angular point, is related to Panum's fusional area. The vergence response is the distance to the points of intersection of the optical or visual axes. Focal distance is the visualisation distance over which the eye would have to focus (accommodate) to create a vividly clear retinal image and represents the depth of focus. Notably, stimuli create sharply focused retinal images only at certain ranges of the depth of focus (ca. ± 0.3 diopters) (Charman & Whitefoot, 1977; Marcos et al., 1999) and at a tolerance vergence distance of between 15-30 arcmin (i.e., Panum's fusional area) (Templin et al., 2014).

As implied in the figure, the human vision system has evolved to employ the parallel action of vergence eye movements (Vienne et al., 2011; Winkler & Min, 2013) and accommodative responses to focus cues. Accommodative response is the distance to which the eye focuses or is accommodated. Fincham and Walton (1957) and Martens and Ogle (1959) demonstrate that accommodation and vergence are paired neural responses; therefore, accommodative changes evoke changes in vergence (accommodative vergence) and vergence changes evoke changes in accommodation (vergence accommodation), meaning that accommodation and vergence distances are often identical (Love et al., 2009).

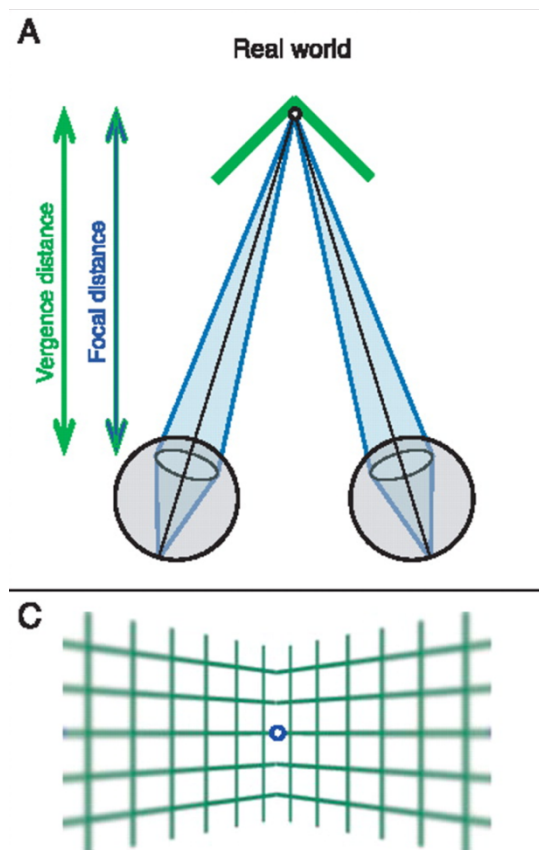


Figure 1-18. Vergence eye movements in relation to focal distance and stimuli presented in the real world showing, firstly, that the focal and vergence distances are equal and, secondly, that only the retinal image is sharply perceived (modified from Hoffman, Girshick, Akeley & Banks, 2008).

In the real-world scenario depicted above, the accommodative response is achieved without excessive force and also without exceeding both the depth of focus and Panum's fusional area (specified above). Moreover, it is coupled with vergence eye movements. The two processes occur simultaneously and instinctively over similar focal and vergence distances as part of the

phenomenon of vergence-accommodation coupling (Hoffman et al., 2008; Kim, Shibata, et al., 2011). Hence, focusing the eyes on an object over a given visualisation distance reflexively triggers vergence eye movements to converge on the same object over the same distance (Vienne et al., 2011). This mechanism occurs as part of the accommodative vergence and the vergence accommodation changes discussed previously.

A benefit of the coupling in natural viewing is increased response speed, specifically to a new object of attention (Shibata et al., 2011b). A failure to converge leads to double vision, while mis-accommodation leads to blurry and uncomfortable images due to lack of sufficient foveation. Vergence and accommodative responses achieved without said discomfort or errors occur within the range referred to as Percival's zone of comfort or the zone of clear single binocular vision (Shibata et al., 2011a). Disparities presented at this range, approximately a third of Panum's fusional volume, can be viewed comfortably. Large accommodative and vergence errors degrade binocular fusion and disrupt stereopsis, causing quantifiable reductions in stereoacuity.

To clarify, accommodative responses are driven by slow-acting retinal blur and fast-acting binocular disparity. Once again, in the real world, changes in both vergence and focal distances are equal, and the slow- and fast-acting components that dictate the accommodative response act in tandem and without conflict.

Blur is an important component driving foveation. Indeed, as depicted in panel (B), it is expected that near-field and far-field objects appear blurry, while the object to which the eye is accommodated appears sharp. This natural correlation between depth and retinal blur facilitates depth perception. In the panel, notice that, in the retinal image, the joined planes (i.e., the sides) of the angular pint are blurred relative to the vertex.

Figure 1-19 shows a scenario in which a viewer is fixated (through vergence eye movements) and focused (through accommodation) on an angular point of a hinge presented on a computer 3D display. In Panel B, the viewer is accommodated to the hinge as displayed on a computer display, while panel C shows the appearance of the stimulus. Unlike in Figure 1-18, the focal distance in Figure 1-19 is now the distance to the computer display and the sides of the stimulus are as equally sharp as in the retinal image.

The mismatch of focal distance compared to vergence distance disrupts the reflexive association between focal and vergence distances: whereas the focal distance is fixed to the planar surface

of the stereo 3D display, vergence distance varies with respect to the point on the projected scene on which the viewer fixates. Consequently, the lack of variance in the focal distance or depth of focus, in turn, ensures that neural commands to the lenticular anatomical architecture constantly command subdued corrections of focal power and signal less depth (Hoffman et al., 2008). The blur-driven, slow-acting and vergence-driven, and fast-acting components of the accommodative response react to these neural commands by slowing the process of retinal foveation to account for conflicts in minimising blur. Indeed, this scenario attempts to set accommodation and vergence at independent and arbitrary values with notable side-effects in terms of viewer comfort. Inherently, stereo 3D displays reduce stereoacuity, increase the time of the fusion of binocular stimuli, reduce fusion accuracy, and evoke unsettling side effects.

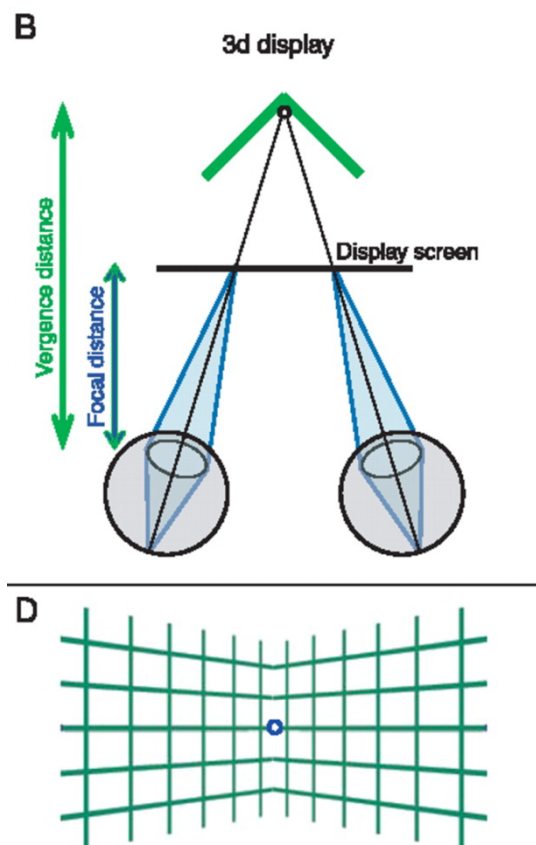


Figure 1-19. Vergence eye movements in relation to focal distance and stimuli presented by a stereoscopic 3D display showing, firstly, the mismatch between the focal and vergence distances and, secondly, that both the sides of the stimulus and the retinal image are perceived as equally sharp (modified from Hoffman, Girshick, Akeley & Banks, 2008).

When a viewer focuses (accommodates) on a stimulus on a computer 3D display, the focal distance stays constant, and retinal images at this focus distance are sharp and blurry if the eyes are focused elsewhere on the simulated visual space. Hence, as can be observed on the panel, the S3D display introduces a blur gradient that indicates perceptual flatness.

In summary, difficulties in veridicality while stereo content is being observed occur because the viewer has to alter vergence and accommodation to different distances (Hoffman et al., 2008). More simply, accommodation stays fixed at the distance between the eyes and the display, while vergence distances vary due to the space (“depth”) produced on the display, i.e., the distance of accommodation = distance to the surface of the stereoscopic display \neq distance of vergence. Hence, accommodation does not take place because focus power remains fixed. A graphical summary is presented in Figure 1-20 below.

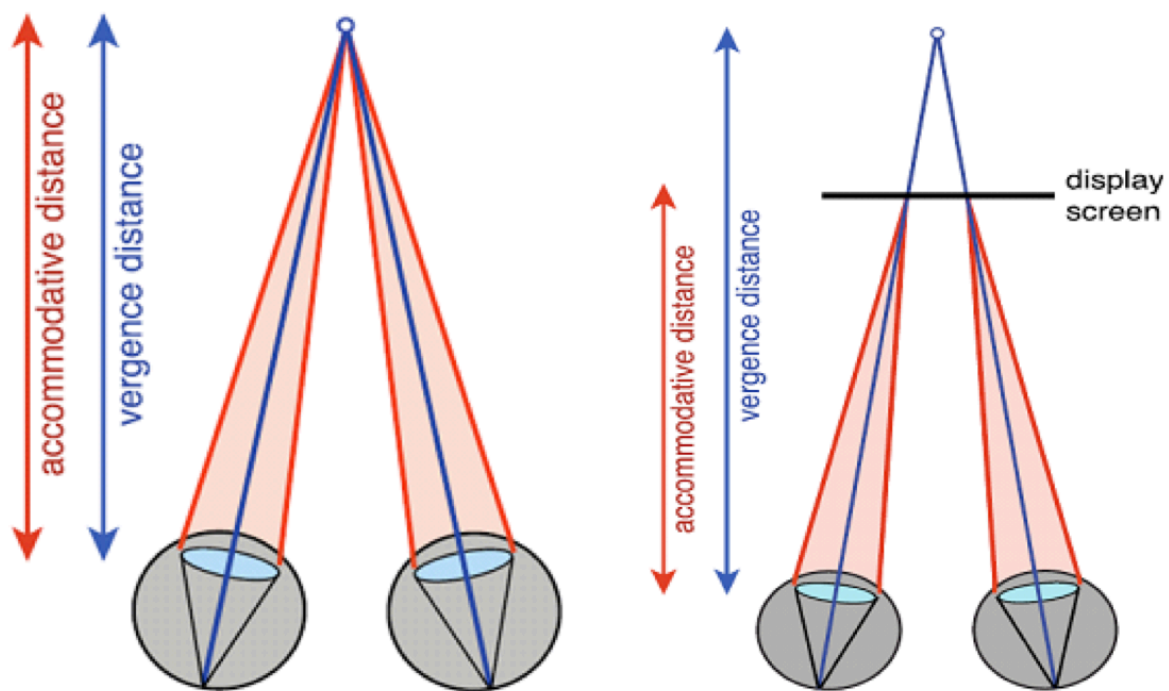


Figure 1-20. Graphical summary of coupled accommodation and vergence in natural viewing (left panel) and uncoupled accommodation and vergence eye movements when viewing content on a stereo 3D display (right panel).

Therefore, accurate accommodation results in a clear view of the image but in the presence of double images, whilst accurate vergence may cause the perception of a fused but blurred image. Blurred images serve as a cue to accommodation to return to the original accommodative state, possibly causing fatigue and eyestrain (Jin, Miller, Endrikhovski & Cerosaletti, 2005). These vergence-accommodation discrepancies may also lead to perceptual distortions (Hwang & Peli, 2014; Ravikumar, Akeley & Banks, 2011).

These are important insights. The disparity in image projections on stereo displays is intended to mimic the naturalistic depth cues necessary for the stereoscopic recreation of scene points (Reichelt, Häussler, Fütterer & Leister, 2010). However, despite the mimicry, the forced decoupling of accommodation and convergence inherent to S3D displays creates an altogether

unsettling visual anomaly termed vergence-accommodation conflict (VAC) (Banks et al., 2003; Hoffman et al., 2008; Howarth, 2011; Shibata et al., 2011a; 2011b; Lambooij et al., 2009; Love et al., 2009; Ukai & Howarth; 2008; Vienne et al., 2011; Wann & Mon-Williams, 2002).

Vergence-accommodation conflict (VAC) is a focus-fixation conflict elicited by artificial geometries introduced during cue acquisition and processing (Banks et al., 2012). For instance, acquisition misalignments can be introduced with the toed-in camera configuration (i.e., keystoneing) while presentation misalignments may occur through the use of a constant vertical disparity across magnitudes of arcmin. These and other misalignments alert the visual system to errors that are otherwise absent in 2D content (Kramida, 2016; Read & Bohr, 2014) and persist even when scene acquisition and presentation are perfectly calibrated.

The suggestion that VAC results in perceptual distortions is supported by Watt et al. (2005), who argue that focus cues are used to create approximations about 3D image structures; it is therefore argued that unsuitable focus cues may contribute to perceived 3D scene distortions. In fact, the scientific consensus is that these displays almost always evoke cue conflicts, a scenario that has inspired significant research (Banks et al., 2012; Shibata et al., 2011b).

Admittedly, VAC cannot be practically eliminated in stereo displays. It is inherent to stereoscopic 3D displays and can only be lessened and not entirely weakened (Reichelt, 2010). This inherent limitation is due to their lack of support for focus cues and the resultant forced decoupling of these cues and vergence eye movements. Solutions such as volumetric displays and holographic technology promise to resolve this conflict by introducing true focus cues (Pei, Yan, Zhao & Jiang, 2014; Reichelt, Häussler, Fütterer & Leister, 2010; Sarma, 2014; Yaras, Kang & Onural, 2010). Several authors have also provided exhaustive reviews of the solution space of methods for vergence control in the S3D display domain (Cakmakci & Rolland, 2006; Kramida, 2016; Kress & Starner, 2013; Terzić & Hansard, 2016). Nonetheless, the form factors and other limitations of these newer technologies means that S3D displays represent the ideal, familiar, and already deployed platform necessary to meaningfully provide viewers an immersive experience. Carnegie and Rhee (2015) agree, noting that hardware-based architectures that ensure near-optimal accommodation cues for diverse depths may be un-deployable in consumer applications due to costs and complex architectural requirements.

Interestingly, it has been argued that the un-coupling of depth perception mediated by accommodation and vergence could have long-term effects, especially on children, for whom the

cue interaction may become unlearned and the development of the binocular circuitry impaired (Banks, 2014; Banks, Aslin & Letson, 1975; Kramida, 2016; Wann & Mon-Williams, 2002). By verging and accommodating at different distances, the viewer's natural cross-linkage between these two physiological mechanisms can be broken, a disruption that results in discomfort in the form of nausea, headaches, visual fatigue, and other motion sickness symptoms (Hwang & Peli, 2014; Kim et al., 2011; Wann & Mon-Williams, 2002), i.e., visually induced motion sickness (VIMS) (Hettinger & Riccio, 1992; Hwang & Peli, 2014; Kennedy, Drexler, & Kennedy, 2010; Keshavarz, Hecht & Lawson, 2014; Naqvi et al., 2013; Solimini, 2013). This is especially recognizable after prolonged use of stereo 3D displays (Shibata et al., 2011a; 2011b). Indeed, the neural coupling is often misleading during S3D viewing, since vergence-accommodation can shift the focusing plane from the screen and increase retinal image blur instead of decreasing it. Where vergence eye movements increase retinal blur, lenticular accommodation activates to remove the blur, creating unfusable retinal disparities and, thereby, double vision.

These negative effects of stereo 3D displays are a significant limitation in the wider adoption of stereoscopic display technology in media and industry.

1.6.4 Vergence-Accommodation Conflict: Applied Principles

While these discrepancies have been shown to elicit visual fatigue and discomfort, previous studies such as Shibata et al. (2011a) have focused their attention on out-of-the-screen stereo content. Indeed, for out-of-the-screen content, accommodation and convergence are equal; however, this is not the case for in-the-screen content.

The difference between the two is based on where the convergent point lies, as it determines where objects will appear in relation to the screen. A camera's convergent point dictates where in relation to the screen an image will be produced. Converged cameras converge in front of the screen and display in-the-screen images, whereas parallel cameras never intersect, and the 3D picture appears out of the screen. Speranza et al. (2002) argue that in-the-screen images may be more comfortable to view as human eyes converge to look at images in natural viewing, thereby causing convergent cameras to possibly produce more natural 3D images.

However, the authors also note that toe-in cameras cause uncomfortable keystone distortions. (For a fuller discussion, see Section 1.5.2: Issues in Image Acquisition). It has been argued that vertical disparities may have a detrimental effect on visual comfort (O'Kane & Hibbard, 2007). Speranza, Tam, Renaud, and Hur (2006) found that converged cameras received better comfort

ratings than parallel cameras, supporting the suggestion that in-the-screen 3D images may be more comfortable to view. Additionally, only large keystone distortions were found to have an effect on comfort ratings. Consequently, it is unclear how comfortable in-the screen S3D imagery will be to view.

Keystoning is inevitable in converged filming without tilt-shift lenses (Woods et al., 1993). The original Stereo Realist camera and others of the era afforded the ability to move the lens horizontally, independent of the film plane (Morgan & Symmes, 1982). The modern equivalent is rare, only seen in the Vision Research Phantom 65 Zepar system (which “ramps” slightly oversized lenses horizontally) (Melkumov, 2010). Another alternative when shooting live action is to either (1) sacrifice horizontal image resolution and zoom the image, resulting in the image being scaled and the effective field of view reduced, or (2) shoot on an oversize sensor and crop pixels. Further discussion of the concept is provided in Section 1.5.2: Issues in Image Acquisition.

CGI uses parallel virtual lens shift to avert this problem. In this way, the viewing frusta, the pyramids formed between the lens centre of each eye and the optical centre of the lens, are shifted horizontally. This lateral distortion produces no vertical screen disparities in the commonly acknowledged problem of filming “toed-in”. Correcting this filming technique is destructive to image resolution and fidelity. The correct fix for horizontal keystoning involves rotating each image about the Y-axis by the corresponding number of degrees. However, filming “toed-in” is *not* destructive to reconverging a shot (a commonly held misunderstanding). It is only the image quality that suffers through the transformation; no innate characteristic of toed-in shooting is destructive to depth information. Therefore, Y-axis-rotated footage can be freely reconverged to a desired camera convergence point through HIT.

The act of converging cameras, regardless of the technique used—be it parallel camera frustum shift, ramping, asymmetrical frustum shift or HIT, or toeing—consistently results in image distortion unless done carefully. It is important to note that, for a fixed viewing position, an undistorted converged image is possible if the following steps are undertaken (Bickerstaff, 2012). The stereo cameras should be aligned so that they are perfectly superimposed, separated to match the typical human eye distance, and then converged to the desired virtual screen distance. In this case, the distance to the point of convergence, modulated through application of HIT, can be stated to be identical to the IA.

A typically misunderstood point about stereography is that a large camera separation will necessarily result in image distortion. When the cameras are calibrated to converge on the correct point, the IA can safely be increased and decreased in a way that causes objects to scale smaller and larger, with their shapes unchanged. In this regard, the least distortive technique is referred to as the deRobe method (named after deceased 3D film-maker Alain deRobe). In this method, the cameras' convergence point is fixed, the distances from the cameras' optical centres to the nearest object are measured and then are adjusted accordingly to form a triangle of identical dimensions between the apex of the nearest object and the optical centres of the two cameras (Pennington & Giardina, 2013). Due to the misunderstanding on the impact of large camera separations on image distortion, it is rare to see the deRobe technique consistently applied. For instance, even *The Hobbit: An Unexpected Journey* (2012) changed the convergence plane throughout the film. A successful implementation of this technique was demonstrated by the production of *Storm Surfers 3D* (2012) under the stereographic supervision of the late Robert Morton (Morton, 2012a; 2012b).

Another important relationship is that between IA and the human IPD of 60 mm (Banks et al., 2009; Bickerstaff, 2012; Grinberg, Podnar & Siegel, 1994; Harper & Latto, 2001; Spottiswoode & Spottiswoode, 1953). If IA is different from the IPD, there will be a scaling issue. For example, if IA is smaller than the IPD, then the replayed scene will appear at a larger scale than in reality. This is known as gigantism. Conversely, if IA is larger than the human IPD, miniaturisation will result (Lipton, 1997). In practical terms, however, gigantism is less noticeable than miniaturisation (Benzeroual, Allison & Wilcox, 2011; Häkkinen, Hakala, Hannuksela & Oittinen, 2011; Harper & Lotto, 2001; Kurtz, 1937; Masaoka et al., 2006), and high IAs result in an image having less "real" depth available and subtending one fusion zone (approximately 1° of arc). As a result, there is a misconception that large IAs automatically induce eyestrain; instead, the permissible parallax budget of large IAs is less than that of small IAs.

While IA affects image scaling, HIT, on the other hand, plays a role in manipulating depth. Too much or too little HIT results in warping. When a subject nearer than the screen target is attempted to be brought from in front of the screen to the screen plane, by using too much HIT, the background becomes more divergent, but this divergence is now nonlinear to the depth information. With an infinity background, the background will resemble a diorama.

When a subject located beyond the screen is attempted to be brought from behind the screen to the screen plane, using too little HIT, the background information occupies more stereo space than it would when captured correctly, thereby creating a stretched effect.

Kytö, Hakala, Oittinen, and Häkkinen (2012) argue that depth budget, the amount of 3D depth between the nearest and furthest items presented on a 3D (see also Section 1.5: Issues in 3D Stereography), is smaller for out-of-the-screen 3D. This would suggest that using larger depths may cause increased discomfort. In this way, in-the-screen 3D images may become more comfortable to view as the depth budget is enlarged.

This may be due to the roundness factor (r), which is the ratio of a particular object's size magnitude and depth magnitude (Devernay & Beardsley, 2010). If the size magnitude is bigger than the depth magnitude so that the roundness factor is less than 1, a flattening effect will occur compared to its accurate representation (Kytö et al., 2012). Further, the authors suggest that camera separation, defined as the yoked or slaved combination of IA and HIT, controls perceived depth. Black, Meyer, and Wuerger (2012) argue that camera separations affect the point of subjective equality (for a definition, Section 1.7.2: 3D Percept Distortions and Section 2.1.8: Psychometric Function and the Point of Subjective Equality) and, ultimately, veridicality.

1.6.5 Relationship between Viewer Discomfort and Limiting Parallax

With stereoscopic displays, visual discomfort is a major and active issue (Kim, Park, & Oh, 2011). In most studies, the term 'visual discomfort' is used interchangeably with 'visual fatigue', but the two are distinctly different. Visual discomfort is subjectively estimated and is associated with jitter, flicking, image motion, and poor resolution (Kim, Park, & Oh, 2011), whilst visual fatigue comprises objectively measurable symptoms and implies any dysfunction caused by the use of one's eyes (Sheedy, Hayes & Engle, 2003; Howarth, 2011). These can be measured by using either a subjective measurement or objective measurement methods (Blehm et al., 2005). Generally, normal people experience visual comfort after around 29 (Yang & Sheedy, 2011) or 30 minutes (Kim, Park, & Oh, 2011) of viewing stereoscopic content, but the discomfort can occur more quickly or later.

Investigating various visual factors associated with users' vision is important to solving issues of visual discomfort (Kim, Park, & Oh, 2011). Furthermore, being able to predict the level of visual discomfort from the specification of binocular viewing systems greatly helps the design and selection process (Kooi & Toet, 2004).

There are numerous potential causes of visual discomfort when stereo displays are viewed (Shibata et al., 2011a), including the eyewear required to separate the two eyes' images and ghosting, or crosstalk, i.e., imperfect separation of the two eyes' images resulting in the left eye's image being partially visible to the right eye and vice versa (Banks et al., 2009; Shibata et al., 2011a). Additionally, misalignment of the two eyes' images may arise from differences in the optics in pairs of stereo cameras (Banks et al., 2009), inappropriate head orientation, vergence-accommodation conflict, visibility of flicker and motion artefacts, and visual-vestibular conflicts (Kooi & Toet, 2004).

In any 3D project, both consistency of the depth cues and avoidance of binocular rivalry must be seen to. Many authors have attributed visual discomfort associated with viewing 3D images to a vergence-accommodation (accommodation-vergence) conflict, mainly because it is present in all conventional stereo technologies (Banks et al., 2012; Tam et al., 2011).

Moreover, previous publications provide data demonstrating a linkage between parallax values and level of viewer discomfort: in particular, high parallax values equate to increased levels of discomfort (Ide et al., 2002; Lee, Jung, Sohn, Speranza, & Ro, 2013; Shibata et al., 2011a). However, even conservative screen parallax values have, in some instances, been found to evoke eyestrain, and high screen parallax values have been capable of being viewed comfortably.

Natural viewing involves motor fusion facilitated by vergence eye movements (i.e., motor fusion) (Vienne et al., 2011) and sensory fusion undertaken by local pattern matching and cortical processing (Custurdis et al., 2011). Disparity values that exceed fusional capacity lead to unaligned images due to inadequate motor fusion and, consequently, lack of fusion. This scenario leads directly to eyestrain and visual fatigue due to the greater effort needed to achieve fusion.

Stereoscopic content producers are aware that a viewer will usually look at a screen with defined, visible edges and, therefore, that it is undesirable for them to present a scene requiring the viewer to use motor fusion. In the first instance, this would overlap the screen upon itself, creating a ghosted outline of the edges of the screen on the image. Secondly, it would create a situation in which the convergence, or triangulation, and the focus of the eyes, or the accommodation, would be significantly mismatched (Franzén, Richter & Stark, 2000; Hoffman et al., 2008). For this reason, content producers (BBC, 2012; Coppin, 2011) aim to present images with screen disparity values that minimise vergence adjustments.

It follows that content producers favour using low parallax values that sit within the range of sensory fusion, wherein the point of convergence never varies more than a small distance (± 0.3 prism dioptres) from the focal accommodation at the plane of the screen. At this range, retinal images are observed to remain sharply focused (Charman & Whitefoot, 1977; Marcos et al., 1999). Content producers are encouraged to limit screen disparity to two percent of screen width (see Section 1.5.5: Industry Standards for Stereoscopic Production).

This distance (or detail) around the screen is known as the zone of comfort (ZoC) (Shibata et al., 2011a). However, the real world contains much larger parallax values that can be represented solely within the sensory fusion range, and a nonlinear compression of the natural parallax values in a scene that fit within this range will often lead to distortion, at least mathematically.

It bears repeating that, due to the relationship between IA and IPD can give rise to gigantism ($IA < IPD$) and dwarfism ($IA > IPD$) (Lipton, 1997). It is noteworthy that gigantism does not have the noticeably marked effect on viewer perception that would be expected (Benzeroual et al., 2011; Harper & Lotto, 2001; Kurtz, 1937; Masaoka et al., 2006) (For a fuller discussion, see Section 1.6.4: Vergence-Accommodation Conflict: Applied Principles). Also, using a matched focal length greatly reduces these apparent effects, whereas a wide-angle lens exacerbates miniaturization.

Important insights influence the long-standing debate regarding orthostereoscopy (Harper & Lotto, 2001) and the requirement for life-sized reproduction (elicited when IA matches the IPD). Scale distortions from changing IA do not result in shape distortions provided HIT is set to match the typical IPD (Bickerstaff, 2012). Therefore, the emphasis of this debate has rested disproportionately on IA as opposed to the HIT. Also, due to acquisition field of view (FOV) almost never being matched to the angle of view (AOV), as Read and Bohr (2014) and Bereby-Meyer, Leiser, and Meyer (1999) report, there is limited purpose in making the acquisition IA life sized, especially when a near-standard lens is used.

However, in compression of the parallax values to achieve the zone of comfort even under orthostereoscopic conditions such that $IA = IPD$, the point at which the images triangulate is closer to the viewer than it would be in reality. Therefore, the image is under-converged relative to the eyes' convergence in what could also be described as a foreshortening of perspective with significant shape distortion, creating a stretched effect as the background image occupies a larger stereo space, emerging from within the screen space to the screen plane. For example,

converging to a 20-mm HIT instead of a 60-mm HIT results in a 90° angle being flattened to approximately 150°.

We argue that this geometric distortion and the cue mismatch created by the compression of the parallax after image acquisition causes discomfort as the eyes attempt to reconcile the disparities between the real world and the forced perspective of the stereoscopic image (Howard & Rogers, 2012). The necessary correlate of this argument is that comfort is linked to an absence of perspectival distortion and that, therefore, employing higher parallax values with the correct HIT matching the IPD, is better. Motor fusion in this context is non-effortful and automatic.

Vergence movements have been demonstrated to be influenced by prior knowledge of a scene in what Enright (1984) refers to as perspective vergence. Horwood and Riddell (2012) demonstrate that a cloud (far away) evokes a divergent eye movement towards parallel, whereas a coffee cup (near) evokes a convergent movement. Thus, comparing different real-world scenes interchangeably, as is common practice, introduces a confounding factor. Consequently, the convention is taken in our experiments to use artificial scale and context-ambiguous hinge stimuli with the caveat that real-world objects may well evoke unpredictably different responses that could affect both distortion and comfort ratings.

Previous publications have largely focused on out-of-the-screen stereo content (Bruder, Argelaguet, Olivier, & Lécuyer, 2016; Qian, Wang, Lan, & Li, 2013; Shibata et al., 2011a), for which accommodation and convergence are equal. Since in-the-screen content contains accommodation-vergence discrepancies and, considering Ravikumar et al. (2011) identified these discrepancies as potential sources of visual fatigue, this hypothesis was timely and appropriate.

This informs H₄: The vergence-accommodation conflict is more pronounced out of the screen than into the screen.

1.6.6 Relationship between Image Comfort and Distortion

Extensive research has been performed on random dot stereogram-based stimuli (Harris & Parker, 1992; Landy, Maloney, Johnston & Young, 1995; Tyler & Clarke, 1990). Disparity-based stimuli produce predictable results for both distortion and comfort metrics. Human performance shows little deviation from mathematical prediction; the amount of disparity present in a scene dictates the shape of the stimulus and how comfortable it is to the observer.

The next stage from disparity-based stimuli is to introduce monocular cues as to shape. Here, a large amount of literature is based on the relationship between linear perspective and disparity cues (Grove, Sachtler & Gillam, 2006; van Ee & Erkelens, 1996) and on cue combination models such as the modified weak fusion model (Landy et al., 1995; Winkler & Min, 2013).

For instance, Banks, Held, and Girshick (2009) examined stereoscopic distortion in detail for simple hinge objects. Their stimuli were defined by a regular textured grid, and they investigated the perception of the non-stereoscopic hinge as a control. Their first experiment concluded that the perceived angle was commensurate with the drawn shape and did not find a bias. Hence, it can be concluded that monocular cues in isolation do not cause distortion. Harris (2014) had already demonstrated that stereoscopic cues in isolation do not cause distortion. Combining monocular and stereoscopic cues, Banks et al. (2009) found no distortion. (For a fuller discussion of this material, see Section 1.7.2: 3D Percept Distortions.)

However, Banks et al. (2009) always used conditions approaching orthostereo, where the camera stereo base, convergence point, and field of view matched that of the observer. It is this point that is important, since even for single-observer situations, the chances of all the stereo projection factors matching the position of the observer are very low, excluding head tracking.

The most conclusive study of stereoscopic image comfort was that of Shibata et al. (2011a), which measured the impact of a controlled accommodation-vergence conflict on comfort. From this study, the authors extrapolated the amount of disparity that would be required to maintain a comfortable image at different accommodation/vergence ratios. Some studies have investigated this by examining the effects of stereo display parameters on complex visual scenes (Yamanoue, Emoto & Nojiri, 2012; Vatolin et al., 2013; Voronov et al., 2013). However, these studies used existing scenes from commercial video content for which the display parallax was obtainable (for instance, the amount of screen disparity at any one time). What cannot be obtained automatically were the acquisition settings, that is, the camera interaxial, convergence point, and field of view measures. Vatolin et al. (2013) and Voronov et al. (2013) identify other areas capable of causing discomfort such as disparity budget, vertical disparity, and colour mismatch. Of these, the disparity budget is most relevant.

The disparity budget represents the total amount of parallax information on the screen (see Section 1.5: Issues in 3D Stereography). Vatolin et al. (2013) and Voronov et al. (2013) also describe scenes where the amount of parallax is higher than the recommended values. Yamanoue

et al. (2012) measure the comfort of participants on a five-point Likert scale for various placements in parallax. In summary, the comfort literature currently reflects on granular issues with regard to abstract scenes and very high-level uncontrolled scenes.

Previous publications have demonstrated a link between parallax distribution and visual comfort. Nojiri et al. (2003) and Yamanoue et al. (2012) report that parallax distribution demonstrated the strongest correlation with viewer comfort. Other researchers report a similar relationship between image parallax and visual comfort (Banks et al., 2009; Choi, Kim, Choi & Sohn, 2012; Ide et al., 2002; Lambooj et al., 2011; Lee, Jung, Sohn & Ro, 2013; Pastoor, 1995; Shibata et al., 2011a; Tian et al., 2016).

Nonetheless, circumstances exist in which conservative parallax values trigger visual discomfort while higher distribution is, in turn, viewed comparatively comfortably. This study was intended to investigate this claim. Indeed, the researcher argues that the forced limiting of parallax distribution to comply with the zone of comfort (ZoC) (Shibata et al., 2011a) by matching the interaxial (IA) separation to the interocular distance (IPD) introduces geometric distortion and cue mismatch. The latter two, in turn, are responsible for eliciting perspectival distortion (Bereby-Meyer et al., 1999; Howard & Rogers, 2012), thereby pointing to the advantage of using higher screen disparity values with correct camera convergence. In this study, the authors define camera convergence to mean matching HIT to IPD. While image parallax determines the ease of fusion for stereo viewers by modulating image distortion (Ide et al., 2002; Woods et al., 1993; Yamanoue et al., 2012), we argue that parallax (arcmin) is independent of angular distortion. By extension, it is hypothesised that matching IA with IPD is in itself a distortive process that encumbers the objective of the stereographer to create comfortable stereoscopic content.

This informs H₂: Parallax is, firstly, not correlated with comfort and, secondly, is not correlated with distortion (i.e., angular distortion).

1.7 2D and 3D Geometric Distortions: The Relationship between Angular Distortion and Comfort

Distortion is not restricted to stereoscopic content. Viewing 2D content can also be distortive. Therefore, this section addresses the causes of distortion in 2D and 3D projections and describes going from a 2D, or pictorial, projection to a 2D image separated by HIT. This argumentation also shows the distortive effect of looking at a normal 2D image binocularly, an effect that vision science literature has failed to consider but one that is a vital missing step. The section also

demonstrates the degree of differences in disparities when HIT matches IPD (i.e., $HIT = IPD$) and is undistorted, and, equally importantly, when HIT exceeds or is smaller than IPD (i.e., $HIT < IPD$ or $HIT > IPD$, respectively) and hence is distorted.

1.7.1 2D Geometrical Distortions

2D imaging elicits a range of distortions and artefacts, including barrel distortion, that, in turn, affect blur (Pockett, Salmimaa, Pölönen & Häkkinen, 2010; Solimini, 2013) and play a larger role in triggering visually induced motion sickness (VIMS) (Hettinger & Riccio, 1992; Keshavarz et al., 2014; Solimini, 2013). Despite the reported distortion inherent in the two-eyed viewing of pictorial images, this distortion, to the best of our knowledge, is understated in the literature with the exception of a single publication (Ujike & Watanabe, 2011).

2D geometrical distortions are especially vivid at small viewing distances or during fixation. For instance, if one were to hold a mobile phone directly in front of one's face, it would look like two trapezoids since there would be no image disparity other than vertical retinal disparities. Also, if one were to fixate at the centre of a picture, a similar situation would result in vertical disparities that increase the further from the centre of fixation one goes. Prince and Rogers (1998) report that as, one moves away from the foveated or reference position, disparity—or, more accurately, angular disparity (AD)—becomes negative and gets positive towards the said position to the point that it eventually assumes zero disparity.

Hence, distortions at the very periphery of the visual field, even for 2D images, are easily unnoticed (Bex, 2010; Hwang & Peli, 2014). Due to this falloff of depth discrimination, it is important for researchers to calculate depth discrimination thresholds (in seconds of arc) and the distances necessary to exceed said thresholds. For the purposes of this study, it is instructive to point out that Prince and Rogers (1998) arrived at a peak peripheral sensitivity threshold of 11 arcsec.

The geometry of stereo 3D projection and its relationship with 2D perspective projection is well understood and further extends the point of 2D or pictorial distortion. Kooima (2009) and Du, Hu, and Martin (2013) provide exhaustive discussions of the assumptions inherent with and techniques used for perspective transformations and off-axis projection. Perspective projections must still be referenced to the IPD to achieve naturalness realism in 3D projections, (Grinberg et al., 1994), bringing us full circle to this study's examination of HIT and the orthostereoscopic condition.

Once again, 2D pictures look distorted because the average distance (c. 60 mm) between our eyes introduces vertical retinal disparities at a picture's edges when we fixate in the centre of the picture, ideally at the centre of projection (CoP) (described later). When an observer is very close to a large picture, points that are away from the "sweet spot"—as already argued, at the middle of said picture—will be out of retinal registration. Moreover, the further away the observer moves from the picture, the larger the sweet spot becomes, as disparity is perceptually reintroduced from the middle outward.

Indeed, as either a) the observer-picture distance increases, b) the viewer's IPD is artificially decreased with a viewing device, or c) the viewer's IPD is artificially decreased by shifting the HIT of the left and right 2D images with 3D glasses, the size of the "sweet spot" increases. The "sweet spot" is the area of perfect fusion with retinal disparities less than the stereoacuity threshold of 20 arc seconds. As the IPD tends towards zero (or the HIT becomes closer in size to the IPD), then, when there are no disparities between the left and right images so that $HIT = IPD$ or IPD is zero with a viewing device (such as the synopter), the "sweet spot" expands to fill the entire image. (Refer below for a discussion on synoptic viewing.) Then, the whole image is in perfect retinal registration between the left and right eyes.

Assuming an equal field of view, 3D pictures appear distorted for the same reason. Of key importance, introducing a correct HIT—in this case, an $HIT = IPD$ —means that the infinity, or horizon point of the image (terms used interchangeably), is set at optical infinity with the eyes parallel, meaning that there are no vertical retinal disparities in the left and right images at the infinity or horizon point. For any stereoscopic image, matching the infinity point to the IPD will mean there is no shear distortion. There may be gigantism—caused by a narrow camera baseline—or miniaturisation—caused by an excessive camera baseline (Koppal et al., 2010), but the shapes of objects from front to back should be consistent. Underlying this, IA is used predominantly for scaling, while HIT is used for parallax correction and, therefore, for alleviating distortion.

Therefore, when HIT—a parameter yoked to the camera baseline—is not equal to IPD—an eye baseline, the effect is a distorted image. HIT greater than IPD indicates a diverged image and so not modelable since the infinity point is beyond infinity, thereby restricting the theatre space. For this reason, HIT equal to IPD is correct, and this statement (i.e., $HIT = IPD$) thus forms the default "initial case" for this study. Stated otherwise, we indistinguishably combine IA and HIT

to form camera separation. Consequently, from now on, we refer to IA/HIT as Camera Separation.

A baseline in which HIT is closer than the typical IPD, specifies the infinity point as being at, for instance, 3 m away, meaning that the infinity point is specified as being closer within the room so that all of the nearer disparities are artificially shifted. This causes distortion, which causes the angles to be perceived differently. Stereographers increase IA or even decrease the angle of the physical shape to mitigate this, but the result is inevitably less comfortable since such approaches are inherently flawed. This logic is diagrammatically illustrated below in Figure 1-21.

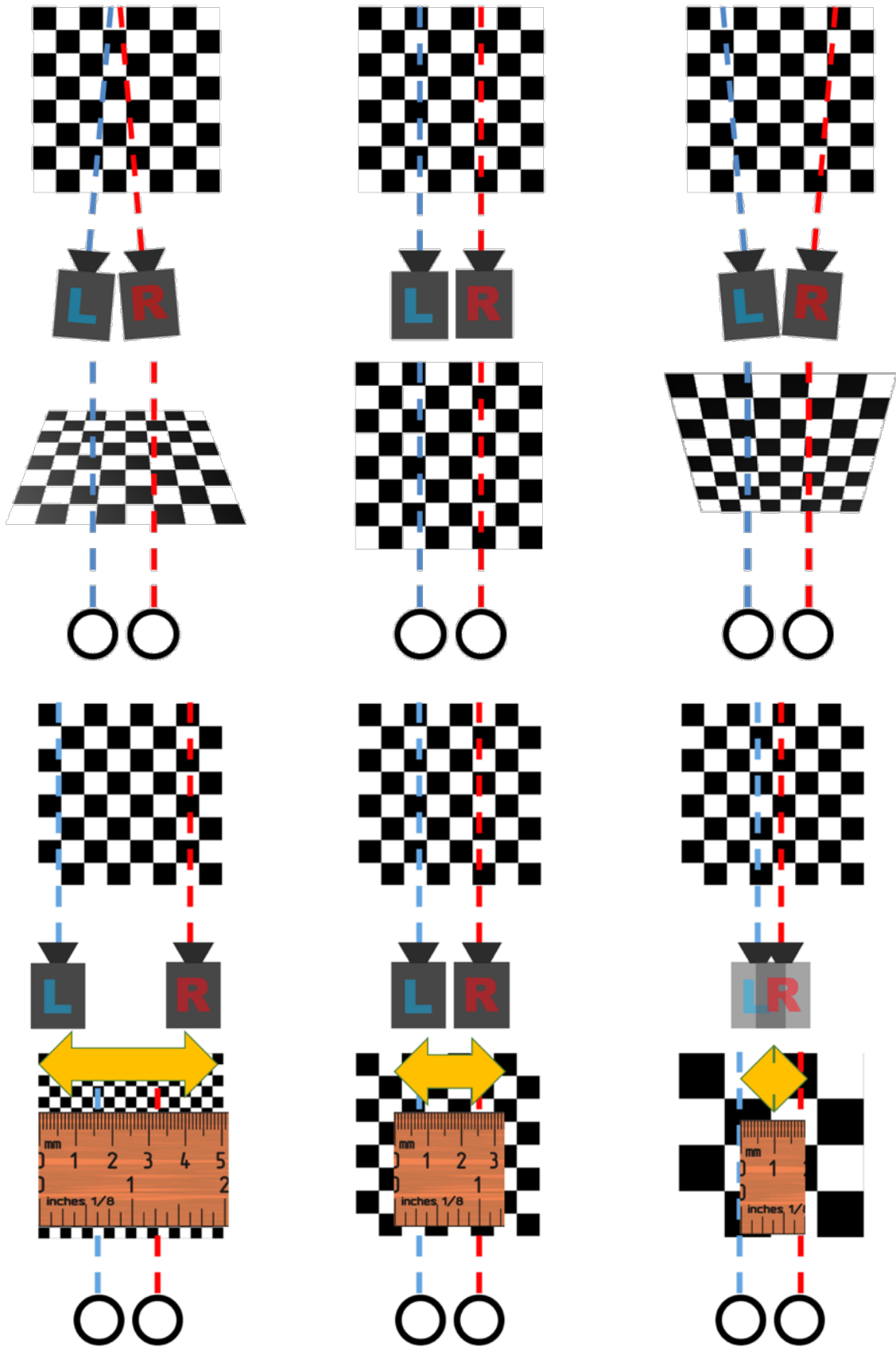


Figure 1-21. Illustration of how HIT warps image depth (top) and how IA affects scale (bottom).

Figure 1-21 shows, firstly, that changes in the offset between the left and right image frames on the screen (HIT) affect depth. Secondly, the figure shows that changes in the horizontal distance between the left and right cameras (IA) affect image scale (for a fuller discussion, see Section 1.6.4: Vergence-Accommodation Conflict: Applied Principles). This figure illustrates the challenges of producing a stereoscopic image that is both comfortable to view and faithful to its original content by creatively increasing IA against the HIT. This flawed approach, consequently, makes it that much more difficult for all observers to experience an optimal image exactly as the creator intended.

These findings are in line with previous findings of distortion for off-axis or dislocated viewing positions (Kubovy, 1988; Rosinski, Mulholland, Degelman & Farber, 1980).

Figure 1-22 shows geometrically predictable distortions for off-axis viewing of correctly converged stereoptic stimuli at different viewing distances (Bereby-Meyer et al., 1999).

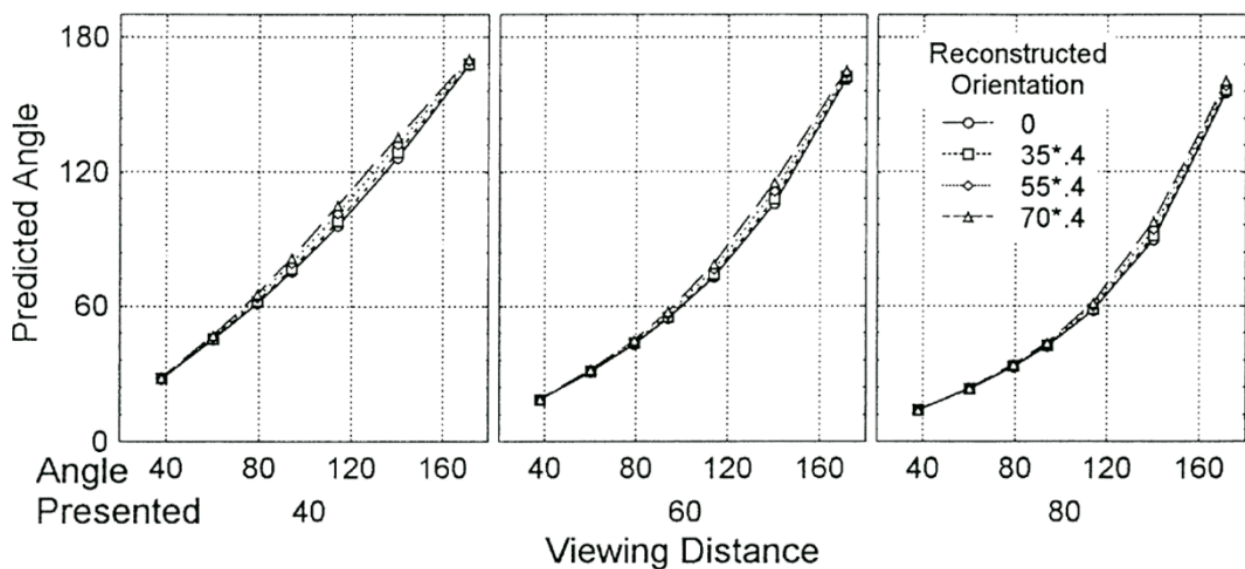


Figure 1-22. Geometrically predictable distortions for off-axis viewing of correctly converged stereoptic stimuli at different viewing distances (40 cm, 60 cm, or 80 cm) indicating that viewers are capable of partial compensation during oblique viewing (adapted from Bereby-Meyer, Leiser & Meyer 1999).

Figure 1-23 plots experimental data on visual compensation for oblique viewing in the stereoscopic condition. The coloured lines represent different viewing conditions, namely, binocular 3D (red), binocular 2D (blue), and monocular (green) across different viewing angles. Despite these noted similarities in distortions between the viewing conditions, the researchers did not investigate any differences in comfort scores from stereo 3D and 2D viewing conditions.

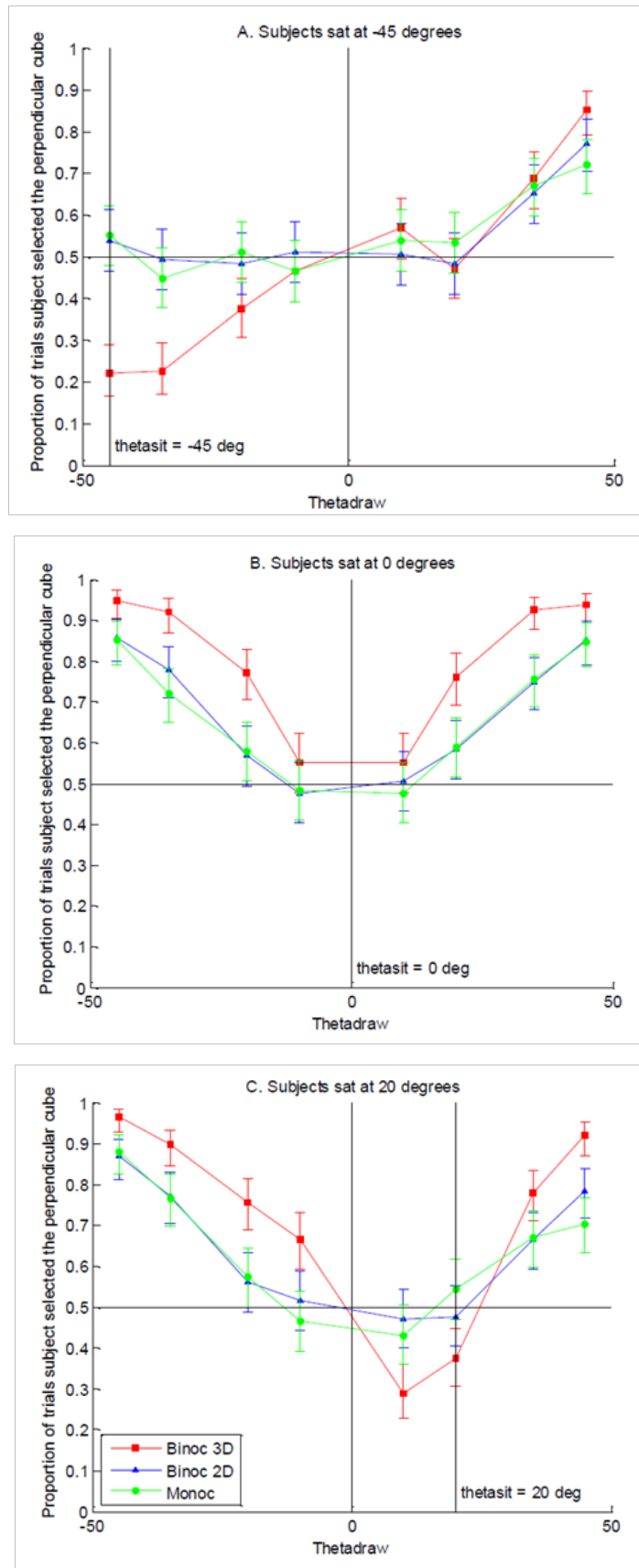


Figure 1-23. Hands, Smulders & Read (2015) report that veridicality and the effects of off-axis viewing (0, 22.5, and 45 degrees) of 3D are very similar to off-axis 2D stimuli except at extreme angles.

A significant gap emerges in the two studies shown in Figure 1-22 (Bereby-Meyer et al., 1999) and in Figure 1-23 (Hands et al., 2015), respectively. Bereby-Meyer et al. (1999) modulate the viewing distance while Hands et al. (2015) study the impact of viewing angles. Importantly, both studies use stimuli that are correctly converged. It remains unclear what happens with incorrectly converged stimuli.

Interestingly, the use of the monocular viewing condition by Hands et al. (2015), denoted by the green line in Figure 1-23, has similar motivations to research conducted by Black et al. (2006). In their publication, the authors noted that the removal of horizontal disparity with a synopter (giving rise to the term synoptic viewing (Arnoldussen et al., 2013; Harper & Lotto, 2001; Wijntjes et al., 2016)) and the coulisse effect (Anderson, Anderson & Bordwell, 2007) enhanced perception of a pictorial 2D relief and are advantageous in scenarios where depth cues are absent or plausibly ambiguous, as in the case of incorrectly converged images.

This logic also borrows markedly from the relatively obscure and little-appreciated works of Raymond van Ee (Kooi, Dekker, van Ee & Brouwer, 2010; van Boxtel, 2008; Vergeer, 2016). Specifically, van Boxtel (2008) notes that the removal of monocular interactions equates monocular, binocular, and stimulus rivalry behaviours, while Kooi et al. (2010) and Kooi (2010) report that Real3D increases the perceived depth over the anaglyphic format without cancelling stereo-anomaly. On a related note, Vergeer (2016) indicates that training of binocular rivalry suppression suggests that there is stimulus-specific plasticity in monocular and binocular visual processing.

1.7.2 3D Percept Distortions

Banks et al. (2009) investigated the perception of stimuli presented with monocular and stereoscopic cues to establish their relationship to distortion. Banks et al. (2009) presented the open end of a stereo hinge, defined by a regular textured grid, in front of and toward an untracked observer similar to how one would read a book. In addition, the study's stereo stimuli were presented at eye-level such that the viewer had a fixed point of view (PoV) in the fixed tracking (FT) stereo perspective.

Furthermore, the selected wireframe texture provided the only monocular cue to depth, linear perspective. Participants were required to determine their perception of the 90° angle from a centre of projection (CoP) and upon displacement from the CoP. The study showed that

stereoscopic image distortion increases when participants experience angular displacement from the centre of projection (CoP), as is often the case in multi-viewer environments.

An equally significant finding from the study was that perceptual errors elicited by viewer displacement from the CoP were nearly statistically identical to the predictions from a standard ray-intersection model. The success of this intersecting-ray approach suggests that perceptual distortions in stereoscopic viewing conditions can be accounted for by epipolar geometry. The relative accuracy of this geometric model was confirmed in stereo viewing conditions presenting monocular cues in a previous study (Vishwanath, Girshick & Banks, 2005) and in a more recent publication (Pollock, Burton, Kelly, Gilbert, & Winer, 2012). Woods et al. (1993) and Held and Banks (2008) also demonstrated the utility of a similar ray-intersection stereo approach.

Crucially, the assumption that a purely stereo geometrical model could accurately predict and account for perpetual distortions in S3D viewing had not been evaluated prior to the publication of the Banks et al. (2009) study. Furthermore, these findings explain the lack of viewer compensation in off-axis viewing, although Vangorp et al. (2013) contend that this failure to compensate is a function of distance from the stereo stimuli. Several other authors advance similar arguments (Adams, 1972; Cooper, Piazza & Banks, 2012; Hands et al., 2015; Lumsden, 1983; Todorović, 2009).

Interestingly, the unavailability of additional monocular cues may have adversely affected the ability of the research participants to compensate for oblique viewing (Burton et al., 2012). Such a non-compensation is especially probable given that 2D scene projections contain all the visual cues available for stereoscopically projected images save for binocularity (Kelly et al., 2013; Piryankova et al., 2013).

Granted, Banks et al. (2009) compared the participant perception of non-stereoscopic and 3D stimuli. However, only two participants were exposed to this experimental setup. Hands et al. (2015) disputed the failure of compensation during off-axis viewing, reporting that viewer compensation stubbornly persisted even in stereo 3D conditions.

Returning to Banks et al. (2009), the first of two experiments dealt with the 2D case (i.e., with conventional pictures as stimuli) with the stimuli binocularly presented 45 cm from the viewer at a fixed point of view. That is, the observer did not move, but, rather, the hinge rotated around

a vertical axis to achieve angular displacement from the CoP. Once again, the stimulus was presented on a monocular display in a wireframe texture.

For the 2D case, a hinge stimulus with a wireframe texture (Figure 1-24) was presented to the two observers ($n = 2$) on a conventional 21" NEC flat-screen CRT monitor. The display was rotated about a vertical axis with the rotations corresponding to different viewing angles for the static observer, ranging from a frontoparallel viewing position (the CoP condition) to oblique angles to the left and right. In this respect, the researchers defined the viewing angle as the angle between a line from the 2D hinge to the centre of projection and a line from the hinge to the viewer. The viewers were required to judge the perceived angle of the 90° vertical hinge stimulus.

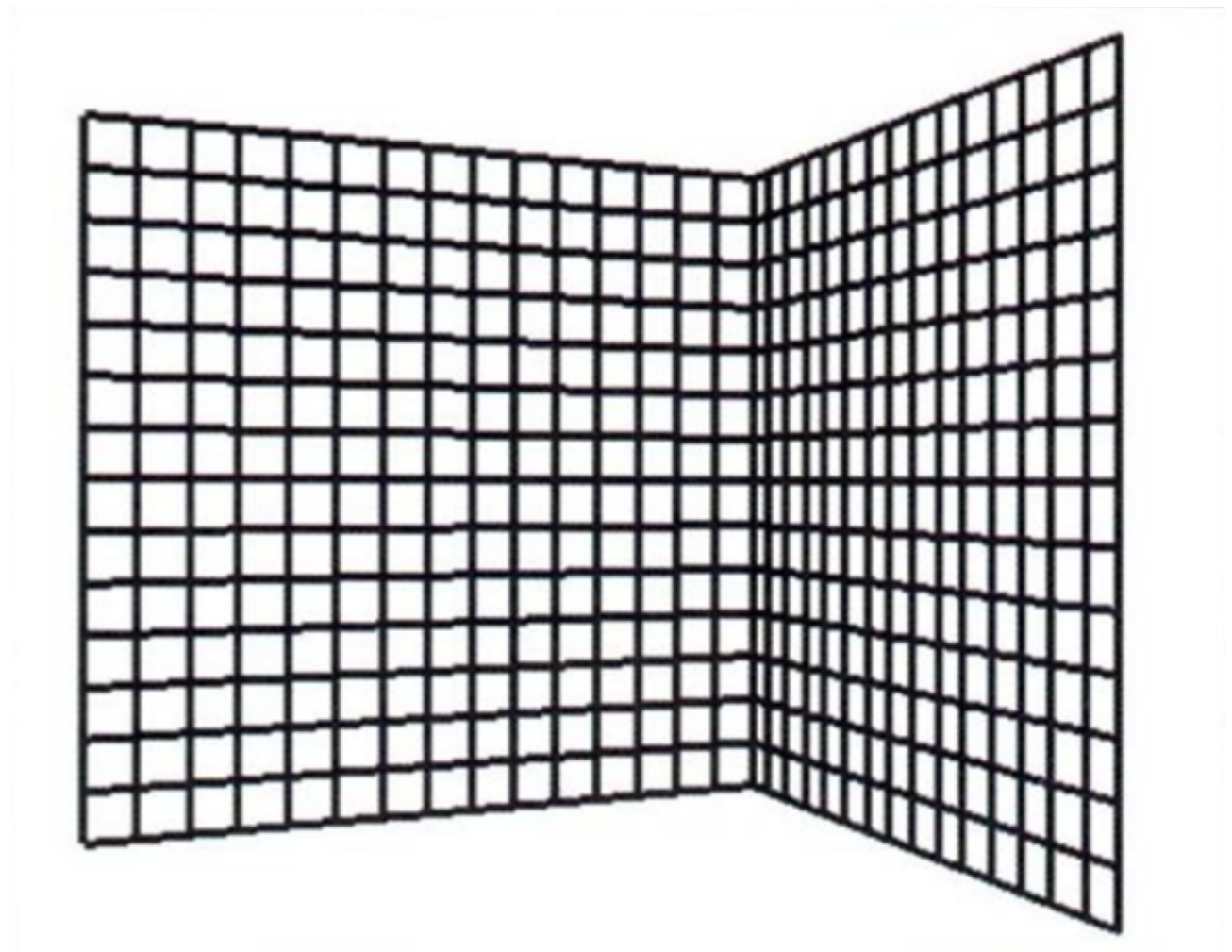


Figure 1-24. The wireframe-textured hinge stimulus presented in the 2D experiment (adapted from Banks et al., 2009).

Figure 1-25 shows data for two subjects initialised as DMH (left) and HFR (right). The dashed coloured lines represent the no-compensation predictions at different displacements. The horizontal black lines at 90° represent compensation prediction, and the dashed coloured curves represent results of actual viewer perception, with each colour or line representing a different base slant. The predictions were calculated using a standard ray-tracing algorithm. The 2D experiment showed that compensation during off-axis viewing for the 2D stimulus remained generally intact; the authors found that subjects perceived the angle of the 2D stimulus essentially correctly, provided they were viewing the display binocularly. This was consistent even when they were more than 20° from the centre of projection (CoP).

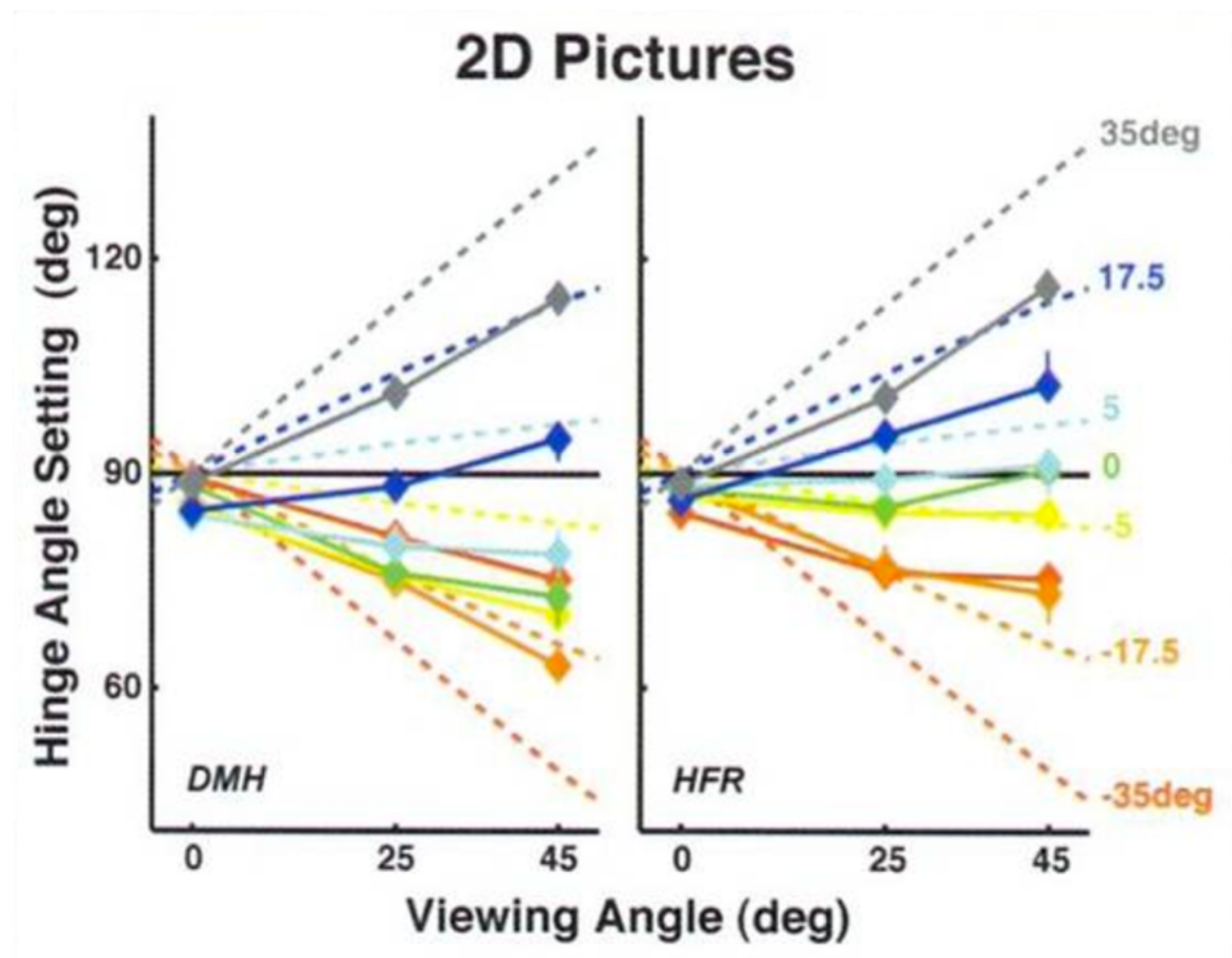


Figure 1-25. Ray-tracing predictions and experimental results for the 2D experiment for participants DMH (left panel) and HFR (right panel). The horizontal black lines represent the compensation prediction and the dashed coloured lines represent the no-compensation predictions (adapted from Banks et al., 2009).

In the second experiment, the researchers dealt with the 3D case (i.e., stereo pictures), with the stimuli presented along stereo display parameters (Banks et al. 2009). In both experiments, the

selected hinge was similar: a vertical stimulus with a 90° hinge. Its stereoscopic presentation simulated the following parameters: image acquisition from a parallel stereo camera configuration with an IA of 6.2 cm and a 6.5 mm focal length presented on a 21" display as a 30x30 cm vertical hinge with a picture magnification of 69.2. Once again, the "viewing angle" was manipulated by rotating the stereo hinge around a vertical axis.

Figure 1-26 shows the stereo hinge stimulus with stereoscopic simulation provided by viewing through liquid-crystal shutter glasses.

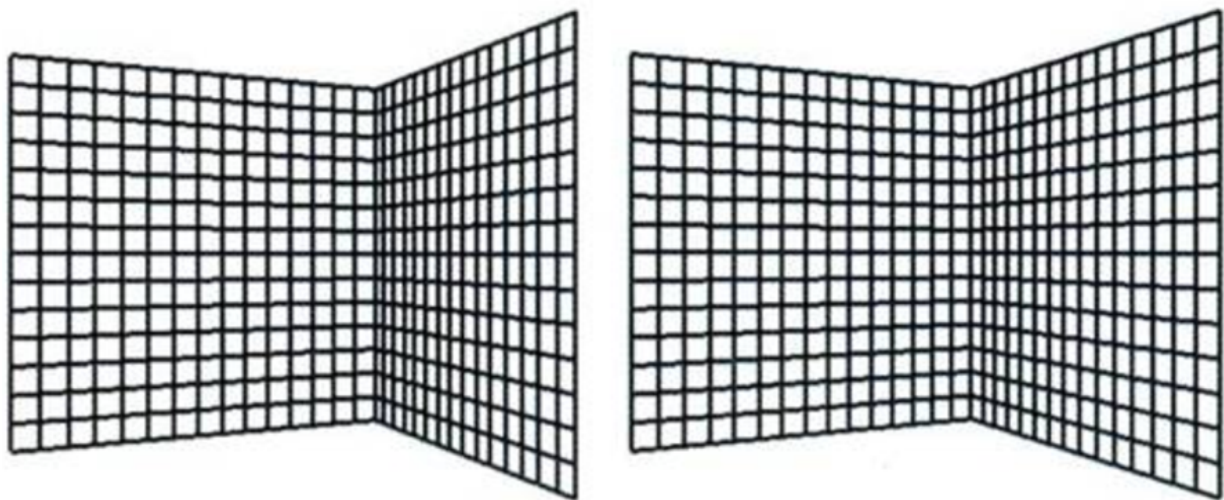


Figure 1-26. Cross-eyed view of the stereo hinge as used by Banks et al., 2009.

Figure 1-27 shows the results for two subjects initialised as DMH (left) and RTH (right) for the 3D portion of the study. As with the 2D case, data from the two subjects were plotted against the compensation prediction at 90° (i.e., the two horizontal black lines) with the dashed coloured lines representing the no-compensations predictions for viewing a 90° stereo hinge from different displacements. The dashed coloured curves, on the other hand, represent results of actual viewer perception, with each colour representing a different base slant. If the two subjects were able to compensate for incorrect viewing position, any hinge that was depicted as 90° would be perceived as such, and, therefore, the results would lie on the horizontal black lines at 90° . However, if the observers did not compensate for incorrect position and instead estimated the hinge angle from the retinal disparities, a 90° hinge would no longer be perceived as 90° . Consequently, the results would then follow the dashed coloured curves (Banks et al., 2009).

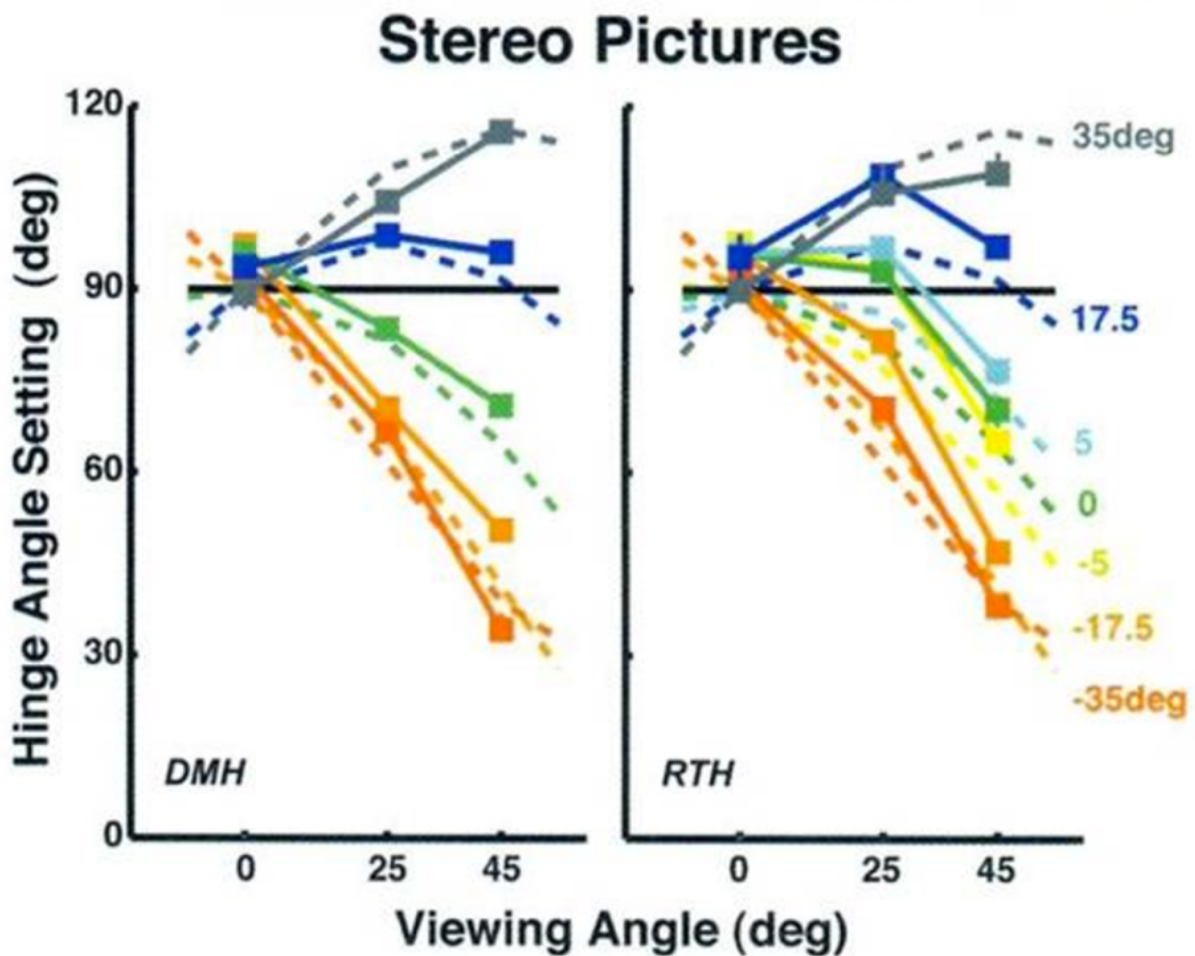


Figure 1-27. Ray-tracing predictions and experimental results for the 3D experiment for participants DMH (left panel) and RTH (right panel). The horizontal black lines represent the compensation prediction and the dashed coloured lines represent the no-compensation predictions (adapted from Banks et al., 2009).

The no-compensations predictions for stereo viewing represented in the dashed lines were nearly identical to the results: if observers used retinal disparities and did not compensate for off-axis viewing, the 90° hinge would be distorted. At short viewing distances, the perceived hinge angle would be obtuse and acute at larger distances. The 3D percept would also be significantly distorted under oblique viewing. These results reflected the predictions in the ray-tracing model for stereo viewing.

While Kooi and Toet (2004) demonstrated that the amount of 3D directly affected visual comfort, Banks et al. (2009), in turn, report that stereo 3D viewers were unable to compensate for incorrect viewing position; their study's viewers were unable to compensate for off-axis viewing but were able to report a right angle without bias. Thus, Banks et al. (2009) found that the predicted hinge

angle was a good indicator of perceived hinge angle for off-axis viewing (i.e., positional distortion as opposed to angular distortion).

Furthermore, the authors found that, when the IPD was 6.2 cm, the viewing angle was 0° , and the viewing distance was 45 cm, a stereoscopic hinge stimulus of 90° was perceived correctly as 90° . This is referred to as the point of subjective equality (PSE). However, when the viewer was positioned too closely to the screen, the perceived hinge angle was greater than 90° , whereas when this viewer was positioned too far from the screen, the perceived angle was less than 90° (Banks et al., 2009).

However, Hands and Read (2013) found that the human visual system (HVS) competently compensates for oblique viewing angles in 3D content (i.e., is tolerant of viewing stereoscopic 3D content even from the "wrong" position), except at extreme angles. Interestingly, even at the most extreme viewing angles, veridicality never declined below 62% of optimal perception (see Figure 1-23). This is a significant contradiction.

This informs hypothesis H₃: Distortion is affected by hinge placement on-screen while comfort is nuanced.

The configurational problem of stereoscopic presentation presented above is especially acute in cinema where every viewer in the cinema is seated at a different vector in the XYZ space. These differences, in turn, present unique viewing distances and viewing angles, both horizontal and vertical, that can elicit considerable perceptual distortions. One way to solve this problem would be to reduce capturing stereo content at fractional disparities so as to minimise potential distortion. However, this approach produces active but imperceptible disparity cues and does not eliminate distortions for off-axis viewers.

Another solution involves removing the accommodative load so that the convergence point can be independently manipulated for the different rows and seats. This can be achieved variously through the use of synoptic viewing devices (Arnoldussen et al., 2013; Black et al., 2006; Harper & Latto, 2001; Wijntjes et al., 2016). Another technique involves presenting a screen through an aperture in a blackout such that the screen's contextual information is not available (Banks et al., 2009; Knill, 2007). The latter technique is undermined by inter-individual differences in the natural fixation points of the different viewers' eyes.

Another solution would be to adopt the orthostereoscopic convention (Harper & Latto, 2001; Spottiswoode & Spottiswoode, 1953) on the grounds that naturalistic information distorts less from off-axis presentation. This solution is also constrained by substantial inter-observer IPD differences that cannot be dynamically emulated during scene capture or presentation. The inadequacies of the solutions introduced above in presenting comfortable stereo content to off-axis viewers are an important focus of this study.

Burton et al. (2012) report that lateral displacement from the centre of projection (CoP) markedly influences both distortion and comfort. Moreover, Li and Schonfeld (2014) demonstrate that viewer motion also generates stereoscopic distortions.

This relates to H₅: Distortion is not affected by viewer position, but instead, comfort is affected.

1.7.3 Summary

In summary, the premise described is that, firstly, having laterally separated eyes is distortive for viewing 2D images or 3D images perspectively projected onto a 2D surface. Secondly, the tolerable way to rectify this distortion is to transform the 2D surface using HIT so that the projected stereo image is frontoparallel to each eye (that is, HIT = IPD). Thirdly, not transforming the 2D surface using HIT results in intolerable amounts of distortion.

Indeed, viewing 2D images normally is in itself a very distortive process. It follows that looking at 3D images normally is also distorted, especially if HIT does not match IPD. This approach validates the orthostereoscopic condition and the superior viewing comfort of the observer that the approach elicits.

Calculating off a peak sensitivity threshold of about 11 arcsec (Prince & Rogers, 1998), this methodology affords researchers the ability to calculate what percentage of an image is in perfect registration below the stereoacuity threshold. Any values above the stereoacuity threshold are stereoscopically defined as a flat plane image. The only way to avoid having a stereoscopically defined plane is to place the image at optical infinity, by either using parallel cameras or HIT.

The whole content of the image is thus defined as being at infinity. Only then can disparities be dialled into the image to give an undistorted stereoscopic viewpoint without distortion. The issue is that HIT and IA can be specified separately and independently in CGI stereo, whereas in camera capture stereo, introducing IA inherently introduces HIT. Therefore, to cancel the HIT,

the camera lenses toe-in, but as the cameras move, HIT changes unless both IA and HIT are yoked.

Substantively, as long as HIT matches IPD, there is never image distortion. Hence, our normal 2D image perception is inherently distorted, unless HIT matches IPD such as with the synopter or when IA is 60 mm. The extant literature, while agreeing with this approach (Banks et al., 2009; Shibata et al., 2011a), glosses over the fact that maintaining the subject at the screen plane by linking IA to the camera convergence results in crossed disparities and distortion. In this sense, HIT should categorically never be used creatively. To avoid distortion, HIT must be slaved to IA so that camera horizontal separation changes result in a constant HIT.

1.8 Gaps in Research

Research into orthostereoscopic conditions has often been scant and theoretical. Current studies of stereoscopic comfort are based on screen parallax or the disparity budget and vertical disparity or colour mismatch using metadata from cinema releases. Conventional wisdom has been that controlling these variables will produce a comfortable stereoscopic image or projection. Where the role of distortion has been explored, it has mainly been studied using abstract hinge objects on neutral backgrounds in orthostereoscopic conditions.

On the other hand, real-world stereoscopic production seldom uses orthostereo conditions. Due to this lack of scientific investigation into comfort under the ortho condition, it is important to measure both comfort and distortion for typical IA, FOV, and camera convergence acquisition values used by stereoscopic content producers. Indeed, a significant amount of research has been conducted on display parallax, but limited amounts on acquisition factors, particularly IA, HIT, and field of view (FOV). A recent study by Yamanoue et al. (2012) focused on the amount of display parallax in the scene, abandoning work on acquisition settings previously undertaken. Banks et al. (2009) had a small number of participants with a controlled hinge stimulus, and Shibata et al. (2011a), in a separate paradigm, measured comfort with relation to accommodation/vergence conflicts.

To re-state the principle of orthostereoscopy, IA, an acquisition parameter, should equal the IPD of the observer, a human factor. The demand to match these two parameters, however, is unrealistic as it implies that viewers would have to adjust viewing distances and positions for every projected scene, which would, in turn, have to be continually re-calibrated. Furthermore, IPD distributions differ based on gender, age, and race.

In applied terms, this means that the scientific definition of autostereoscopy would be otherwise impractical in a literal and everyday broadcast setting. For this precise reason, research into the orthostereoscopic condition has been markedly depressed. Besides, due to the rarity of FOV-AOV matching (Bereby-Meyer et al., 1999; Read & Bohr, 2014) when using standard lenses, there is limited utility in making the acquisition IA be life-sized.

In addition, the reference material for a content producer to simultaneously answer (i.e., will this content look distorted or not, will it hurt or not) is not currently available. More clearly, there are no data for viewing conditions where the acquisition parameters are changed. Indeed, extensive research has been done into S3D display issues, that is, either how an image looks or how an image feels (Bando, Ijima & Yano, 2012; Lambooi et al., 2009; Lambooi, Ijsselsteijn, & Heynderickx, 2007; Yamanoue et al., 2012). However, there is no bridge between studies examining how S3D images are captured and displayed. The extent of this bridgeable gap can be stated as follows. Firstly, there are no known studies which simultaneously measure perceived 3D shape and user comfort on a trial-by-trial basis. Secondly, most psychophysics studies do not emulate the display errors of stereographers.

Regardless, several researchers have attempted an examination of subjective viewing comfort in ortho. Notable among these are the relatively dated findings of Yamanoue, Nagayama, Bitou, and Tanada (1998), later elaborated in Yamanoue, Okui, and Yuyama (2000), applied in Yamanoue, Okui, Okano, and Yuyama (2001), and sparsely “monographized” in Yamanoue et al. (2012).

Despite the practical limitations of ensuring naturalness, the ortho condition is ideal in certain situations such as in teleoperation works in nuclear stations with work being performed in confined spaces, some of them millimetres in diameter (Fuchs, Moreau & Guitton, 2011). The orthostereo condition is also an important dimension of immersion-based cinema and its most recognisable incarnation, IMAX 3D format (Zone, 2005), and several other devices and methods (Collar, Smith & Nolan, 2013; FrontNiche, n.d.)

Outside these findings, there is an absence of research into solving the problem of viewer discomfort as it pertains to the orthostereo condition. Where solutions have been proposed, they have been restricted mostly to calibrating viewing conditions and map projections (Benzeroual et al., 2011; Morris, 2010) with practically no investigation of acquisition parameters. The same, however, cannot be said for the impact of HIT.

Subjective tests reveal that IA, a central acquisition parameter, uniquely and markedly modulates binocular disparity (Yamanoue et al., 2000) and can therefore be used to manipulate parallax values. The disparity introduced by the horizontal image separation between camera lenses, best illustrated for the binocular stereo camera approach, can be modified in post-production by adjusting the horizontal distance between the acquired distance. This adjustment of the convergence point is accomplished through HIT.

Despite its prominent use in post-production, HIT is inherently yoked to both IA and camera separation and is crucial for the correct calibration of the parallax budget. Furthermore, Kytö et al. (2012) demonstrated that perceived depth is directly controlled by camera separation, meaning that scenes captured with, for instance, wide IA will have a large depth range, thereby distorting the perceived distance (Broberg, 2011) and leading to poor stereoscopic picture quality (An et al., 2011). In this context, HIT is used to prevent edge violations and divergence (that is, excessive positive parallax).

Evidently, stereo camera parameters have been shown to affect visual comfort (Nojiri, Yamanoue, Hanazato & Okano, 2003; Mendiburu, 2012). Also, the utility of HIT in alleviating viewer discomfort has already been established in both industry and academia (An et al., 2011; Broberg, 2011; Eickelberg, 2015; Hwang & Peli, 2014; Kim, Choi & Sohn, 2013; McVeigh, Siegel, & Jordan, 1996; Northam, Asente, Istead & Kaplan, 2013; Smith & Collar, 2012). (See also Section 1.5.2: Issues in Image Acquisition). However, there are formidable gaps in its utilisation.

For instance, an enduring debate concerns the limits of HIT optimisation in the cinematic setting and when broadcasting content for “home” 3D TV. This debate extends when the post-conversion of content captured with different interaxial settings for different screen sizes within a perpetual “zone of comfort” for viewers is contemplated. It remains unclear whether, as screen sizes decrease from cinematic proportions (with the IMAX format with an angle of view of 120°) to the smaller television (40°) and mobile device sizes (20°), the angle of view (AOV) should match that of the camera lens for an ideal stereo projection. Also, it is unclear what are the tolerance thresholds for positive (into-screen) and negative (out-of-screen) disparity for small and large screens and what are the thresholds in the orthostereo condition. Furthermore, there is a lack of generalizable production techniques on optimal interaxial settings that elicit greater

tolerances, consistent post-conversion approaches, and selection of the angle of view (AOV) and depth of field (DOF) for stereo camera lenses.

Another contentious topic revolves around adjusting the parallax budget using HIT in parallel and toed-in camera configurations and the attendant conundrum that it presents to stereographers. Crucially, there is virtually no extant literature on HIT optimisation in the orthostereo condition. Furthermore, there is little evidence of perceptual models for human factors when HIT and IA are adjusted.

To summarise, although a great deal of applied research is ongoing (Banks et al., 2009; Shibata et al., 2011a; Yamanoue et al., 2012), fundamental challenges exist regarding the true cause of distortion and comfort, and the answers to these questions will markedly impact the development of stereo 3D technologies.

This dissertation reports on experiments that sought to measure tolerances and thresholds of a predictive model of stereoscopic space for 3D content generators that require flexibility in acquisition parameters. Therefore, it was desirable to undertake a low- to mid-level study where image energy and intensity were kept constant, but stereo parameters were changed, thereby aiding in identifying what image attribute caused discomfort.

This research makes an important contribution to the body of work surrounding stereoscopic research by bridging the technical and perceptual issues in 3D image creation. It also introduces new data necessary for a new line of inquiry into the role of HIT and its impact on distortion and viewer comfort.

1.9 Significance of Research

As conceded, the cinematographic field lacks sufficient empirically derived information. and, while vision science is converging in terms of its knowledge base, stereo film production is diverging regarding flexible standards necessary to create realism in 3D content and viewer comfort. Moreover, there is little cross-pollination between academia and industry on applied principles of IA setting selection, HIT optimisation guidelines, and stereo production standardisation. Despite the persistent gap between vision science researchers and stereographers, an opportunity for dovetailing does exist.

However, as long as said gap exists, media professionals will continue to shoot in the proverbial dark. The three most important technical problems that curtail a deeper dovetailing are the expertise necessary to (1) ensure that the only difference between two images is horizontal disparity, (2) minimise on-screen parallax due to ghosting or eyestrain issues, and (3) avoid warping or size distortions based on adhering to minimising on-screen parallax. The limiting of on-screen parallax imposes an artificially near horizon, thereby making depth distortion inevitable.

Indeed, minimising on-screen parallax is predicated on parallax being the problem, and parallax is only a problem when HIT is incorrect. Also, avoiding warping or size distortions is possible because of the artefacts generated by production complexity or creative choice made by producers.

Furthermore, the psychological and stereo graphics communities often approach the task of reproducing reality from opposite ends. Where the former studies the human visual system (HVS) from the neurological and psychophysical standpoints, the latter recreate depth perception within the dire confines of cinematic art. As a result, one end of the stereoscopic community views stereo as a purely creative choice and the other end elects to define it purely mathematically, the issue here being that the stereographic community does not have access to empirical expertise necessary to utilise knowledge of human factors in enhancing the realism or “naturalness” of stereoscopic content. Indeed, vision scientists have access only to a remarkably small proportion of the published literature that has been practically implemented by content producers. This gap has had a material impact on the production and consumption of stereoscopic content.

Resolving these gaps and proposing a new line of inquiry into the interaction between human factors and stereoscopic acquisition factors has significance and industry relevance. As opposed to the over-simplified focus on horizontal or on-screen disparity, the capture IA is the prime determinant of scale-independent object size relations (Lin, 2015) and is critical to encoding for the live interaxial repurposing of appreciable orthostereoscopic content (Mendiburu, 2011).

A clearer understanding of how interaxial settings affect viewing quality is also essential in ensuring a safe viewing environment, engineering greater tolerance for ghosting, preventing frame violations, restricting artefactual and textural degradation, and facilitating post-production conversion of content with acceptable viewer-centric results. In totality, a greater understanding

of the interaction between human factors and S3D scene acquisition lends itself to ergonomically safe and naturalistic 3D.

Ultimately, insights gained from this analysis can be integrated into quality control solutions deployed by 3D broadcasters and other content producers. Additional benefits of this research include applying gained insight into angle of view (AOV) matching across different screen sizes, discerning the theoretical limits to the image size increases necessary to confer stereoscopicity, and, lastly, designing superior orthostereoscopic production techniques. Taken together, the flexible acquisition parameters proposed will enhance our understanding of stereoscopic content perception and may prove particularly valuable in reducing barriers to deploying the cinematic form of 3D content. The latter is especially relevant considering the high costs necessary to acquire S3D content.

1.10 Hypothesis Statement

There are two Independent Variables (IVs): Camera Separation, and Hinge Angle. In Experiment I, Viewing Distance is substituted for Camera Separation.

There are two Dependent Variables (DVs): Distortion (2AFC) and Comfort (Five Point Likert Scale).

H₁: An increase of viewing distance for stereoscopic stimuli should increase comfort due to the reduction in the vergence-accommodation conflict (VAC).

Consequently, we posit that, as viewing distance increases, viewer comfort does not degrade substantially. Experiment I tests this hypothesis directly by moving the display surface along five different viewing distances to give the appearance of a moving screen.

H₂: Parallax is, firstly, not correlated with comfort and, secondly, is not correlated with distortion (i.e., angular distortion).

Consequently, we argue that parallax has no predictive power, i.e., both image and display parallax are insufficient to predict viewer comfort. It is worth noting that this is the very premise of this study.

Hypothesis H₂ was tested by investigating whether comfort would be determined by the apparent departure from 90° (i.e., the angular disparity) as predicted by the ray-tracing model. The

experimental series, therefore, set out to ascertain whether comfort ratings could be predicted from changes in percept of the hinge stimuli. We performed a direct test of this hypothesis primarily in Experiments II and III. However, as with those two experiments, Experiments I, IV, and V also assessed the relationship between perceived distortion and comfort at the various acquisition and presentation settings introduced in Chapter 2.

H₃: Distortion is affected by hinge placement on-screen while comfort is nuanced.

Under experimental conditions, we anticipate that comfort would be determined by the apparent departure from 90°, as predicted by a ray-tracing model, and hence the nuance. Once again, this departure from 90° is also expressed as 1) the difference between the 2D angle rendered and the 3D angle predicted by the ray-tracing model and 2) changes in perceived shape. To elicit this relationship, this researcher placed a stereo hinge in front of the screen plane as reported in Experiments II and III.

H₄: The vergence-accommodation conflict is more pronounced out of the screen than into the screen.

Content presented out of the screen is said to be in negative disparity, known within the industry as negative parallax and hence a source of extreme confusion for the industry reader. That presented into the screen is in positive disparity, known in the industry as positive parallax, another source for significant confusion. Ultimately, we predict observing a perceptual bias between stereoscopic content presented with positive and negative disparity. To test this hypothesis, we conducted Experiment IV.

H₅: Distortion is not affected by viewer position, but instead, comfort is affected.

Experiment V tests this hypothesis directly by presenting stimuli at different viewing positions.

CHAPTER 2 - METHODOLOGICAL OVERVIEW

This chapter describes and justifies the methodological issues underlying the psychophysical methods used including procedural choices made and inclusion criteria selected relating to study participants; the stereo capture system selected to capture our selected stimuli, the selected texture, and display environment for presentation; and the experimental design and basis for data analysis.

2.1 Justification for Experimental and Procedural Logic

2.1.1 Experimental Methodology

The core of the methodology selected for use in this study was meant to support an investigation into how particular 3D camera separations (for our precise definition, see Section 1.6.4: Vergence-Accommodation Conflict: Applied Principles) affect viewer comfort ratings for stereoscopic 3D content. Indeed, this study investigated perceived distortion and comfort as a function of acquisition parameters—IA, FOV, and camera convergence angle. Also, methodological choices were made to investigate whether differences exist between viewer perceptions of in-the-screen and out-of-the-screen stereo content. Furthermore, the methodology extends an earlier study and claims (Banks et al., 2009) of an inability to compensate for off-axis stereo viewing but with a larger participant pool. Therefore, participants were asked to judge orthoscopically presented stereo hinges at different camera separations for their distortion by evaluating hinge angle and comfort.

2.1.2 Participants

All participants in Experiments I, II, III, IV, and V had 20/20 acuity with normal vision or corrected eyesight with correction of less than three dioptr spheres. The exclusion criterion was the inability to discriminate stereoacuity below 100 arc seconds as measured by the Titmus Fly Stereo Test (i.e., pre-screening) as shown in Figure 2-1. However, participant pools for all experiments were different.



Figure 2-1. Participant during one of several Titmus Fly Stereo Test pre-trial screenings in the study.

Stereoacuity pre-screening was justified as it provided robust experimental validity.

Also, selection of 100 arcsec as a cut-off was justified for several reasons. Firstly, it was reasonably within the range predictive for normal vision (Walraven & Janzen, 1993). Secondly, the selection accounted for the possible underestimation of thresholds due to use of anaglyphic (red/green) 3D glasses during the test (Heron & Lages, 2012; Yamada, Scheiman, & Mitchell, 2008). Lastly, it accounted for a possible reduction in stereoacuity following exposure to the stereo stimuli. Peli (1998) reports $a \geq 20$ arcsec reduction for 13% of participants, requiring a rest period to ensure recovery.

Moreover, the number of participants was selected so as to provide sufficient statistical power. Banks et al. (2009) had a small number of participants (hence the initials DMH, HRF, and RTH as the study used the experimenters themselves as participants), and, consequently, this foundational study lacked experimental power. Broadly speaking, it is possible that the study could not, as a result, inherently discern additional or different relationships between viewer comfort and stereoscopic presentation (Button et al., 2013).

Several rules of thumb related to power calculations for sample sizes are available; one such suggests $N > 30$ (Begg & Mazumdar, 1994; Berenson, Levine & Rindskopf, 1988; VanVoorhis & Morgan, 2007). The statistical underpinning behind these rules of thumb is that larger sample sizes confer higher powers.

Furthermore, the size of the participant pool in this study met and exceeded the standards prescribed by ITU-R BT.500-11 (ITU-R, 2002). The latter recommends at least 15 non-expert observers with no experience as assessors when subjective assessments are to be conducted. Logically, adhering to this guideline would preserve experimental reliability, consistently surface results that affirmed or nullified our hypotheses, and ensure generalizability of experimental results. Interestingly, other studies compensate for smaller participant pools by using a large number of stimulus presentations. For instance, in a study investigating the diplopia limits for S3D content using autostereoscopic content, Häkkinen, Takatalo, Kilpeläinen, Salmimaa, & Nyman (2009) exposed one of the study's three participants to almost 13,000 stimulus presentations. Our study used a reasonable amount of presentations, ranging from 250 trials in Experiments I to IV and 750 in Experiment V. These amounts were anticipated to eliminate the possibility of visuomotor and cognitive fatigue [also, see Ochs & Aminoff (1980), O'Toole & Kersten (1992), Sowden, Davies, Rose & Kaye (1996), O'Toole & Walker (1997), Maxwell (2004) for related commentary and Wilkinson (1999), Abraham & Russell (2008), Cohen, Cohen, West, & Aiken (2013), and Cumming (2013) for conventions]. We are confident that the sample size and effect sizes delivered robust statistical significance and a power level necessary to detect a variety of effects.

2.1.3 Stereo Capture System

A three-stage system was used to set up stereo capture (Bickerstaff, 2012). The first stage was to present an identical stereo image to the left and right eye. Second, the stereo window was separated by a chosen baseline, so that the images were shown on the display screen so as to match perception at the typical human IPD. Third, an IA appropriate to the desired amount of parallax was selected. Please see Figure 4-20, Figure 4-21 and Figure 4-22 for more details.

2.1.4 Display Environment

In the experimental series described in Chapters 3, 4, 5, and 6, participant responses were obtained using a Microsoft Sidewinder Pro gamepad with keystroke mapping through the JoyCur

application. The display environment was stereoscopic presentation software written by Ian Bickerstaff in OpenGL and C++, adapted by the author to display experimental trials and allow users to record responses and run on a Windows 7 PC. The experimental stimulus was a 3DS Max model in the .obj file format. The software draws two buffers in memory and then parses an OBJ file. The OBJ file was generated in Blender and contained a standard hinge in a build volume of 20 cm x 20 cm x 20 cm such that it could be presented at life size on an LG 21.5" 3D monitor (see Figure 2-2). The stereoscopic camera parameters could be set in the world files that contained the "scenes" used by the software. The order of these was randomised for each participant.

A computer-rendered format was selected due to initial challenges sourcing a stereo camera. Although we did tests with a DSLR camera on a slide bar, we ran into problems, necessitating a stereo rig and shift lenses. The rig, however, required its own set of parameters. Industry collaboration facilitated access to Bickerstaff's empirical software (Bickerstaff, 2012), allowing for manipulation of the convergence point and achievement of orthoscopic presentation.

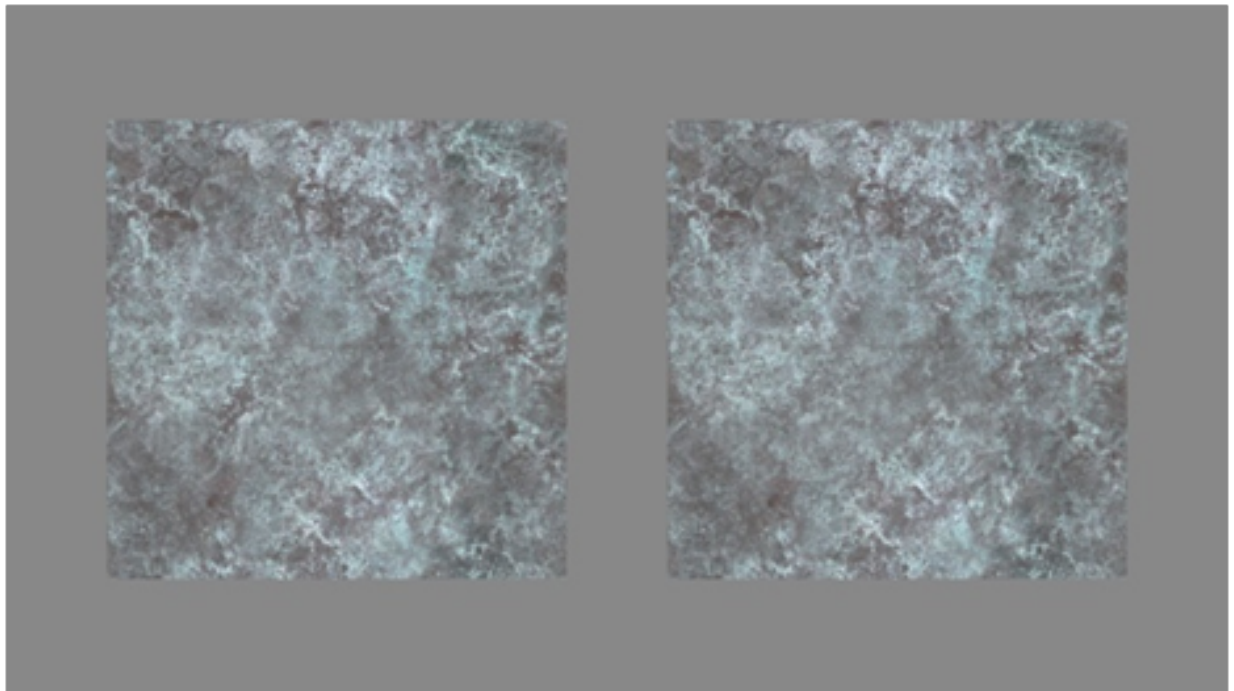
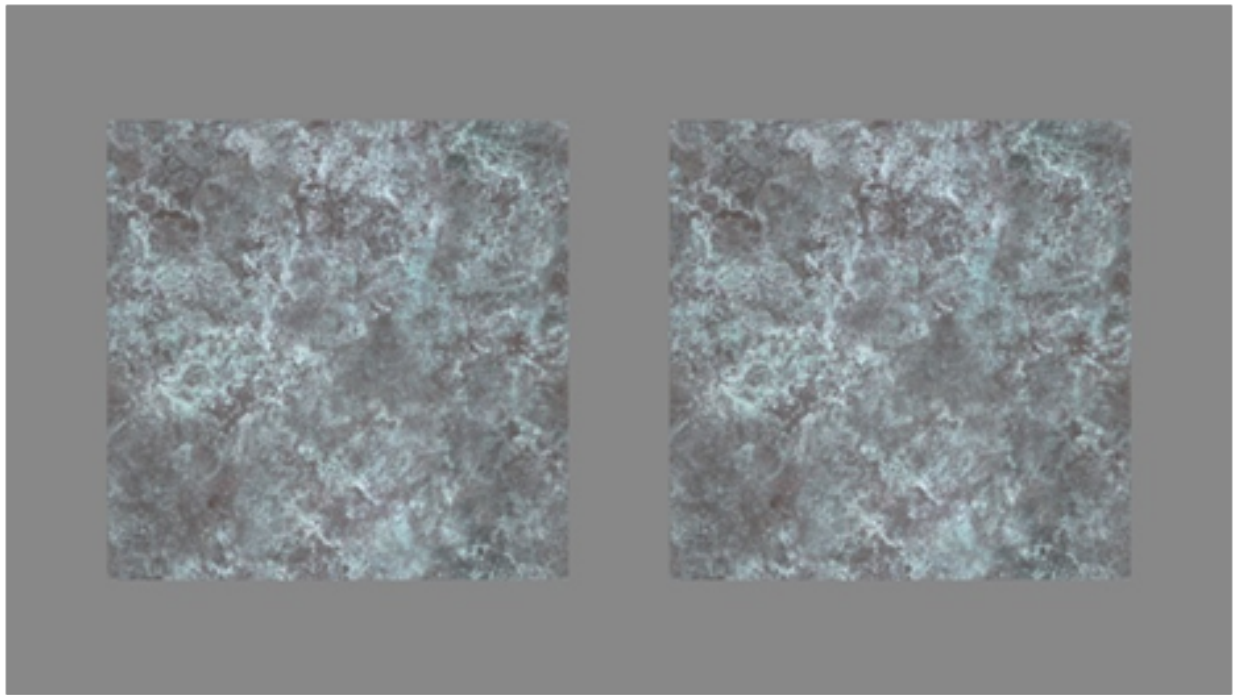


Figure 2-2. The experimental stereo images generated in the proprietary OpenGL-based programming environment modified to be an experimental display environment. The stimulus was a 3DS Max model in the .obj file format.

Although Bickerstaff's software was written from the ground up (with the notable exception of depth of field) to be a mathematically accountable model of stereoscopic rendering, it quickly emerged that distilling the code from this programming, and that from a foundational study

(Banks et al., 2009), line by line into Excel/MATLAB was necessary so we could actually see how to generate it. Also, this process taught us that there is a fundamental difference between, on one hand, CGI representations where HIT is dialled in separately and, on the other hand, photographic representations where changing IA arbitrarily changes the HIT simultaneously. Clarifying this was vital to generating correct models.

To verify the hinge geometry, a physical hinge replica was built out of LEGOs[®] to produce an exact right angle and was photographed on a standard lens with a 45° horizontal field of view at the same camera separations as in the subsequent experiments (that is, 20 mm, 40 mm, 60 mm, 80 mm, and 100 mm). The replica's texture was also input into the software. When viewed from the same viewing distances as the experimental stimulus, observers reported the physical object to subtend at an angle of 120° despite observers' knowledge that the object was, in fact, at a 90° angle. A validity check was completed so that the physical object was also calibrated to be an exact match for the computer rendering by placing the physical hinge and the virtual hinge next to each other on the screen plane as illustrated in Figure 2-3 below.

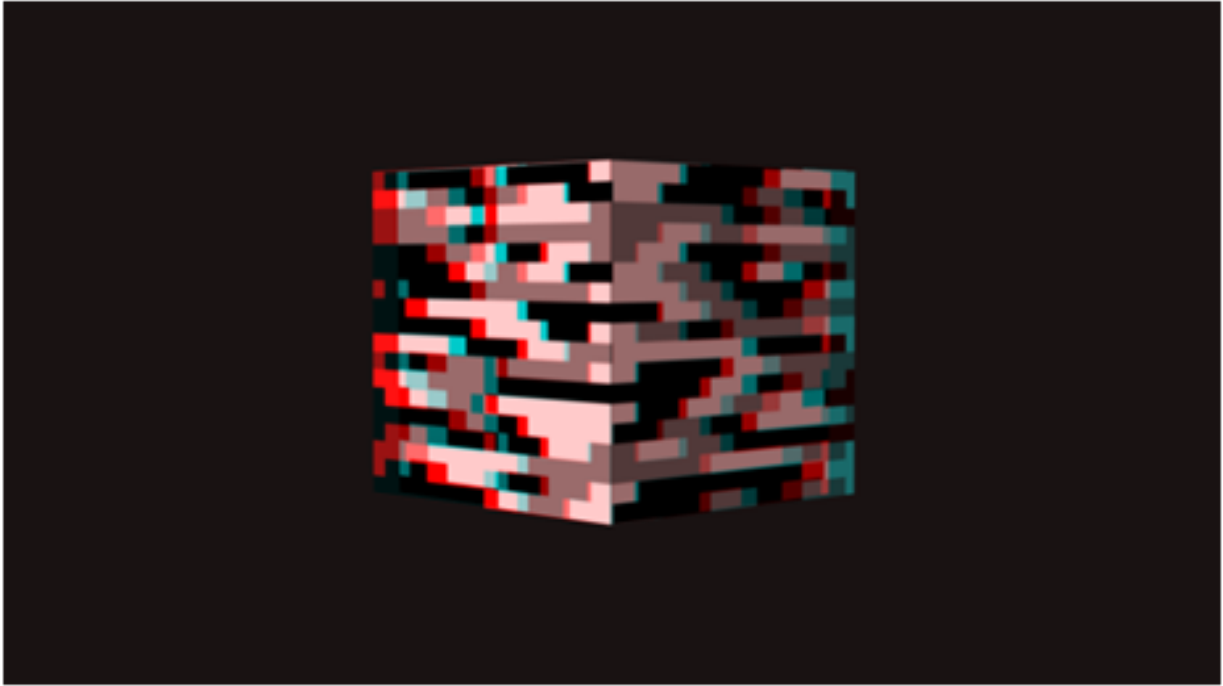


Figure 2-3. The physical hinge (top) and the virtual hinge (bottom).

The physical object was reported by a group of four observers to precisely match the stereoscopic rendered object in use of stereoscopic space (the front and back of the physical object matched the disparity-defined locations of the virtual object). However, the physical object was perceived as being flatter, possibly due to the limiting constraint of depth not normally exceeding width.

2.1.5 Stimuli

This study employed simple stereoscopic hinges as stimuli based on the approach used by Banks et al. (2009). The experimental stimuli were texture mapped using a high-resolution stock marble texture as denoted in the anaglyphic representation below (see Figure 2-4) and global lighting controlled to be uniform. The selection of the marble texture and uniform lighting minimised confounds from ghosting/crosstalk and controlled for lighting cues (Yamanoue et al., 2000) respectively. A pilot investigation (see Section 2.1.6: Methodological Issue: Texture Selection) had revealed that the wireframe hinge stimuli employed elsewhere (Banks et al., 2009) generated unacceptably high levels of crosstalk with our choice of 3D screen. The generic marble texture resulted in substantially less (albeit still visible) crosstalk (refer to Section 2.1.6: Methodological Issue: Texture Selection).

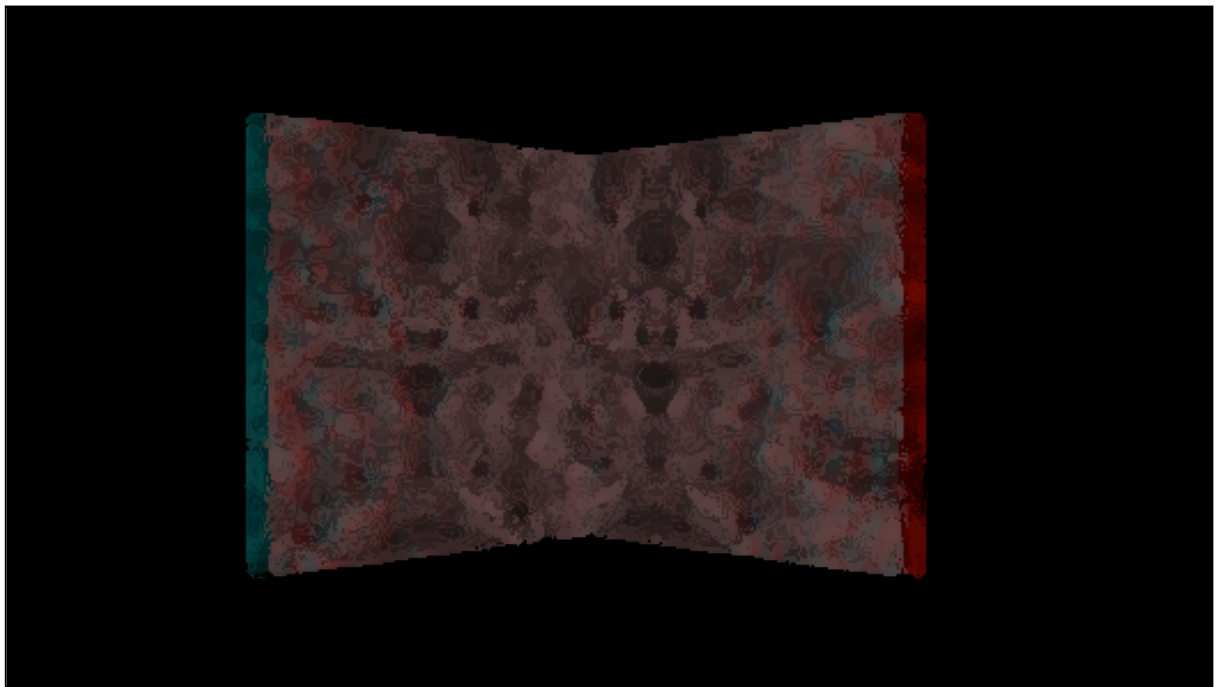


Figure 2-4 - Anaglyphic version of the hinge stimulus image.

The pilot investigation showed crosstalk to be well below thresholds, even for the stricter $<1\%$ crosstalk limit, far lower than the 0.5° hinge angle disparity observed when piloting the wireframe texture of Banks et al. (2009) on a passive display screen.

Hinges were chosen as being the third point on an arbitrary five-point scale of the following:

- 1). Random-dot stereogram, which, although offering no depth information, possessed disparity but still contained a size-disparity conflict;

- 2). Simple stimuli such as used by van Ee and Erkelens (1996), Grove et al. (2006), and Banks et al. (2009) containing line drawings (i.e., linear perspective with disparity cues);
- 3). Medium stimuli used by us. These actual shaded stimuli were globally lit, rendered, and contained ambiguous, scale-invariant objects;
- 4). Advanced stimuli containing actual objects with meaning and representation; and
- 5). A full scene containing an object and background (disregarding a probable sixth point where the scene would actually move like a movie).

The experimental stimuli were hinges comprised of two rectangles, configured base to base in the shape of the angle desired and were rendered in the 3D rendering packages Blender/MAYA (rendering package version 2.64) from a waveform .obj file. The adjunct apexes of these hinges, which rested on the screen plane, formed a 90°, prism-shaped hinge resembling an open book hinge stimulus, and were adjusted accordingly.

Following Banks et al. (2009), the (viewer's) perceived angle was measured as a function of the virtual camera separation, which, in turn, was adjusted by linking IA and HIT such that the apex of the stereoscopic hinge was always at the screen plane (zero parallax).

To generate different angles, the hinges were expanded uniformly in Blender about the vertical X-axis in depth. The texture map was stretched or compressed to fit the dimensions of the new hinge. The purpose of altering the texture was to conceal the change in shape in monocular viewing, thus making the amount of the disparity the independent variable.

A stereoscopic rendering of the hinges was carried out, whereby a virtual rig, consisting of two cameras, was set up with the following parameters: horizontal field of view (FOV) set to 45° (equivalent 35-mm photographic focal length 40.9 mm), parallel projection, sensor size 36 mm x 20.25 mm, and the f aperture at infinite. The IA was altered by horizontally separating the two cameras. HIT was altered by moving the two camera lenses horizontally relative to the sensor plane.

The stereoscopic parameters of the scene were matched as closely as possible to acquisition settings such that the image was orthoscopic. HIT was done by shifting the viewing frusta of the hinge by a parallel projection. When convergence is done by toeing in, vertical disparities are

introduced. So, by using parallel projection, this cue was eliminated, but makes exact comparison with camera convergence difficult since the centre of projection does not move obliquely to the plane of the sensor unless the shift function of a tilt-shift lens is used. Lens shift allows the point of convergence to be altered without introducing a new section of background (and commensurately increasing the parallax content of the scene). However, its usage is rare and more common practice is to oversample by capturing a wider field of view onto excess sensor area and then cropping down (Wattie, 2012). However, this process is seldom as accurate. Consequently, the exact remaining field of view after zooming in is unknown, making matching to the observer field of view that much more difficult.

In live-action capture, the images are normally post-processed by either corner pinning or by rotating them about the Y-axis and then zooming in to crop the reverse keystone. This technique corrects for distortion and, assuming sufficient sensor resolution, should produce a result indistinguishable from that generated by parallel projection. (See Section 1.5: Issues in Image Acquisition and Section 1.6.4: Vergence-Accommodation Conflict: Applied Principles).

2.1.6 Methodological Issue: Texture Selection

Recent work by Shibata et al. (2011a) has measured a zone of stereoscopic comfort. This parameterisation of factors contains a series of iterated experiments with a robust and credible methodology. They illustrate Percival's and Sheard's zones of comfort under a unified topography. The basic paradigm involves manipulating the visual angle as a product of either horizontal or vertical viewing distance, or by altering the presentation disparity.

The target is a simple hinge stimulus, with the criterion task of the participant responding when it subtends a perceived angle of 90° . The apparatus used in many of these studies is haploscopic (Wheatstone stereoscope), which eliminates crosstalk through total extinction between the eyes, which are looking at different displays.

However, the piloting experiment reported in Chapter 3 quickly revealed that the stimulus used by Banks et al. (2009) was prone to ghosting/crosstalk when used with several different stereoscopic displays (i.e., Zalman 20.5" passive, LG 23" passive, and Sony 52" active shutter). The hinge stimulus was high-contrast black on white, resulting in a difficult target when used without perfect extinction. The experiment showed that a generic marble texture for the stereo hinge was compatible with our choice 3D monitor and that, for a hinge with an angle of 90° presented at a camera separation of 60 mm, the angle perceived as 90° was approximately 90° .

In this case, the experiment produced a veridical result at these parameters with the least crosstalk possible.

2.1.7 Experimental Design

Participants did a two-alternative forced choice (2AFC) task (for a detailed overview, see Macmillan and Creelman (2004) and Ulrich and Miller (2004)) based on hinge stimuli to measure distortion and their comfort assessed using the five-point ITU-R BT.500-11 comfort scale (ITU-R, 2002). The 2AFC tests asked observers whether each presentation of the stereo hinge appeared greater than or less than 90° (Banks et al., 2009; Vienne et al., 2011). Post-exposure, participants were screened using the Simulator Sickness Questionnaire (SSQ) by Kennedy et al. (1993).

No _____

Date _____

POST-EXPOSURE SYMPTOM CHECKLIST

Kennedy, Lane, Berbaum, & Lilienthal (1993)

Instructions : Circle how much each symptom below is affecting you right now.

1. General discomfort	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
2. Fatigue	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
3. Headache	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
4. Eye strain	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
5. Difficulty focusing	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
6. Salivation increasing	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
7. Sweating	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
8. Nausea	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
9. Difficulty concentrating	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
10. « Fullness of the Head »	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
11. Blurred vision	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
12. Dizziness with eyes open	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
13. Dizziness with eyes closed	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
14. *Vertigo	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
15. **Stomach awareness	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
16. Burping	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>

* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

Figure 2-5 - Simulator Sickness Questionnaire (Kennedy et al. 1993).

Psychophysical studies employing a standard multiple-interval forced choice scale to evaluate sensory thresholds have been reported elsewhere (Banks et al., 2009; Hoffman et al., 2008; Ulrich & Miller, 2004; Vienne et al., 2011). Although this study extends the use of this psychometric

paradigm, more specifically, the 2AFC methodology, a gradient adjustment task was investigated but deemed superfluous.

In addition, other loads of measures of comfort were evaluated. These included PERCLOS (percentage of eyelid closure) measurement (Li, Barkowsky & Le Callet, 2011; Sommer & Golz, 2010), blink duration, blink frequency, and saccade lag (Kim, Choi, Park & Sohn, 2011; Kim et al., 2011). However, their efficacy was reduced by the 3D glasses used in our experiments. This reduction in efficacy is in keeping with published findings (Kim, Kishi, Kawai & Hatada, 2009; Kim et al., 2011; Malik et al., 2015). Unsuccessful attempts were also made at reanimating a scleral search coil machine and utilizing a specially commissioned pupil binocular tracker. Ultimately, a standardised Likert scale was selected as recommended by ITU-R BT.500-11 (ITU-R, 2002). This particular comfort scale allowed for a robust and rapid power of depth perception and comfort discrimination (Goldmann, De Simone & Ebrahimi, 2010; Yang, Hou, Zhou, Zhang, & Guo, 2009; Yasakethu, Hewage, Fernando & Kondo, 2008).

Two factors were manipulated. The first was virtual camera separation (20 mm, 40 mm, 60 mm, 80 mm, and 100 mm), which linked IA to HIT. This kept the point of zero parallax at the hinge apex. Second, the rendered angle of the hinge (in a series ranging from 50-130°) was changed in 10° steps, meaning that each hinge angle series was presented on any one particular trial after changing by 10°. This step was essential in obtaining a psychometric function for each camera interaxial separation. Psychometric functions (Weibull curves) were fitted to the data for each camera separation separately, and the point of subjective equality (PSE) was calculated for each camera separation (see below). These observed PSE's were then compared with the predictions obtained from a ray-tracing model. This ray-tracing disparity model fully incorporated the HIT and the results compared with the perceived 3D shape obtained psychophysically.

The analog alternative to the ray-tracing model would have been to generate cardboard stereo hinges and use hyperstereoscope/hypostereoscope devices to change the viewer's effective IPD. However, these devices were not reliably available nor did they contain convergence controls. Also, automating the observers' ability to record responses would have been difficult. Nonetheless, we did investigate the feasibility of a single-board microcontroller solution and mechanical hinges that changed angle, although a practical implementation proved elusive.

2.1.8 Psychometric Function and the Point of Subjective Equality

A data analysis tool used extensively in this thesis is the psychometric function and point of subjective equality. This is described below.

For each camera separation, participants were presented with five (5) hinge angles, ten (10) times each. For each angle, the relative frequency of its being perceived as greater or less than 90° could be calculated. By fitting a Weibull sigmoidal function (the psychometric function) to this relative frequency curve as a function of hinge angle, we could estimate the angle at which an observer says “larger than 90° ” with a probability of 50%. This estimate is referred to hereafter as the Point of Subjective Equality (PSE) (Figure 2-6). This angle was, on average, what was seen by the participants as 90° for this particular camera separation.

The slope of the psychometric function at the 50% point provided a good sensitivity indicator of the difficulty that the participants experienced in discriminating between the different angles. A high slope was indicative of good (i.e., easy) discrimination, while a low slope indicated poor, difficult discrimination.

This process was repeated for all participants for each of the camera separations. By such an approach, the angle that was perceived as 90° at each camera separation was estimated. The data were analysed using MATLAB, SPSS, and R.

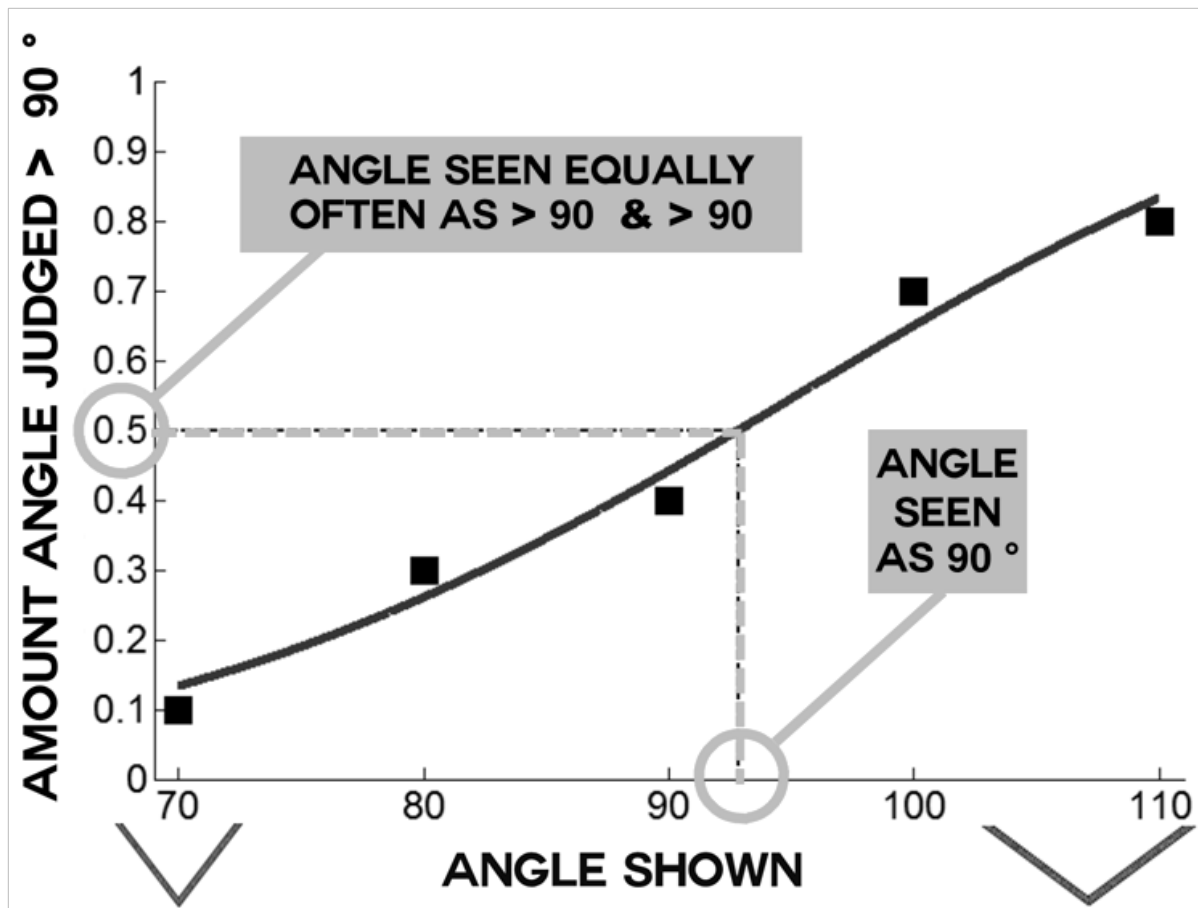


Figure 2-6. Graphical depiction of the estimate referred to as the Point of subjective equality.

2.2 Conclusion

In summary, the stimuli were simple stereoscopic hinges. We compared the perceived 3D shape obtained psychophysically with the predictions based on a ray-tracing model, recorded the viewing comfort of each experimental condition, and assessed these in relation to the tolerable limits of parallax at different horizontal disparities (or IAs).

CHAPTER 3 – EXPERIMENTAL: VIEWING DISTANCE

The first section of this chapter describes a pilot experiment undertaken to inform texture selection. This pilot experiment was necessary to account for how we selected the hinge texture and the angles of view for the individual camera separations. Final sections describe an angle estimation task (i.e., Experiment I) investigating the impact of viewing distances on perceived angle and viewer comfort.

3.1 Pilot Experiment

As a preface to the experimental investigation of viewing distances (Experiment I), positive and negative disparities (Experiments II, III, and IV), and the multi-view condition (Experiment V), we conducted our first attempt at hinge experiments at positive parallax (behind the screen plane) and fixed screen width. Viewer comfort data were not recorded during this pilot, whose purpose was selection of a texture for the hinge stimulus.

To assess the degree to which hinge texture introduced geometric distortions and establish an appropriate range of angles of view for each camera separation, we replicated the Banks et al. (2009) method. The standard model behind the misperception of 3D shape and scene layout is geometric (Held & Banks, 2008), an approach that is dependent on several factors that include viewing distance, as demonstrated in the previous chapter, and image parallax (Woods et al., 1993). Importantly, the texture pattern of the 3D image introduces binocularity and, therefore, determines the sensation of depth (MacDonald, 1978). Indeed, texture pattern anisotropy can facilitate or impede 3D perception (Interrante & Kim, 2001), plays a significant role in conveying the veridicality of concave and convex surfaces (Li & Zaidi, 2001; Zaidi & Li, 2002), and encodes shape and shape percepts (Li & Zaidi, 2004; Rauschecker, Solomon & Glennerster, 2006) and material properties (Marlow & Anderson, 2016; Tam, Shin & Li, 2013) of stereo content.

In this trial-and-error investigation, we set out to determine the class of texture that, firstly, would qualitatively convey the veridical shape of the stereo hinge and, secondly, would be compatible with the selected 3D screen used in subsequent experimental setups. Lastly, the researcher wished to ascertain whether participants were able to distinguish between different hinge angles at each camera separation: did they see the shapes as being distinct from each other?

3.1.1 Methods

In the pilot involving twenty observers ($n = 20$), we replicated the Banks et al. (2009) method to confirm that changing the texture of the image, taking care to use a matching 13x13 red, textured rendered hinge object, introduced no geometric distortions. All participants had 20/20 acuity with normal vision or eyesight correction of less than three dioptries. The exclusion criterion was defined as the inability to discriminate stereoacuity below 100 arc seconds as measured by the Titmus Fly Stereo Test.

Furthermore, each camera separation had five angles that were selected by trial and error to establish an appropriate range. As throughout subsequent experiments, we used the same range of angles 20 mm (50 to 90) through to 100 mm (90 to 130), tested at 20-mm increments. For the pilot, the viewing distance was set at 80 cm for an angle of view (AOV) of 35°. At the time of testing, all participants were uninformed as to the experimental objective.

3.1.2 Results

Pilot research using the original settings of Banks et al. (2009) showed that for a hinge with an angle of 90° presented at a camera separation of 60 mm, the angle perceived as 90° was approximately 90°; in this case, the experiment produced a veridical result.

Additionally, piloting quickly revealed that the stimulus used by Banks et al. (2009) was prone to ghosting/crosstalk when used with several different stereoscopic displays (Zalman 20.5" passive, LG 23" passive, and Sony 52" active shutter). The hinge stimulus was high contrast black on white, resulting in a difficult target when used without perfect extinction. When this hinge object was shown on an LG LCD passive display, any disparity of over 0.5° resulted in very marked intra-ocular crosstalk and unacceptably degraded the 3D stereoscopic image. Hence, our feedback from the pilot was that the wireframe texture hinge was incompatible with our choice 3D screen. Therefore, the experiments reported here used a generic marble texture for the stereo hinge that resulted in substantially less (albeit still visible) crosstalk.

A relatively recent report by (Vatolin, 2011) has confirmed the appropriateness of different textures for stereoscopic presentation. It classifies such textures as “hard” or “easy” in a subjective categorisation. While unempirical, the psychophysical results demonstrated that so-called “hard” patterns simply do not fuse stereoscopically, and a literature search has not yielded

a consistent mechanism for defining patterns in relation to their predictive performance in stereoscopic environments.

Additionally, participants produced normal PSE response curves similar to those in later experiments, but we manipulated the range since the angle-selection criteria were not suitable (for instance, a 20-mm condition showed a load of flat angles not reaching 90°). This was partially due to the mismatched observer and display field of view, unsurprising considering Howard and Rogers' (2012) find that matched FOV and AOV are an essential base condition.

3.2 Experiment I: Review

The objective of this experiment (Experiment I) was to ascertain whether, in the undistorted rendering condition and the absence of visual cues, observers would report a significant difference in observed angle and/or a significant difference in comfort, between a hinge image rendered so that it appeared to be behind, at, or in front of the screen plane. The data collected determined where the participants' eyes converged: at the hinge apex, at the screen, or at some intermediate position. This approach enabled an evaluation of the impact of the accommodation-vergence conflict, the unique issue underlying this experiment.

During natural, full-cue viewing, ocular vergence is useful to maintaining stereopsis, especially at distances within which typical displays would be functional. However, stereoscopic displays, in presenting artificial geometries within such an interaction space, misalign focus-fixation processing, leading to discomfort (Banks et al., 2012; Howarth, 2011; Shibata et al., 2011a; 2011b). This misalignment has been variously indicted as causing the aversive symptoms reported during S3D viewing. Consequently, experimental psychophysical studies into viewer comfort reflect the considerable interest dedicated to investigating the issue of the contribution of the misalignment—that is, the vergence-accommodation conflict—to viewer comfort.

Tresilian, Mon-Williams, and Kelly (1999) examined the relationship between accommodation and vergence through prism perturbations. In their experiments, the researchers presented stimuli through an aperture (9 cm x 4 cm) in front of a rectangular viewing box, and observers were required to conduct motor tasks (blind reaching) under prism-induced discrepancies. The five ophthalmic prisms used in the experiment allowed for vergence manipulations independent of the viewing distance. Three viewing conditions were presented, from conditions with rich cues to those with but one, whilst the stimuli varied from a full scene to advanced stimuli. This contrasts with our choice for medium intensity stimuli, that is, the stereo hinge stimuli.

Ultimately, however, the Tresilian et al. (1999) study demonstrated the lapse into prism-based vergence changes in accommodation/vergence literature, repeated elsewhere in other prism adaptation experiments (van Beers, Sittig & van Der Gon, 1999). Moreover, prism-induced discrepancies lead to persistent visual distortions known as the curvature-of-bowl effect (Ebenholtz, 1974; Ebenholtz & Wolfson, 1975; Gibson, 1933; Priot et al., 2012; Sethi & North, 1987; Stuart et al., 2009; van Beers, Wolpert & Haggard, 2002; Wallach & Smith, 1972), making the generic approach unsuitable for an applied context.

Diopters (Ebenholtz & Fisher, 1982) and mirror devices are also utilised in changing the fixation distance of a stimulus relative to its vergence plane with varying degrees of cue information (Heuer & Rapp, 2009; Howard, 2008; Jainta, Hoormann & Jaschinski, 2007; Jaschinski, Jainta & Hoormann, 2008; Martel, Grealy & Coello, 2006; Priot et al., 2012; Priot et al., 2015) although these are not without azimuth errors.

Vienne, Blondé, and Mamassian (2015) depicted random-dot stereogram (RDS)-based stimuli on a 46" polarised 3D TV screen across three display distances. As with the experiment detailed in this chapter, the authors utilised a cue-conflict paradigm, varying the vergence distance while keeping accommodation constant.

Presenting visual stimuli on a display is a standard that has been deployed in various pertinent stereoscopic studies (MacKenzie, Hoffman & Watt, 2010; Shibata et al., 2011a). Other cue-conflict publications have explored the relationship between accommodation and vergence using a variety of disparity-based techniques ranging from binocular stimulation (Hung, Semmlow & Ciuffreda, 1983; Semmlow & Hung, 1981) to RDS-based images (Hoffman et al., 2008; Huang et al., 2015; Poulakos et al., 2014; Vienne et al., 2012; Watt et al., 2005).

Several studies have utilised stereo hinge stimuli to investigate the accommodation-vergence relationship in stereoscopic 3D displays. Vienne et al.'s (2012) empirical work entailed task-discrimination by observers viewing a stereo hinge at different disparity-defined vergence distances. In their experiment, the accommodation distance remained unchanged. Watt et al. (2005) and Hoffman et al. (2008) used stereo hinges to investigate visual perception across several accommodation distances, the latter elicited by changing binocular disparities, achieving vergence manipulation by changing the viewing distance to the hinge stimulus.

Important psychophysical findings have also been reported following the use of stereo hinges to investigate systematic biases in three-dimensional shape judgements (Hogervorst & Eagle, 1998) and visual performance in the recovery of three-dimensional structure-from-motion (SFM) (Eagle & Hogervorst, 1999). A dihedral angle moving along a vertical axis was simulated by horizontally-moving dots in another study (Braunstein, Liter & Tittle, 1993), although stimuli projection and dihedral angle discrimination were under orthographic conditions.

The vastness of the accommodation/vergence literature guarantees ongoing orthoptic research into the relationship between these two human factors. However, a significant amount of literature, including that reviewed here, comprises generic experiments where prisms, mirrors, or diopters are used to change the focal plane of an image relative to its vergence. The one study (Vienne et al., 2014) found to move the display screen physically, moving a slider device on an optical bench, used a vertical beam splitter. Ultimately, no study was found that presented stereo hinge stimuli observed through apertures under cue-conflict conditions while the 3D screen was being moved imperceptibly.

Hence, our experiment involved presenting a hinge through an aperture (see Vishwanath, 2014) in a darkened room, with the screen moved imperceptibly toward the observer. The difference in distortion and comfort judgments under different amounts of accommodative load determined whether the vergence-accommodation conflict or simply the context of the screen caused biases in angle estimation when the apex of the target was not at the screen plane and the target was in out-of-the screen 3D space. Of interest was determining how much mismatch between accommodation and vergence an observer can tolerate. Although several of the conditions listed above effectively never occur in commercial 3D content, the task was nonetheless valid. By mapping the space where a 3D target could be presented comfortably and evaluating the effect of position in the parallax of the target, complementary data to Yamanoue et al. (2012) could be used.

Experiment I tests the first hypothesis H_1 : An increase of viewing distance for stereoscopic stimuli should increase comfort due to the reduction in the vergence-accommodation conflict (VAC).

3.3 Method

3.3.1 Participants

All participants ($n = 40$) had normal 6/6 vision or corrected eyesight and stereoacuity better than 40 arc seconds according to the Titmus Fly Stereo Test. Participants with optical correction wore the correction during the experiment. All participants were naïve as to the purpose of the experiments. Mean age and IPD (\pm SD) of participants were 20.38 years (\pm 1.694) and 56.49 mm (\pm 3.781), respectively. Nineteen participants were male, and 21 were female.

3.3.2 Apparatus

A 52" active shutter 3DTV displayed computer-generated stimuli showing a stereoscopically rendered hinge in space from the observer as indicated in Figure 3-1 below. The 3D TV was mounted on a trolley so that it projected the stereoscopic hinge stimuli in the same position in space, with the 3D TV at five (5) different viewing distances in a darkened laboratory environment, thereby giving the appearance of a floating screen.

Figure 3-1 shows the apparatus used in Experiment I. In the figure, the participant wearing 3D glasses is viewing, through an aperture, a 3D TV that moves on rails.

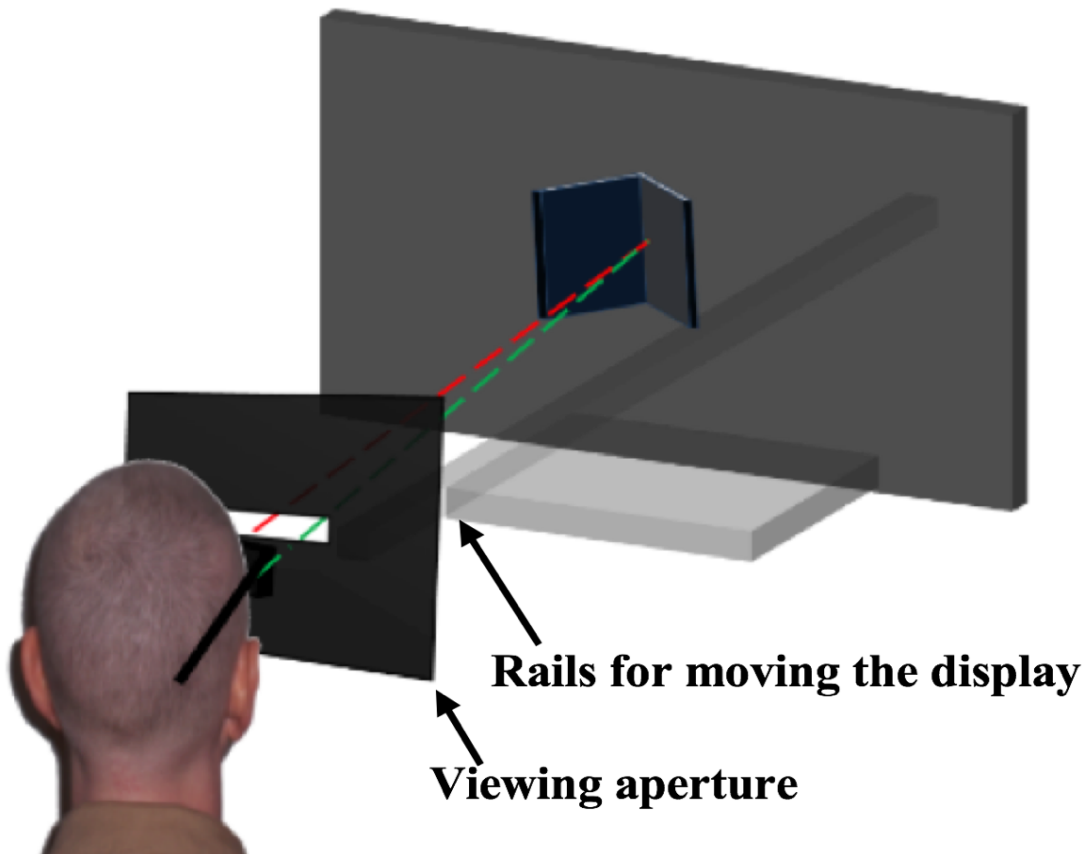


Figure 3-1 - Experiment I: Apparatus.

3.3.3 Design

The viewing distances were 52.7 cm, 62.8 cm, 75.1 cm, 90.4 cm, and 110.6 cm with corresponding fields of view (FOV) 95°, 85°, 75°, 65°, and 55°, respectively. At the two nearer positions, the image was rendered behind the screen plane (positive parallax); at the middle position, it was rendered at the screen plane (zero parallax); and, at the two further positions, it was rendered in front of the screen plane (negative parallax).

Five hinge angles ranging from 70° to 110° were tested at a constant visual angle (hinge scaled inversely to distance) at these different viewing distances. The study was conducted at a HIT customised to each participant's measured IPD.

In all experimental setups, the viewing distances were tested at a constant visual angle by scaling the stereo hinge inversely proportional to distance, in agreement with previous research on the matter (Allison, Gillam & Palmisano, 2009). The hinge was rendered to appear the same size regardless of screen distance.

The independent variable was the viewing distance, which implicitly changed the screen field of view (FOV) and the screen disparity of the image. The hinge was rendered to be at a constant stereoscopically defined distance of 75.1 cm, and the render FOV of each hinge was calculated to match the screen FOV as defined by the viewing distance.

The possible points for participant ocular convergence are represented diagrammatically in Figure 3-2 below.

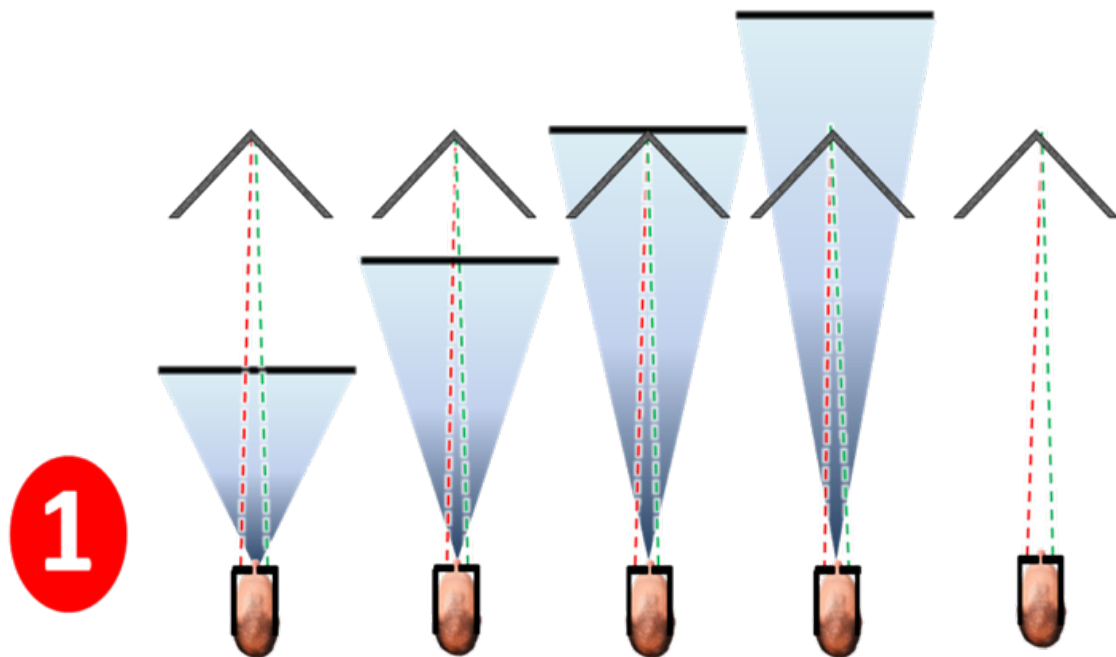


Figure 3-2. Experiment I: Experimental condition when ocular convergence is at the hinge apex.

Figure 3-2 depicts the condition in which participants' eyes converge at the hinge apex, with a convergence angle of 2.29° . Note that the first two conditions are positive parallax while the last two represent negative parallax.

Figure 3-3 depicts the condition in which participants' eyes converge at the screen plane, with a convergence angle varying from 3.30° to 1.72° . Note that there is no parallax.

Figure 3-4 depicts the condition in which participants' eyes converge at the screen plane, with a convergence angle varying (say) from 2.8° to 2.0° . Once again, note that the first two conditions are positive parallax while the last two represent negative parallax.

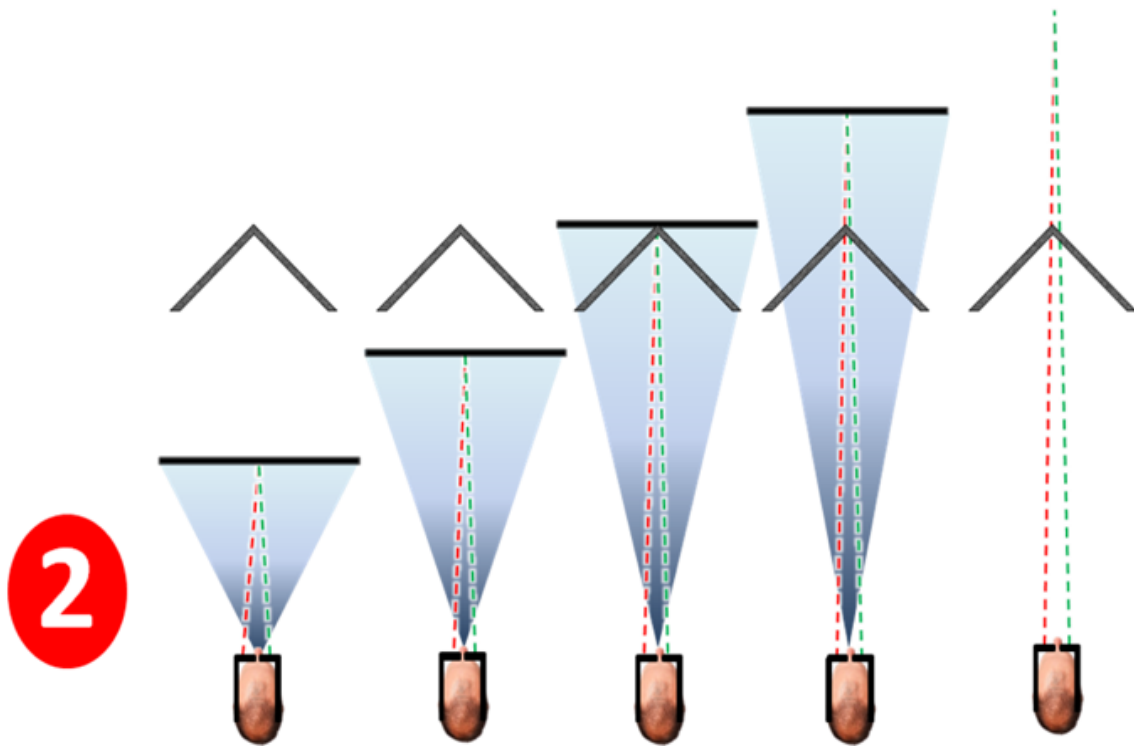


Figure 3-3. Experiment I: Experimental condition when the ocular convergence is at the screen plane.

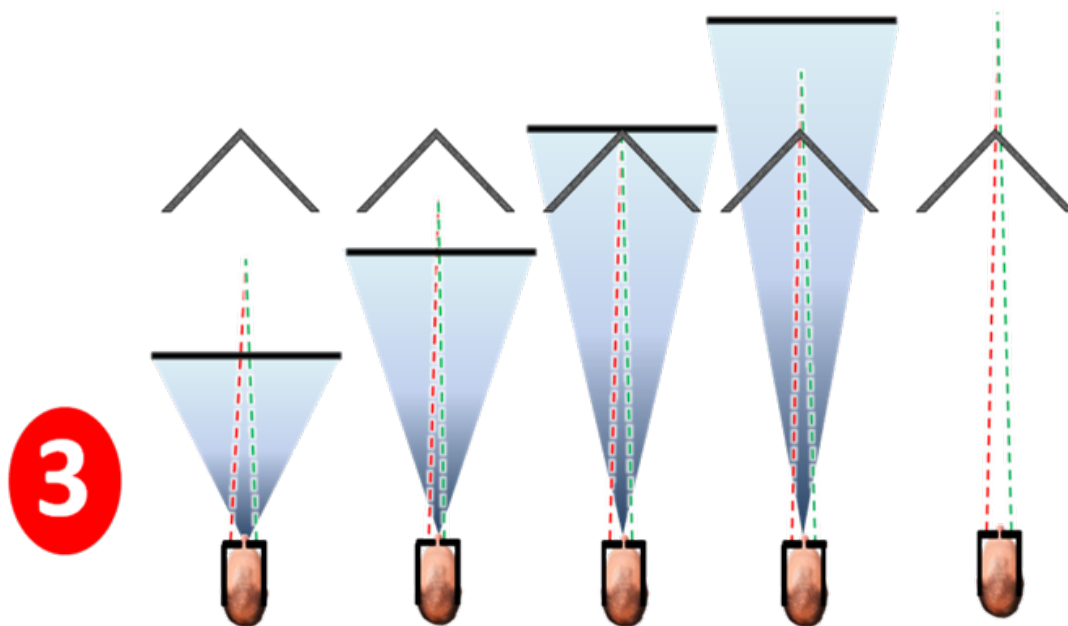


Figure 3-4. Experiment I: Experimental condition when ocular convergence is intermediate, between hinge apex and screen.

3.3.4 Procedure

For each viewing distance (52.7 cm to 110.6 cm), observers were required to judge whether the hinge angle was greater than or less than 90° and to provide a comfort rating, in blocks of 50 trials. The screen was kept at a fixed distance for each block and then moved unbeknownst to

the observer between blocks. Within each block, a randomly interleaved set of five hinge angles (70-110) were presented 10 times each to the observer. There were an overall total of 250 trials. Participants also completed an electronic version of the Simulator Sickness Questionnaire (SSQ) by Kennedy et al. (1993). The presentation software used was PsychoPy (Peirce, 2007; 2008).

3.4 Results

3.4.1 Perceived Distortion

Table 3-1 summarises and Figure 3-5 depicts the results of the perceived angle measurements in Experiment I.

Table 3-1. Experiment I: Mean and Standard Deviation for Point of Subjective Equality.

Field of View	Screen Distance	Perceived Angle		
		N	Mean	S.D.
55°	110.6cm	40	89.2°	12.7°
65°	90.4cm	40	90.7°	11.4°
75°	75.1cm	40	90.3°	13.5°
85°	62.8cm	40	86.4°	23.5°
95°	52.7cm	40	91.0°	13.7°

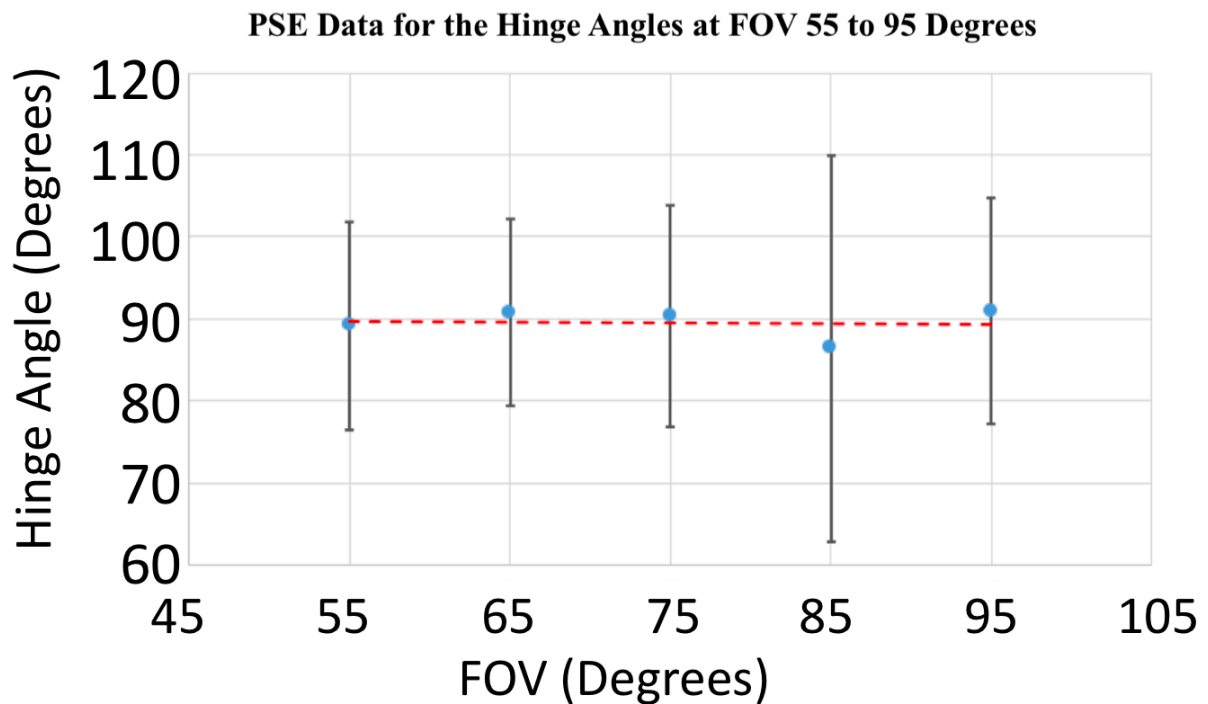


Figure 3-5. Experiment I: Perceived hinge angle plotted against FOV (FOV represents the various viewing distances), with the furthest screen distance (110.6cm) to the left.

Table 3-1 shows and Figure 3-5 plots the point of subjective equivalence (see Chapter 2 – Methodological Overview) against FOV representing the different screen distances, with the furthest screen distance (110.6 cm) to the left. The PSE values represent the angle perceived as 90° and show no statistically significant deviation from the rendered angle of 90° at any screen distance.

3.4.2 Psychometric Function Slope

The slope of the psychometric function indicates how challenging the participants found the discrimination. Table 3-2 and depicted in Figure 3-6 depict the data.

Table 3-2. Experiment I: Mean and standard deviation for psychometric function slope.

Field of View	Screen Distance	Psych Function Slope		
		N	Mean	S.D.
55°	110.6cm	40	7.65	2.91
65°	90.4cm	40	7.60	2.86
75°	75.1cm	40	7.33	3.12
85°	62.8cm	40	5.83	3.66
95°	52.7cm	40	6.31	3.44

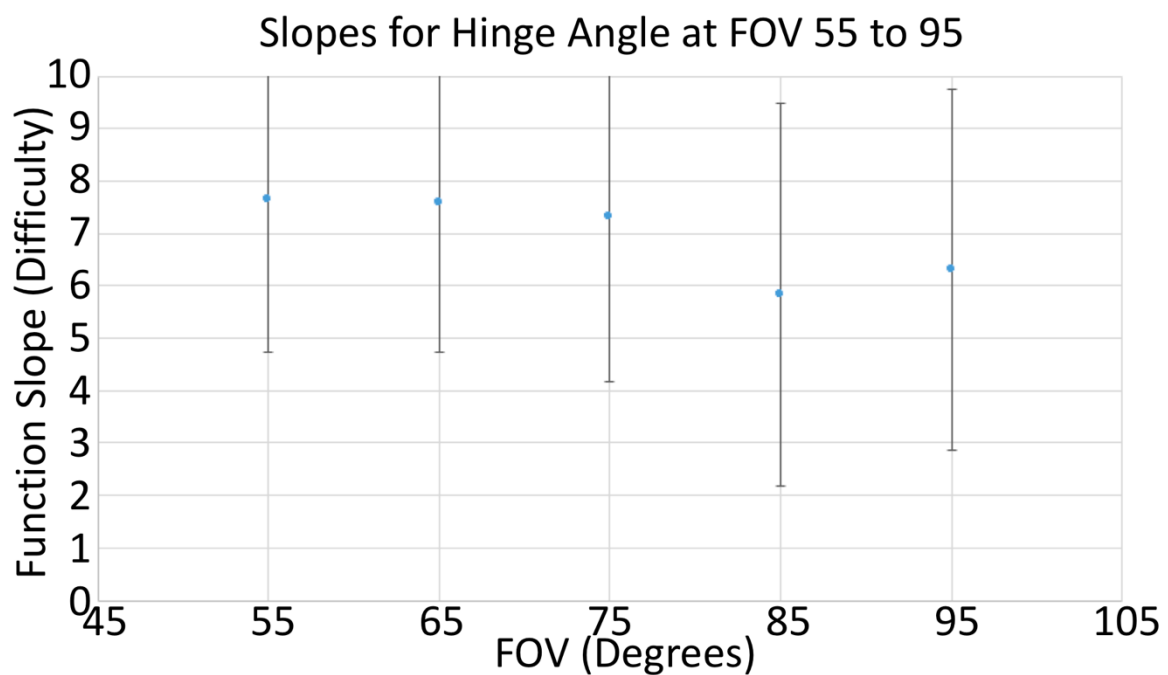


Figure 3-6. Experiment I: Slope of Psychometric Function plotted against FOV (FOV represents the various viewing distances), with the furthest screen distance (110.6cm) to the left.

Figure 3-6 plots the slope of the psychometric function against FOV representing the different screen distances, with the furthest screen distance (110.6 cm) to the left. Lower values of the slope indicate that the participants found discriminating between hinge angles more difficult.

3.4.3 Comfort

Table 3-3 and Figure 3-7 show the results relevant to Experiment I's comfort data.

Table 3-3. Experiment I: Mean and standard deviation for comfort data at each field of view (screen distance).

Hinge Angle	N	FOV 55°		FOV 65°		FOV 75°	
		Mean	S.D.	Mean	S.D.	Mean	S.D.
70°	40	3.43	1.05	3.43	1.21	3.29	1.00
80°	40	3.40	0.94	3.26	0.96	3.07	0.65
90°	40	3.24	0.79	3.22	0.76	2.96	0.58
100°	40	3.11	0.69	3.19	0.68	2.75	0.54
110°	40	3.08	0.87	3.05	0.67	2.63	0.48
Overall	40	3.25	0.88	3.23	0.85	2.94	0.68

Hinge Angle	N	FOV 85°		FOV 95°		Overall	
		Mean	S.D.	Mean	S.D.	Mean	S.D.
70°	20	3.27	0.95	3.26	0.99	3.33	1.04
80°	20	3.07	0.79	3.21	0.91	3.20	0.86
90°	20	3.02	0.70	3.06	.086	3.10	0.74
100°	20	2.90	0.74	3.05	0.87	3.00	0.71
110°	20	2.87	0.69	3.03	0.85	2.93	0.72
Overall	20	3.02	0.78	3.12	0.90	3.11	0.83

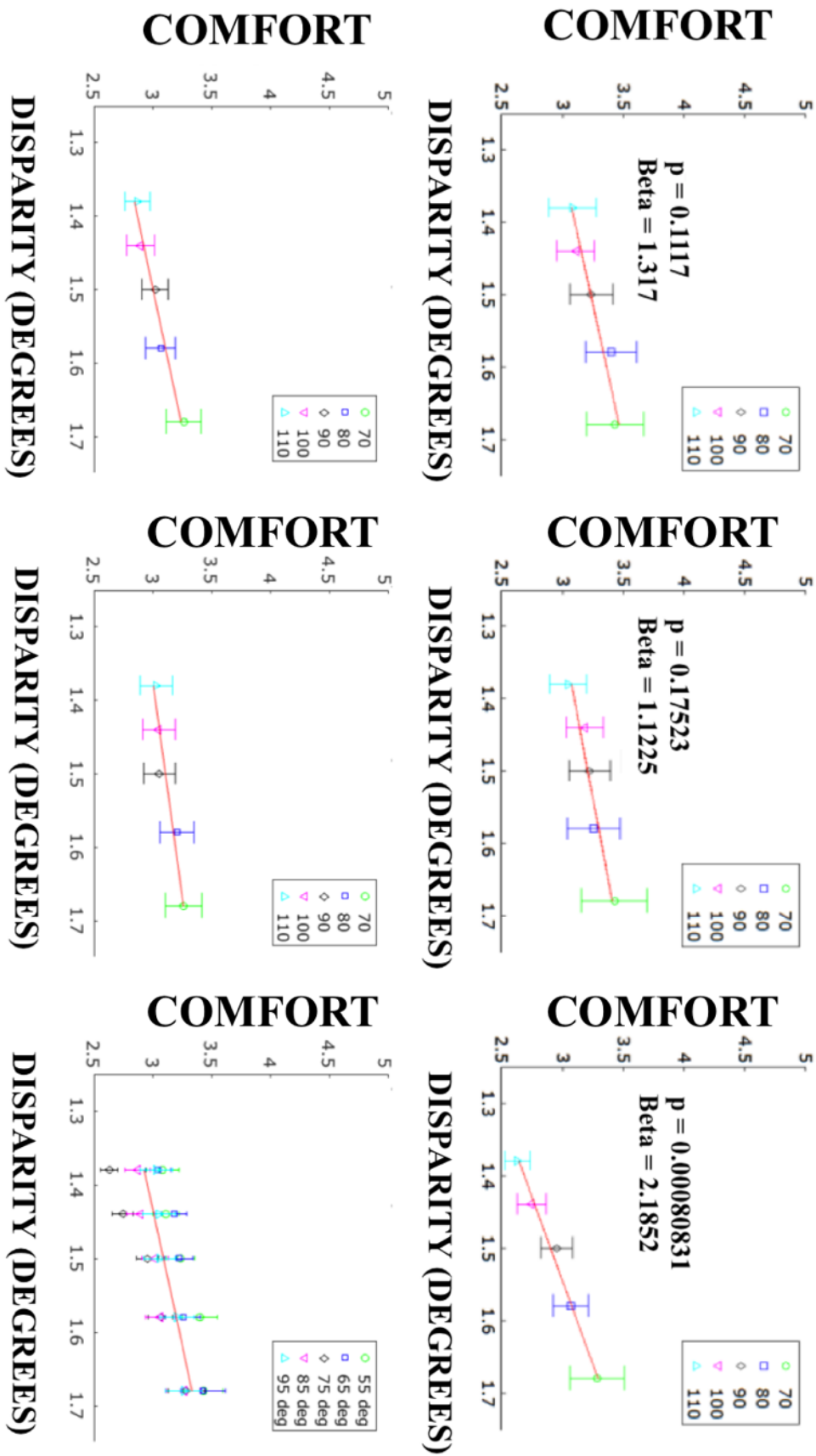


Figure 3-7. Experiment I: Comfort plotted against disparity (hinge angle) at each of the five screen distances (110.6cm top left through to 52.7cm bottom centre), and an overall figure (bottom right), with the relevant trend lines.

Table 3-4. Experiment I: Line of best-fit parameters for comfort vs disparity.

Screen Distance	P	Beta
52.7cm	0.31623	0.84654
62.8cm	0.0738	1.3141
75.1cm	0.00080831	2.1852
90.4cm	0.17523	1.1225
110.6cm	0.1117	1.317

Figure 3-7 shows comfort plotted against disparity (hinge angle) for each of the screen positions (110.6 cm top left through to 52.7 cm bottom centre) and an overall figure (bottom right), with relevant trend lines. For each screen position and overall, the comfort measure increases with increasing disparity.

Overall, there appears to be a slight increase in comfort as screen distance increases. However, the correlation is not strong.

3.5 Discussion

The aim of Experiment I was to investigate the relationship between viewer comfort, the viewing distance for stereoscopic stimuli, and the vergence-accommodation conflict. More specifically, the experiment was intended to investigate hypothesis H₁, which states that an increase in viewing distance for stereoscopic stimuli should increase comfort level due to the resulting reduction in the vergence-accommodation conflict (VAC).

In Experiment I, we measured the impact of viewing distances on perceived angle and viewer comfort. The experiment was conducted at the ideal condition as defined by orthostereoscopic parameters. Also, the investigation was conducted with the interaxial separation functioning as the field of view (FOV) and at a constant visual angle, as suggested by Allison, Gillam, and Palmisano (2009). The hinge size was scaled to be inversely proportional to the viewing distance to maintain a constant apparent size to the participants.

No discernible differences were noted in the angle perceived as 90° (as measured by the PSE) at the different screen distances.

An increase in difficulty of discriminating between angles (as measured by the slope of the psychometric function) was seen at closer screen distances, possibly indicative of vergence-accommodation conflict. However, the effect was not sufficiently robust to indicate where the participants' eyes were converging.

The experiment showed screen distance as slight correlated with comfort such that an increase in screen distance elicited an increase in viewer comfort. Allison, Gillam, and Palmisano (2009) found that binocular vision does extend beyond distances that were previously considered perceptually non-functional, with depth constancy observed at up to 40 metres. Regardless, Tresilian et al. (1999) showed that the contribution of vergence to distance fixation falls off with increasing distances, indicating a concomitant drop-off in VAC as well; hence, observers seated closer to the S3D display would experience greater discomfort than those seated further away.

The availability of linear perspective, a monocular cue, in our stereoscopic hinge stimuli appeared to have assisted in sustaining depth constancy. Pollock et al. (2012) and Benzeroual et al. (2011) make a similar observation, although they do not investigate the implication of this insight into scene acquisition factors, specifically, HIT. van Ee and Erkelens (1996) and Grove et al. (2006) also report on the relationship between linear perspective and binocular vision. Additionally, Allison and Wilcox (2015) found that monocular depth cues normalise 3D perception. Our study extends previous research by reporting that viewing distance, within the experimental range, appears to enhance viewer comfort for stereoscopic perception, albeit slightly.

H₁, which states that an increase in viewing distance for stereoscopic stimuli should increase comfort level due to the resulting reduction in the vergence-accommodation conflict (VAC), is partially supported by a weak relationship between comfort and viewing distance.

CHAPTER 4 – EXPERIMENTAL: NEGATIVE PARALLAX

4.1 Introduction

The purpose of the two experiments described in this chapter was to investigate the effect of interaxial camera separation and disparity on the perceived shape and viewing comfort of 3D images under conditions of negative parallax (i.e., the rendered image was in front of the screen). The two experiments (i.e. Experiments II and III) study both distortion and comfort in stereoscopic displays under a single paradigm and, therefore, are reported in the same chapter.

These experiments are intended to verify our hypotheses as stated in Section 1.10: Hypothesis Statement. Hypothesis H₂ states that parallax is, firstly, not correlated with comfort and, secondly, is not correlated with distortion (i.e., angular distortion). The second hypothesis-hypothesis H₃- is that distortion is affected by hinge placement on-screen while comfort is nuanced.

The chapter is organised into three sections, leading with a review, experimental sections describing both experiments, and closing with a discussion of the results.

4.2 Review

Several studies have reported on the interaction of stereoscopic parameters and distortion perceived by viewers. Few, however, have been quantitative. Among these are studies which combine 2D and 3D cues. For instance, van Ee and Erkelens (1996) extended several studies (Ohtsuka & Ono, 1998; Regan & Hamstra, 1994; van Ee & Erkelens, 1995) and investigated veridical performance for rectangular random-dot stimuli presented monocularly and stereoscopically. Stereoscopy was created by presenting a rectangular stimulus via a projection TV and viewing through anaglyph glasses. Raghunandan (2011) further explored the study's main findings, that regardless of presenting the stimulus in front or behind a fixation point, the aspect ratio perception is nearly veridical if the stimuli are presented stereoscopically.

Other researchers also use monocular gap stereopsis (Gillam, Blackburn & Nakayama, 1999), i.e. the displacement of monocular information to investigate how parallax distribution is processed. Grove et al. (2006), rather than using the anaglyphic technique, generated disparity by a monocular gap stereogram. The authors established that distortion was introduced when the

stimuli were stereoscopically presented with the equivalent to positive parallax, but not when presented with the equivalent to negative parallax. The basis for this statement of equivalence is provided by Gillam et al. (1999) and Pianta & Gillam (2003). This finding is important because the majority of S3D content is located behind the screen plane.

Kooi et al. (2010) remind practitioners that simple disparity-based stimuli displayed on a 2D display and viewed through anaglyphic stereo glasses have limited generalizability in applied contexts due to their lack of realism vis-à-vis real-world stimuli.

Regardless, despite using simple stimuli, van Ee and Erkelens (1996) and Grove et al. (2006) establish empirically that there is a relationship between linear perspective and disparity cues and this insight is exploited by Banks et al. (2009) when selecting disparity-based stimuli with line drawings for their experiments (see Section 2.1.6: Methodological Issue: Texture Selection). For further discussion about this relationship, refer to Khaustova, Fournier, Wyckens, and Le Meur (2013).

Ujike & Watanabe (2011) presented sophisticated computer-generated 2D and 3D stimuli on a circularly polarizing 46" S3D display to compare the viewing comfort between 3D and 2D. Pre- and post-screening was achieved with the SSQ and viewer comfort assessed using a five-point scale. Other studies found that the stimulus produces motion-like sickness even at average severity (Naqvi et al., 2013; 2014). By finding higher nausea-related SSQ scores when presenting 3D stimulus, the study confirms that, for stereoscopic vision research, 2D stimulation provides a limited level of detail (Keshavarz & Hecht, 2012), implying that stereoscopic stimuli from S3D footage and simulations confers greater realism (Rooney & Hennessy, 2013).

Keshavarz and Hecht (2012) also report a significant effect of stereopsis for 3D presentation compared to 2D and, while a study in viewer discomfort, it goes to show that S3D stimuli generate greater immersion (Diemer, Alpers, Peperkorn, Shiban, & Mühlberger, 2015; Felnhofner et al., 2015; Pausch, Proffitt, & Williams, 1997). Consequently, such stimulus has ecological validity with regard to investigating the relationship between stereo acquisition parameters and viewing discomfort.

Several other studies explore the perceptual differences between watching S3D and 2D content, using movies - however no acquisition settings, disparity ranges, and viewing parameters were provided. Solimini's (2013) observational study surveyed moviegoers on the effects of watching

3D and 2D films in cinema. Rooney and Hennessy (2013) compared 3D and 2D viewing for moviegoers as they left a cinema (. Laboratory investigations of 2D versus 3D conditions provide greater control over pertinent parameters such as the depth budget and seating positions (Yang et al., 2012), luminance and screen background (Read & Bohr, 2014), and field of view (Lubeck, Bos, & Stins, 2016).

In Watanabe and Ujike's (2013) qualitative study into how "improper" 3D settings affected viewer comfort for a 3D movie, the researchers deferred to professional expertise as opposed to empirical recommendations for their definition of what constituted "improper" settings and do not provide any acquisition or post-processing parameters—IA, HIT, and Field of view.

Numerous other studies also use existing stereoscopic scenes from commercial footage in investigating viewer comfort (Yamanoue et al. 2012; Vatolin et al., 2013; Voronov et al., 2013). However, while display parallax could be established for the complex stimuli presented, acquisition settings could not. This failure to strictly control acquisition and post-processing parameters undermines the usefulness of using existing scenes from commercial video in comfort literature.

Simplistic stereogram-based stimuli do not provide a sufficient perceptual model of real-world 3D projection. To assess the interaction of selected acquisition parameters, presentation disparity, and viewer comfort, parallax must be introduced (Bishop, 1996) through manipulations of the hinge's depth and width.

In two experiments involving three participants, Häkkinen et al. (2009) investigated the diplopic threshold by stereoscopically presenting red-coloured pixels against a black background. In the first experiment, all presentations were in negative disparity while positive disparity was used for the second experiment. Only one of the three participants was exposed to all experimental conditions. For this participant, analysis of the Point of Subjective Equality for the diplopic threshold (i.e., the maximum usable depth that will not elicit diplopia) revealed that it increases linearly up to a 35-45 arcmin stimulus width, increasing logarithmically afterwards: interestingly, however, the threshold was lower for positive disparity than negative disparity. Unfortunately, comfort data was not obtained.

Several other studies find a similar relationship between stimulus width and disparity. Tsirlin, Wilcox, and Allison (2012), in an extension of an earlier study and extending experimental

results, *predict* firstly a detrimental effect of S3D display crosstalk on stereoacuity for smaller objects: crosstalk increases at smaller stimulus widths irrespective of the disparity range.

Secondly, the degree of visual comfort increases with the increment of the object size in a certain range and then levels off or decreases slightly after a certain threshold. However, as before, viewer comfort is not recorded and the basis for comfort prediction is using stereoacuity as a proxy.

Chang, Yang, and Wan (2013) confirm this prediction, reporting results similar to Häkkinen et al. (2009): self-reported viewer comfort increased rapidly with the increment in the stimulus size (linear relationship) until it reaches a certain threshold, after which it levels off (logarithmic relationship). The stimuli were composed of computer-generated stereoscopic sequences presented on an active shutter 3D display (120 Hz) and viewed through active shutter 3D glasses. A 3D image dataset used to validate these insights (Sohn, Jung, Lee & Ro, 2013; Sohn, Jung, Lee, Speranza, & Ro, 2014) and a later study confirmed that smaller stimulus width causes more discomfort (Lee, Jung, Sohn & Ro, 2013). When they extend their study to include the relationship between binocular fusion time and stimulus width, the researchers find that, when presented at negative parallax, smaller stimulus width induces greater discomfort and increases time to binocular fusion (Lee et al., 2013). This partially duplicates Häkkinen et al.'s (2009) results. However, as with other psychophysics studies, no acquisition parameters were provided for any of these studies

The previous experiment has already established that the viewing distance, within the experimental range, enhances viewer comfort for stereoscopic perception, albeit slightly. This result is indicative of the vergence-accommodation conflict. This is unsurprising considering that, among others (Naceri, Chellali, & Hoinville, 2011;; Naceri, Moscatelli & Chellali, 2015; Viguier, Clément & Trotter, 2001), Tresilian et al. (1999) show a relationship between distance and vergence especially for conditions typical during stereoscopic 3D viewing. Other studies show that vergence has a far larger range than previously thought (Palmisano et al., 2010) and that accommodation is essentially at infinity beyond three meters (Horwood & Riddell, 2012).

This review clearly shows the limited research into the acquisition and post-processing parameters of IA, HIT, and FOV. Most psychophysics studies, in their selection of stimulation and presentation techniques, do not emulate the techniques of stereographers.

These are important arguments when investigating stereo content and guide the rationale behind hinge selection (see Chapter 2 – Methodological Overview). This also extends beyond being solely a methodological issue. The experiments described in this chapter and the next emulate achievable and controllable acquisition and post-processing parameters to examine if there is a differing bias if the hinge stimulus is presented with positive or negative parallax relative to the screen plane.

The current chapter reports two experiments investigating the relationship between negative parallax, visual comfort, and stimuli hinge. In experiment II, the hinge angle co-varied with the screen disparity of the hinge edges; in experiment III, screen disparity was kept constant, and hinge angle co-varied with the physical screen width. All other methods are identical and apply to both experiments. Both experiments also share in the literature substrate with Experiment III being a logical expansion of Experiment II. This experiment addresses H₂: Parallax is, firstly, not correlated with comfort and, secondly, is not correlated with distortion (i.e., angular distortion) and H₃: Distortion is affected by hinge placement on-screen while comfort is nuanced.

4.3 Experiment II: Method

4.3.1 Participants

Experiment II involved 40 participants ($n = 40$). Of the 40 participants in Experiment II, 14 were male and 26 female. Mean age and IPD (\pm SD) of participants was 20 years (\pm 2.985) and 52.97mm (\pm 5.695), respectively).

All but two participants were recruited by volunteer sampling through the EPR Scheme conducted by the Psychology Department at the University of Liverpool, i.e., were first year undergraduate psychology students. The other two participants were undergraduate students from other disciplines. All experiments were approved by the ethics department at the University of Liverpool and all participants were fully debriefed on completion of the study.

The participants were also provided with an information sheet and upon having thoroughly read this, a consent form. They were reminded of their right to withdraw.

Please also refer to Section 2.1.2: Participants.

4.3.2 Apparatus

An LG D2343P-BN passive display was used. It has a width of 50cm and height of 28.7cm and uses the native resolution of 1920 x 1080 pixels, with a 16:9 aspect ratio. Its refresh rate is 60 Hz but it uses passive polarizing so the flicker is global across the screen, not intra-ocular. The FTFR (film-type pattern retarder) used in the LG display functions by alternately presenting odd and even horizontal lines to the left and right eyes. This results in a vertical disparity intra-ocular difference of 0.025° or 1.5 arcminutes. Tyler et al. (2012) report a nil discomfort rating for vertical disparities of under 10 arcminutes so this misalignment should not influence the results for comfort.

With the 23" LG passive polarizing 3D monitor, circular polarizing glasses (RealD glasses) at a resolution of 1920x1080 pixels were used. The screen had a horizontal screen width of 51cm giving a resolution of 100 PPI. An “above below” stereo image with an individual eye resolution of 1920x540 pixels was processed into a 3D passive line interleaved image. This formatting reduced aliasing and maximised horizontal disparity resolution. Additionally, the screen was set to low contrast and low black values with all image correction disabled.

The passive polarizing monitor was on a table which was raised to be at comfortable viewer height. Affixed to the table was a height adjustable chin rest and participants were seated on a height adjustable chair. A tape measure was used to ensure all participants were the same distance away from the screen (50cm). This configuration ensured that participant eye height was in the vertical centre of the screen. The background room illumination for the experiment was measured with a photometer at 350 cd/m^2 through the polarising glasses.

4.3.3 Design

Following Banks et al. (2009), the stimuli were simple stereoscopic hinges. We compared the perceived 3D shape obtained psychophysically with the predictions based on ray tracing, recorded the viewing comfort of each experimental condition and assessed these in relation to the tolerable limits of parallax at different horizontal disparities (or IAs) using a hinge angle estimation task. The hinge stimulus also contained monocular texture cues.

The investigation in Experiment II used a stereo hinge placed in front of (out of) the screen plane (negative parallax). The hinge was kept at a fixed width as its angle varied, its depth changed.

Five hinge angles were rendered for each of five different camera separations shown in Figure 4-1.

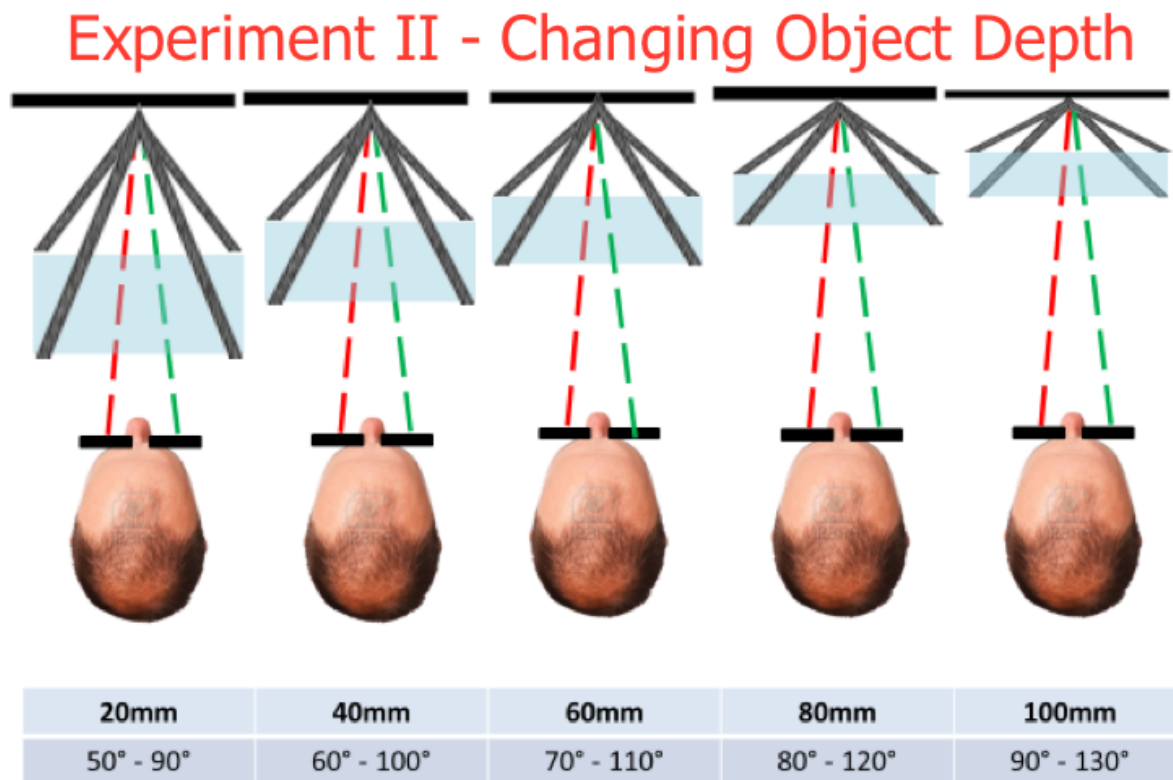


Figure 4-1. Experimental parameters for presenting stereo hinge stimuli for Experiment II, showing the various combinations of the five camera separations (20-100mm) and the hinge angles (50°-130°).

Figure 4-1 shows the various combinations for parameters when presenting stimuli in Experiment II. The top row in Figure 4-2 below illustrates the five hinge angles used at each of the five virtual camera separations of 20, 40, 60, 80, and 100 mm. Each of the five camera separations was interleaved with five angles in 10° steps: 50° to 90° at the 20mm camera separation, 60° to 100° at the 40mm camera separation, 70° to 110° at the 60mm camera separation, 80° to 120° at the 80mm camera separation, and 90° to 130° at the 100mm camera separation (see Table 4-1). These combinations are also denoted in the bottom row of Figure 4-1.

The disparity at the edges of the hinge stimuli co-varies with the angle, while the physical screen width of the rendered hinge object remained constant in all conditions. The hinge object was

deepened to change the rendered angle. The bottom row of Figure 4-2 illustrates how the hinge is predicted to appear based on ray-tracing.

Table 4-1. Experimental conditions for Experiment II.

		Hinge Angle				
Camera Separation	20mm	50 °	60 °	70 °	80 °	90 °
	40mm	60 °	70 °	80 °	90 °	100 °
	60mm	70 °	80 °	90 °	100 °	110 °
	80mm	80 °	90 °	100 °	110 °	120 °
	100mm	90 °	100 °	110 °	120 °	130 °

Table 4-1 lists the five hinge angles presented at each of the five virtual camera separations, 25 in all. These different hinge angles were rendered offline prior to the start of the experiment and loaded before each trial.

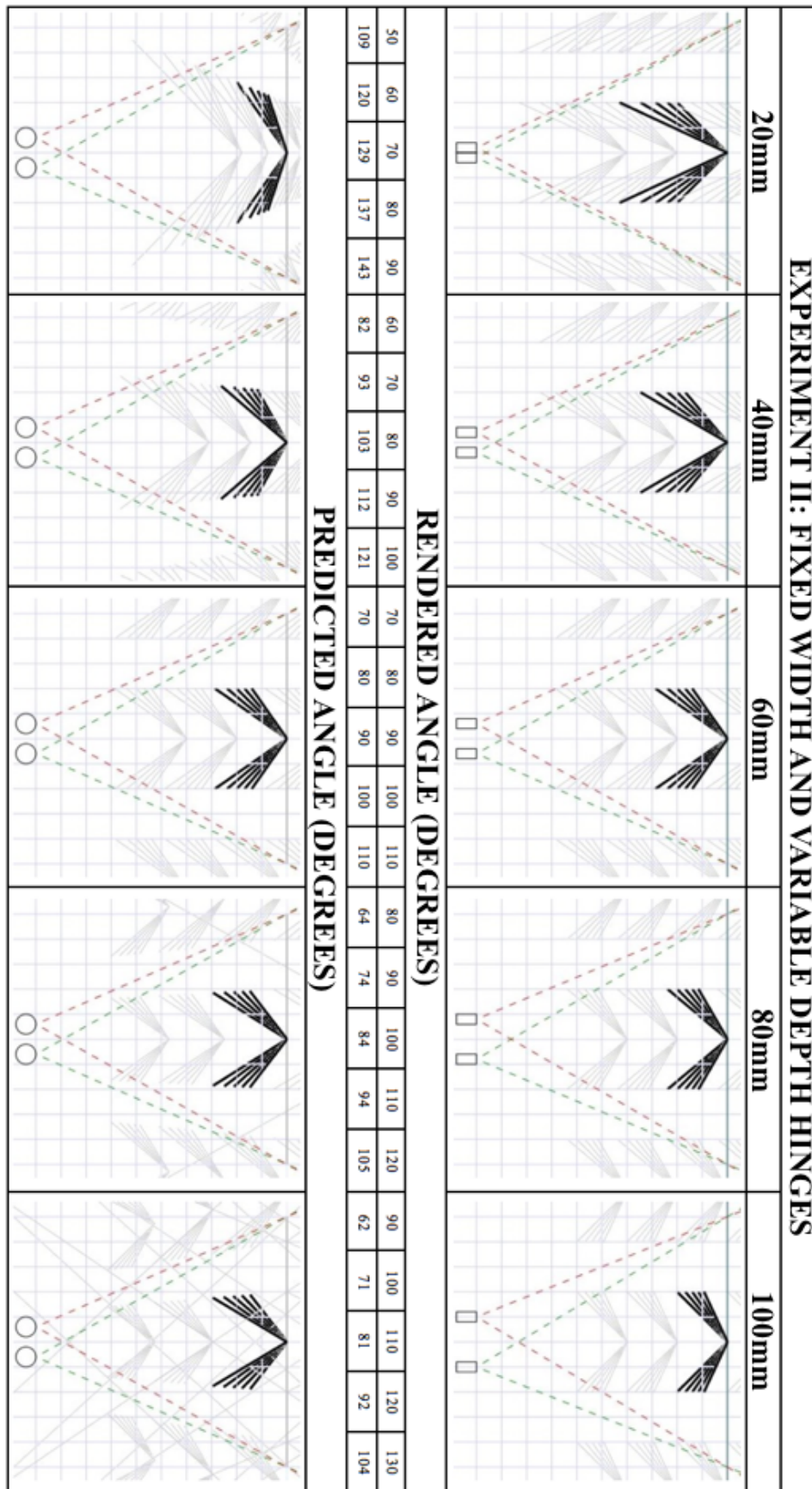


Figure 4-2 - Experimental parameters for presenting stereo hinge stimuli for Experiment II, showing the various combinations of the five camera separations (20-100mm), the rendered hinge angles (50°-130°), the predicted angles, and the perceived shape.

4.3.4 Procedure

Each of the 25 different hinge angles was shown 10 times, resulting in a sequence of 250 images. Camera separations and angles were randomly interleaved within a single experimental session. Participants were instructed to attend to a fixation cross that was presented at the screen plane. Participants were asked to judge whether the angle was larger or smaller than 90° (Banks et al., 2009; Vienne et al., 2011), hence, a total of 250 2AFC judgements. They had to respond on the gamepad using the back-left trigger button for less than 90° and the back-right trigger button for greater than 90°.

The experimental trial sequence consisted of a fixation cross (500-1000msec), a blank screen (100 msec), the stimulus presentation (300-3000 msec), and a blank screen (100 msec). There was also a 1000-msec delay between stimulus presentation and response to ensure the stereoscopic image was fixed. [See van Boxtel, Knapen, Erkelens, and van Ee (2008) for an exhaustive analysis of the relationship between blank periods and the cue conflict condition].

Subsequently, they were asked to rate how comfortable the image was to view on a five-point Likert scale, with 1 being the least comfortable to view and 5 being the most comfortable to view. To adjust the comfort rating, the participants pressed the “A” button on the gamepad. To advance to the next trial, they were asked to press the forward button.

After completing the experiment, participants filled out an electronic version of the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993) as described in Chapter 2. They indicated 16 responses on a four-point Likert scale, where 0 indicated no negative symptoms and 3 indicated severe symptoms. Their total scores on the SSQ represent the overall severity of cyber-sickness experienced. They had a five to ten-minute rest before continuing to the next session. Participants were debriefed and thanked after completing all the sessions.

Figure 4-3 and Figure 4-4 show overview diagrams of the experimental procedure.

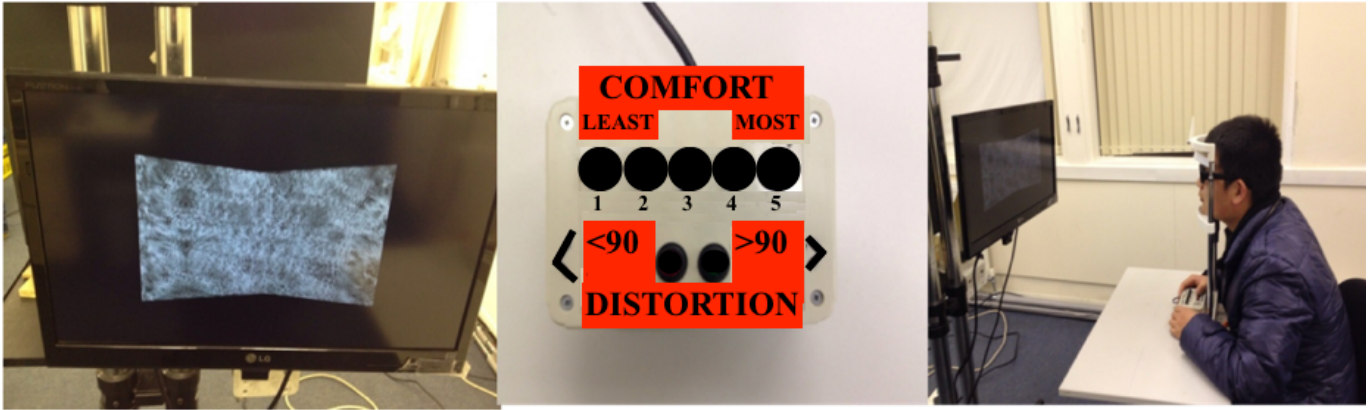


Figure 4-3. Summary of the methodology and procedure of this experimental setup showing the stimuli as displayed (left panel), a gamepad for the comfort rating (centre panel), and the subject's overall setup (right panel). In the right panel, *note* the arrangement of the apparatus, specifically: the display, the chin rest, the 3D glasses, and the gamepad.

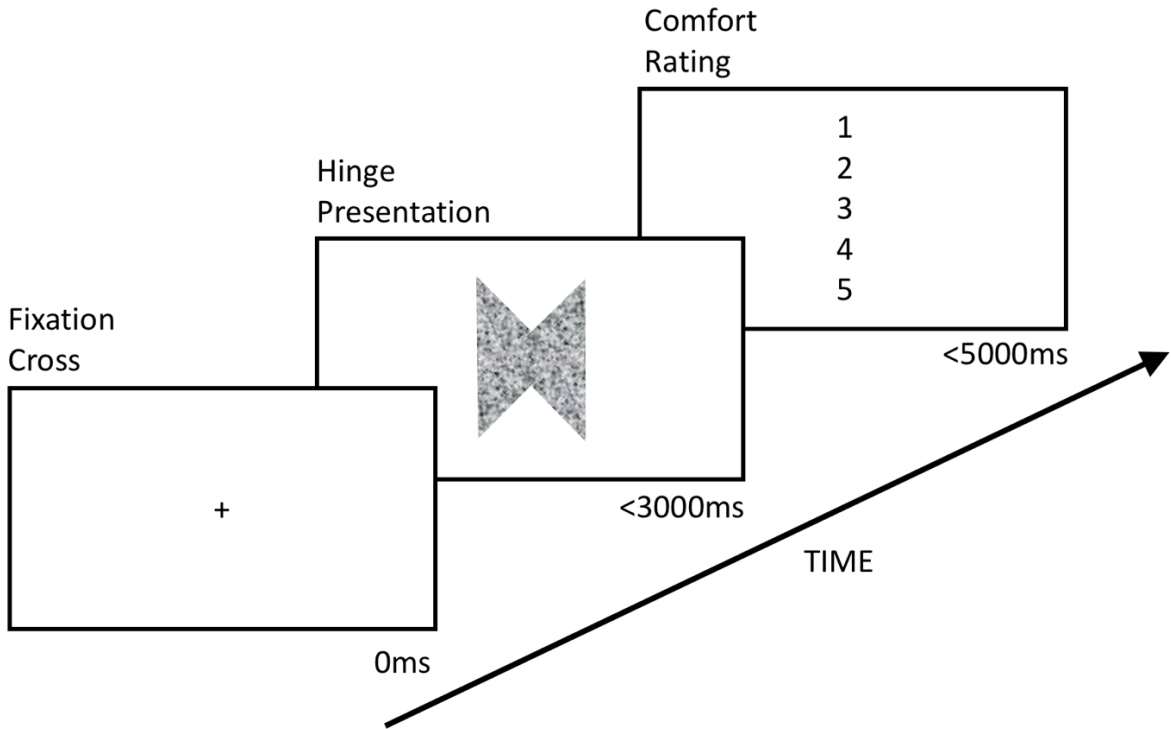


Figure 4-4. Schematic diagram of the experimental trial sequence and times from a fixation cross to hinge presentation and comfort rating.

Overall hinge disparities presented were in the range (30-165 arcmin). As shown in Figure 4-5, screen width (50 cm), viewer distance (60 cm), target width (20 cm), and virtual target distance (60 cm) were calibrated to display an orthoscopic image with a matched 45° horizontal field of view to the angle of view i.e., stimuli were presented in orthoscopic conditions with screen and observer field of view (FOV) matched at 45°.

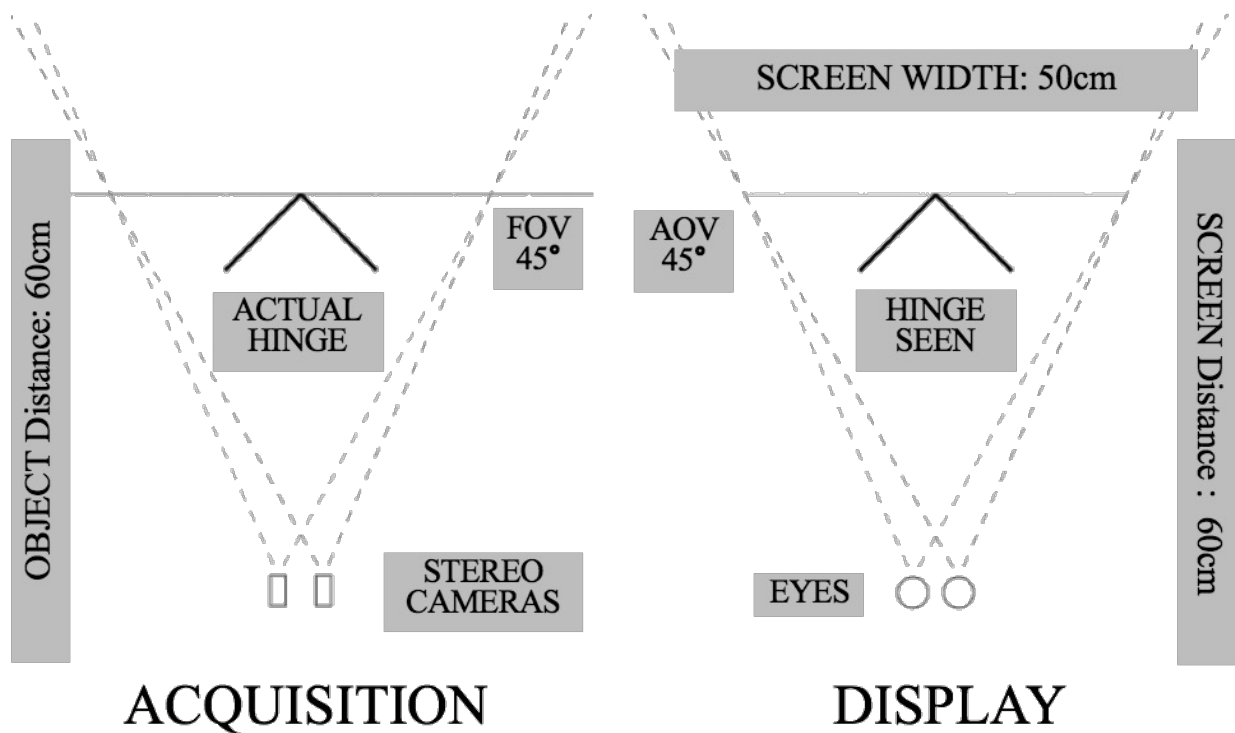


Figure 4-5. Acquisition (left) and display (right) factors used in the experiments showing a match between camera FOV and display AOV (45°) with stimuli presented orthoscopically (i.e. IA = HIT = IPD = 60 mm).

Previous experiments (Banks et al., 2009; Vienne et al., 2011) have used a similar set up. Figure 4-6 shows the layout of the observer's head position on the chin rest 60cm in front of the 3D display. The observer is wearing passive polarizing 3D glasses and the head is position so the eyes are horizontally level with the centre of the screen. IPD subtended a range from 52mm to 68mm, meaning that the selected range of targets at fixed interaxial steps of 20, 40, 60, 80, and 100mm were close to $\frac{1}{3}$, $\frac{2}{3}$, 1, $1\frac{1}{3}$, and $1\frac{2}{3}$ x IPD.



Figure 4-6. Observer's head position when responding to the experiment. *Note* that the observer responds while still positioned on the chin rest.

Angle responses were predicted using a ray-tracing disparity model that fully incorporated the HIT and the results compared with the perceived 3D shape obtained psychophysically. In order for the projection to be orthostereoscopic, the actual hinge and the hinge seen should match exactly as shown in Figure 4-5.

The figures below represent the predicted hinge angles at the different camera separations based on a ray-tracing model. Camera separation ranged from 20mm to 100mm and was varied at 20 mm increments.

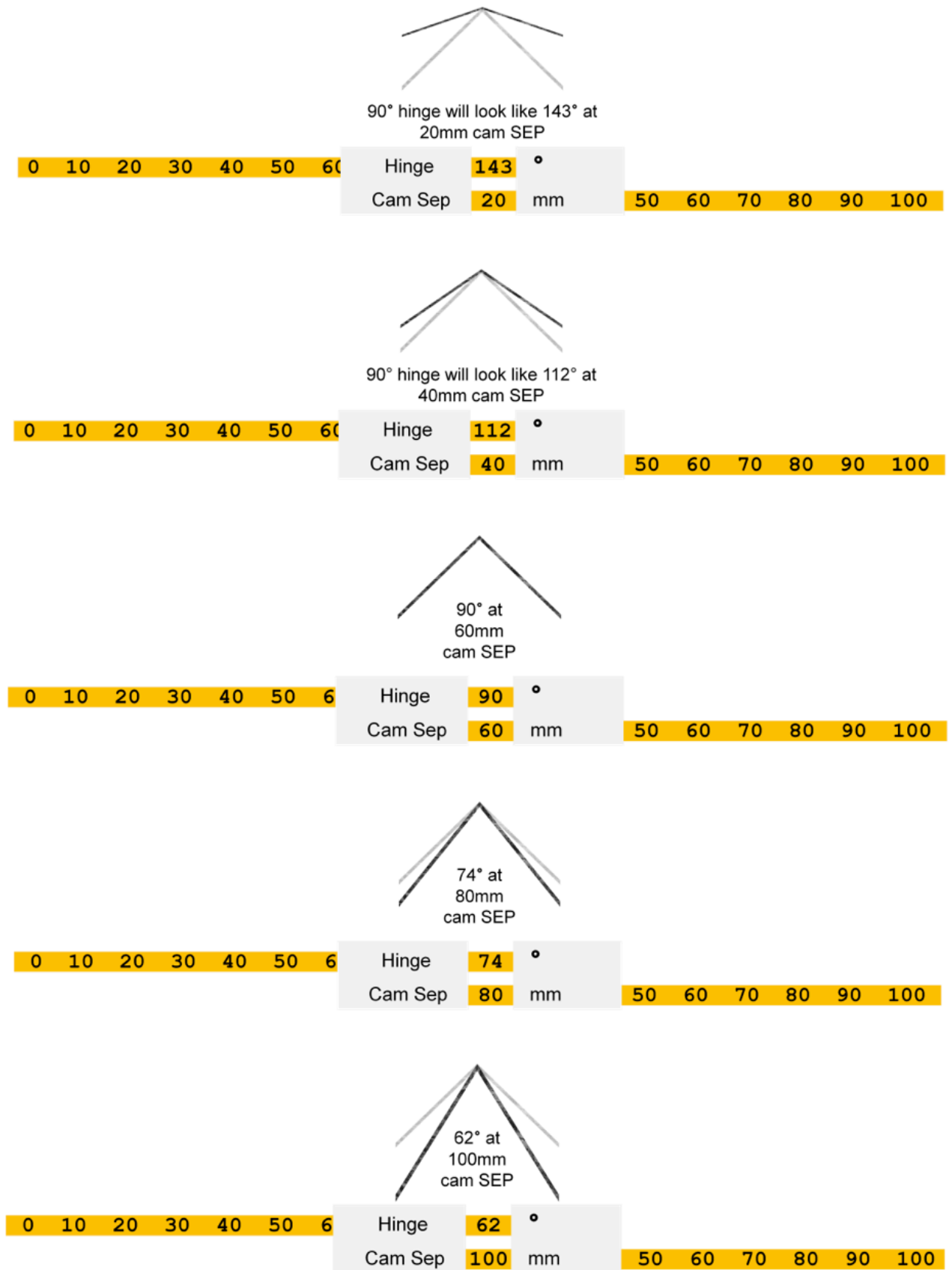


Figure 4-7. The predicted hinge angles at different camera separations based on a ray-tracing model.

This experiment (Experiment II) and those that follow (Experiments III and IV) both investigate whether these predictions agree with the observed hinge angles.

4.3.5 Comparison with Methodology of Previous Researchers

The experiments reported in this dissertation were originally developed by Banks et al. (2009). Banks designed a ray-tracing model, based on a pinhole camera system. His system used a parallel projection stereo rig with a 62-mm IA with a virtual camera rig with a focal length of 6.5 mm. The viewing distance was 45 cm. When devising this experiment, the Banks methodology was the only one considered and adopted as his was based on similar ray-tracing to the application used in this research. However, subtle differences are present between the method in this experiment and Banks et al.'s (2009) work. Firstly, viewing distance was 60cm from a 50-cm wide screen to give a horizontal field of view of 45°, Banks used a 45-cm viewing distance from a 38-cm wide screen to give a horizontal field of view of 46.35°. Despite the viewing distance being different, the visual angle is the same, although the difference in viewing distance may have different magnitude changes for the accommodation/vergence ratio. A fuller discussion of their findings and that of allied researchers is found in Section 1.6.5: Relationship between Viewer Discomfort and Limiting Parallax.

In the experimental series described in chapters 4, 5, and 6, an LG D2343P-BN passive panel was used. This is functionally comparable to a 21" NEC CRT which contains an FD Trinitron tube so that it is neither barrel nor spherically curved but flat, which Banks et al. (2009) used. It is noted that there are reports online and elsewhere regarding excessive ghosting when using this display in stereo mode (PC Mag, 2001; Hernandez, 2008; Li & Caviedes, 2012; Vatolin et al., 2012; Wil_E, 2001; Woods, 2005; Woods & Harris, 2010; Woods & Rourke, 2004; Woods & Tan, 2002).

Banks et al. (2009) report the use of an unusual resolution of 1600 x 1024 pixels which is an aspect ratio of 14.1:9. The CRT has a native resolution of 2048 x 1536 pixels. The width of the display is 38.7cm and the height is 28.4 cm. The 1600 x 1200 maximum refresh rate is 109 Hz. The authors do not report the refresh rate used but it is a theoretical maximum of 54.5 Hz per eye. For a display with a visual angle of 45°, this is likely to cause noticeable flicker in stereo mode albeit limited by the images being static, a finding that was confirmed during piloting (see Section 3.1: Pilot Experiment).

4.4 Experiment II: Results

4.4.1 Perceived Distortion

An initial analysis was undertaken to ascertain whether participants were able to distinguish between different angles at each camera separation: did they see the shapes as being different from each other?

A mixed model was applied to PSE with camera separation. In Experiment II, there was a main effect of camera separation ($\chi^2(1) = 201.43, p < 0.001$). The models are plotted in Figure 4-8 below.

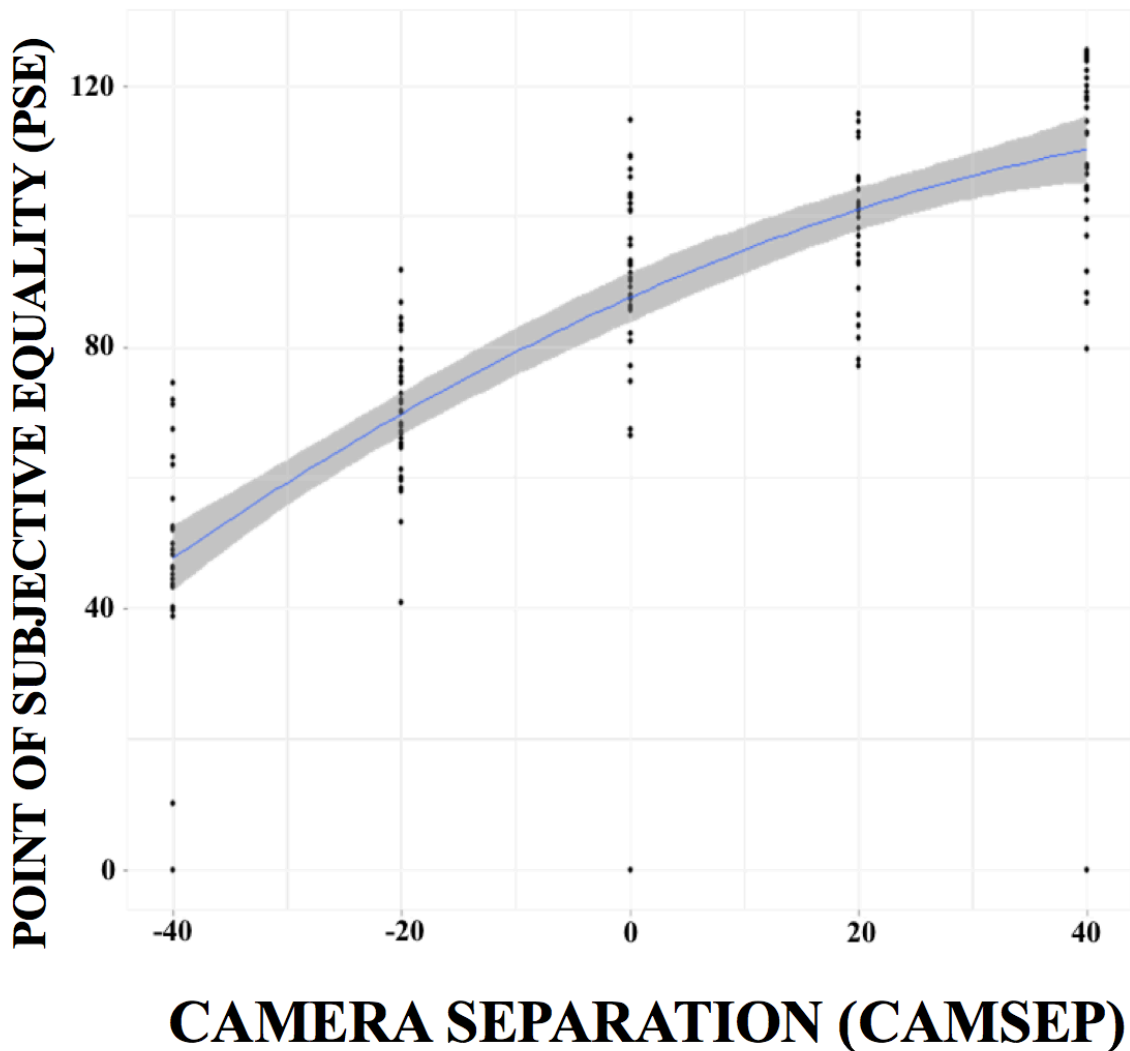


Figure 4-8. PSE Curves for camera separations between 20 mm and 100 mm for Experiment II (60mm camera separation rebased to 0mm).

This indicates that there is a significant main effect of camera separation for the experiment- participants were detecting differences. Can this difference be predicted by a model? And does this model need to be sensitive to the participants' individual IPDs?

The first model tested assumed an IPD of 60 mm for all participants.

A mixed polynomial model was applied to PSE and compared to PSE – pred60 (the predicted value of angle for a participant with a 60-mm IPD). In Experiment II, the 60-mm IPD model correlated with the data: $r^2 = 0.6321$.

The second model was tailored to each participant's IPD (50-75 mm).

A mixed polynomial model was applied to PSE and compared to PSE – predIPD (the prediction value of angle for the participant's IPD). In Experiment II, the tailored IPD model correlated with the data: $r^2 = 0.6235$.

In the experiment, the value of r^2 obtained is very similar between the 60-mm IPD model and the tailored IPD model: that is, 0.6321 vs 0.6235. Thus, there is not a benefit of tailoring the model for individual IPDs and all ray-tracing predictions are based on an IPD of 60 mm.

The results of the perceived angle measurements in Experiment II are summarised in Table 4-2 and depicted in Figure 4-9.

Table 4-2. Experiment II: Mean and standard deviation for point of subjective equality.

Camera Separation		Experiment II		
		N	Mean	S.D.
20mm		40	45.8°	16.8°
40mm		40	70.8°	10.5°
60mm		40	87.3°	23.0°
80mm		40	100.5°	10.4°
100mm		40	110.6°	21.9°

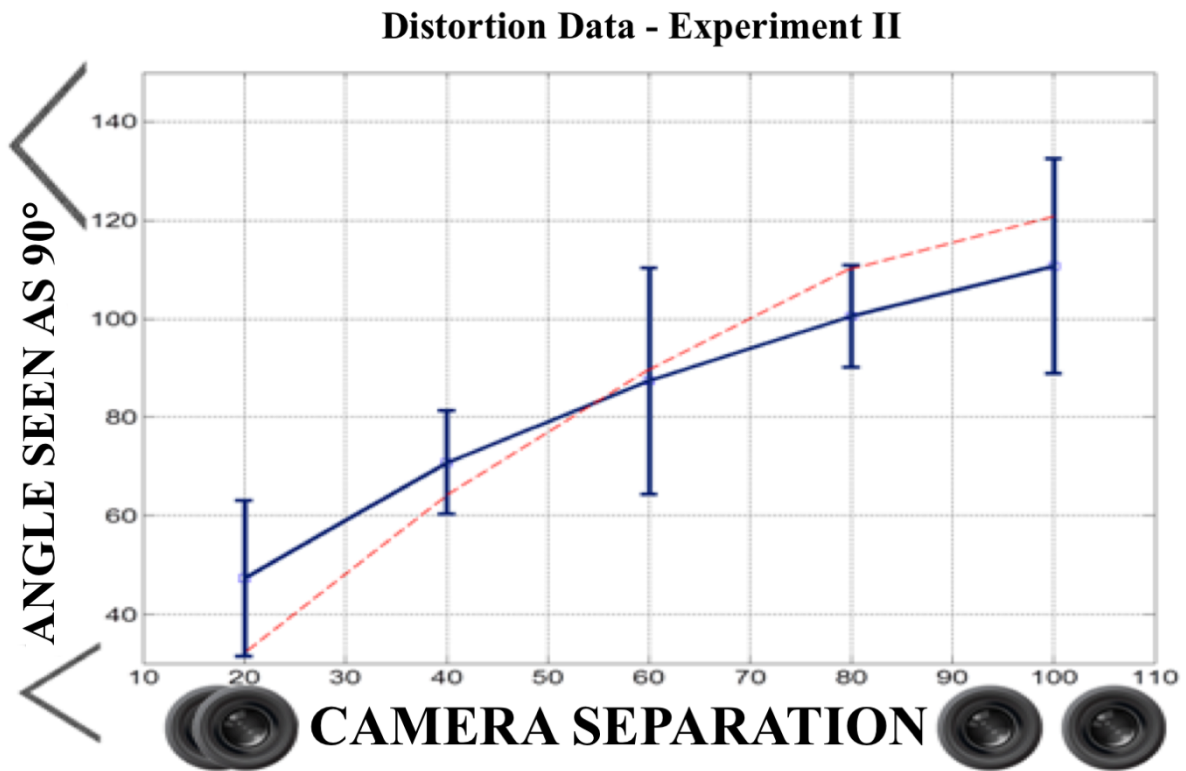


Figure 4-9. Experiment II: Distortion data for fixed-width stimuli.

Figure 4-9 shows the points of subjective equality (PSE), i.e., the angles perceived as a right angle- for camera separations of 20-100 mm in 20-mm steps for fixed-width stimuli. The values predicted by ray-tracing are shown as the red-dotted line.

Experiment II replicated the findings of Banks et al. (2009) for a camera separation of 60 mm: the PSE for a 90° angle is approximately 90°; when the camera separation matched the mean IPD, the perceived angle matched prediction. For other camera separations, the observed results generally followed the predicted, although the 20-mm and 40-mm camera separations were perceived as being more obtuse than the prediction, whilst the 80-mm and 100-mm separations were perceived as being more acute.

Repeated-measures ANOVAs (camera separation) showed a significant main effect of camera separation in the experiment: $\mu = 85.004^\circ$, $\sigma = \pm 0.64^\circ$; $F_{(1,39)} = 307.609$, $p < 0.0001$, $\eta^2 = 0.933$. This confirms the probative result obtained in the initial analysis, i.e., the pilot experiment.

Post-hoc paired samples *t*-tests showed significant differences between all combinations of PSEs (20-40 mm, 20-60 mm, 20-80 mm, 20-100 mm, 40-60 mm, 40-80 mm, 40-100 mm, 60-80 mm, 60-100 mm, and 80-100 mm) in Experiment II: $t_{(39)} \leq -6$, $p < 0.0001$.

A repeated-measures ANOVA (camera separation * experiment) did not find a significant between-participants difference between the PSEs for Experiment II: $F_{(1,76)} = 1.061, p > 0.05$.

4.4.2 Psychometric Function Slope

The data for the slope of the psychometric function are presented in Table 4-3 and depicted in Figure 4-10.

Table 4-3. Experiments II: Mean and standard deviation for psychometric function slope.

Camera Separation		Experiment II		
		N	Mean	S.D.
20mm		40	5.33	3.69
40mm		40	5.93	3.15
60mm		40	6.76	3.18
80mm		40	7.51	3.13
100mm		40	7.84	2.99

Slope Data – Experiment II

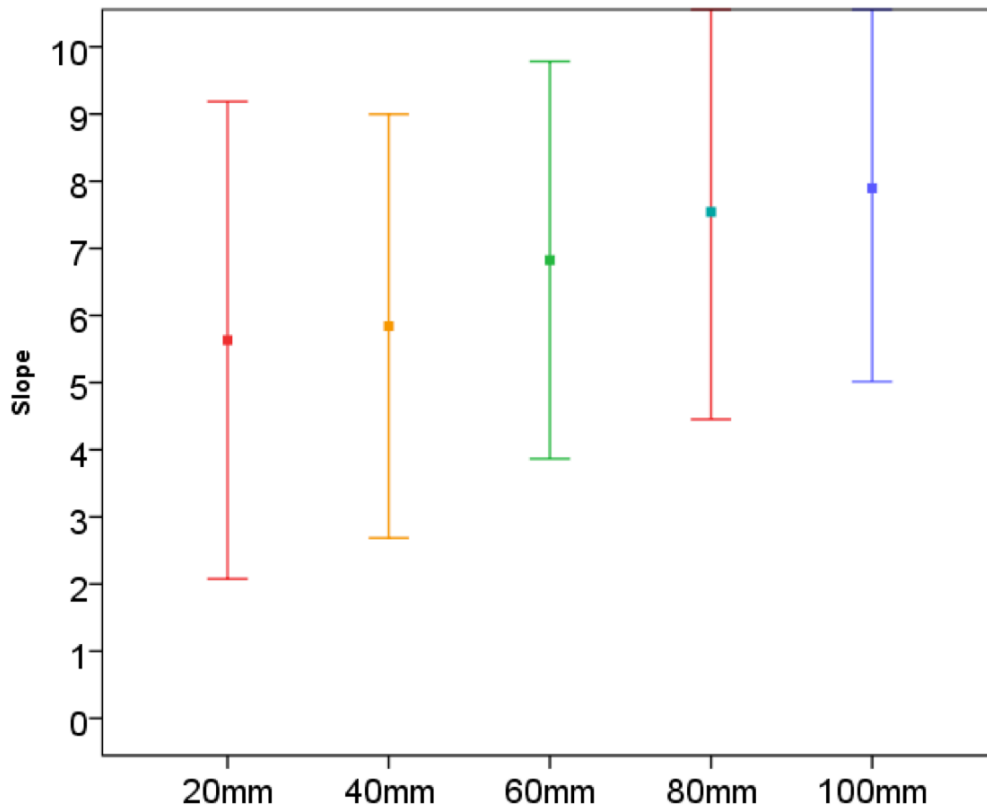


Figure 4-10. Experiment II: Slope of psychometric function for fixed-width stimuli,

The slopes in Figure 4-10 are systematically increasing, indicating the task difficulty increases with camera separation.

Repeated-measures ANOVAs (camera separation) showed a statistically significant relationship between Camera Separation and Psychometric Function Slope in the experiment: $\mu = 6.747^\circ$, $\sigma = \pm 0.0378^\circ$; $F_{(1,39)} = 7.788$, $p < 0.0001$, $\eta^2 = 0.166$), i.e., the task difficulty increased with camera separation.

4.4.3 Comfort

Table 4-4 and Figure 4-11 report comfort values at each camera separation for all hinge angles.

Table 4-4. Experiment II: Mean and standard deviation for comfort data.

Camera Separation		Comfort		
		N	Mean	S.D.
20mm		40	4.08	0.57
40mm		40	3.90	0.69
60mm		40	3.96	0.67
80mm		40	4.14	0.55
100mm		40	4.15	0.56

Comfort Data - Experiment II

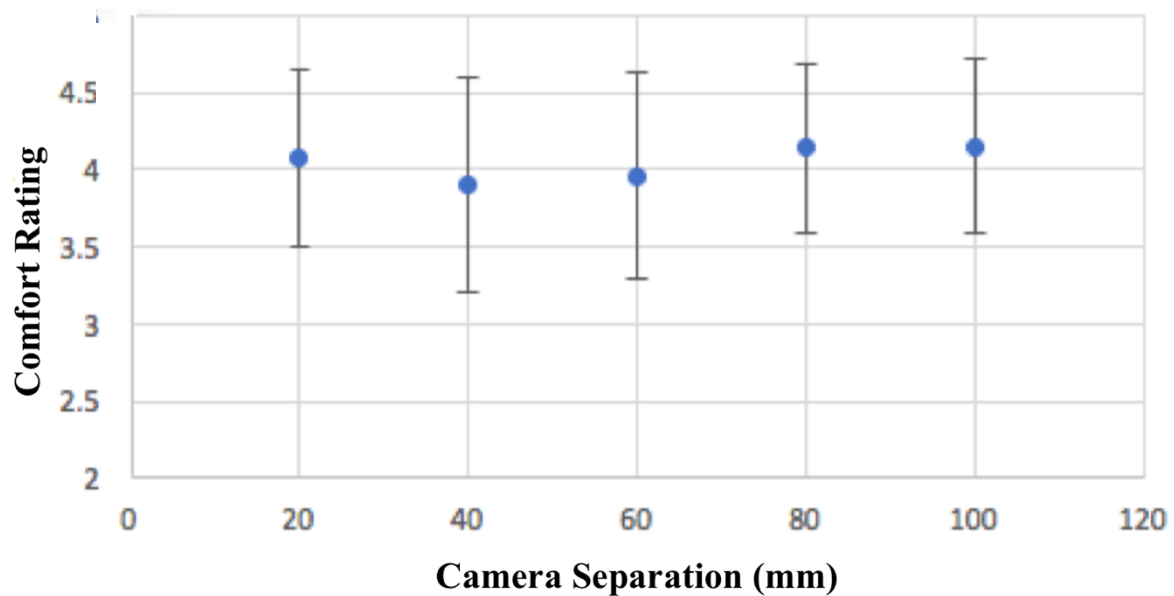


Figure 4-11. Experiment II: Overall comfort data for fixed-width stimuli.

Figure 4-11 shows the overall comfort data plotted against camera separation for Experiment II. The range of comfort values reported by the participants was between 3 (neither comfortable nor uncomfortable) and 5 (very comfortable); no participant reported a strong discomfort for any of the displayed stimuli. Mean values were almost 4 (out of 5) or above. Z-scores were computed but this did not meaningfully expand the effect.

Figure 4-11 shows comfort stays broadly flat across the camera separations for fixed-width hinges. The data indicate that camera separation of itself is not a determinant of comfort with fixed-width hinges. Next, the effect of hinge angle on comfort was analysed, and the data are plotted in Figure 4-12.

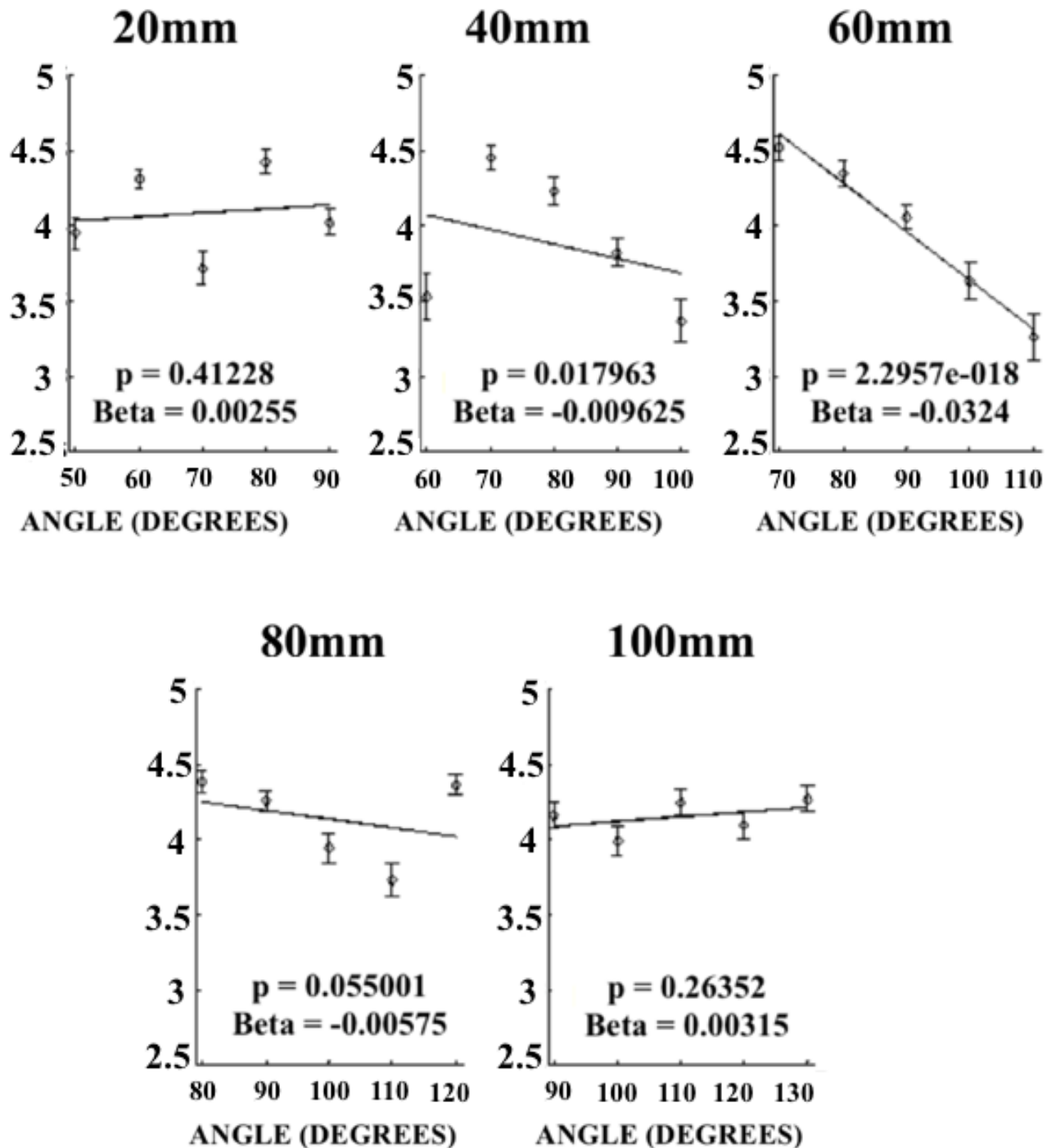


Figure 4-12. Experiment II: Comfort ratings plotted as a function of hinge angle for fixed-width hinges.

Figure 4-12 plots the comfort ratings by hinge angle for each of the five camera separations for Experiment II. It shows that the average comfort ratings are always close to 4 for the largest (100 mm) and the smallest camera separation (20 mm). For the 60-mm camera separation, there is a strong negative relationship between angle and comfort ($p < 0.001$). Since angle and disparity co-vary in Experiment II, it cannot be asserted whether this is due to hinge angle or disparity.

To understand better whether hinge angle, camera separation or both influenced comfort, a mixed effect model was applied to comfort data with hinge angle and camera separation. A maximal model was simplified until it converged.

For Experiment II, there is a main effect of angle ($\chi^2(1) = 57.797, p < 0.001$), and centred camera separation $\chi^2(1) = 10.908, p < 0.001$. There is an interaction of camera separation and angle ($\chi^2(1) = 9.0116, p < 0.01$).

4.4.4 Relationship between Comfort and Distortion

Two hypotheses were tested.

Hypothesis H₂, stated that parallax is, firstly, not correlated with comfort and, secondly, is not correlated with distortion (i.e., angular distortion), was tested by investigating whether the apparent departure from 90° as predicted by the ray-tracing model would determine comfort. For example, an angle of 50° at a 20-mm camera separation is predicted as 102°, 12° different from 90°.

In Experiment II, there was no main effect of departure from 90°: $\chi^2(1) = 0.1173, p > 0.05$.

Hypothesis H₃, which stated that distortion is affected by hinge placement on-screen while comfort is nuanced, was tested in two ways.

The first was by investigating whether the difference between the 2D angle rendered and the 3D angle as predicted by the ray-tracing model would determine comfort. For example, an angle of 50° at a 20-mm camera separation is predicted as 102°, a 62°-difference from the 50° 2D angle. A variable, distortion, was created to represent this difference.

In the experiment, there was a main effect of distortion: $\chi^2(1) = 4.2255, p < 0.05$.

The second means of testing Hypothesis H₃ was whether changes in the perceived shape would determine comfort. A linear regression model was fitted, but the results were not statistically significant.

4.4.5 Screening

Pre-screening with the Wirt/Titmus Fly Stereoacuity Test confirmed that our participant pool was normal, with stereoacuity falling within normal accepted tolerances and boundaries.

Table 4-5. The Wirt/Titmus Fly Test results for Experiment II.

Fly Test	Experiment II		
	N	Mean	S.D.
Stereoacuity	40	52.75	37.14

Table 4-5 presents the mean and standard deviation for participants' stereoacuity (expressed in seconds of arc) for Experiment II. It is possible that the stereoacuity results presented above simply reflect a bimodal split indicating that participants did not have universal opportunity to achieve feedback completion during stereoacuity analysis. The rationale underlying the validity of these results, despite the higher exclusion criterion, is provided by Tidbury et al. (2015): the authors find that, in the presence of any clinically measurable stereoacuity, depth perception when viewing S3D content will still persist. A related study by the same authors had found that stereoscopic perception of S3D content persisted in the complete absence of any such measurable stereoacuity (Tidbury, Black, & O'Connor, 2014). A similar observation can be made for Table 4-5.

Post-screening by the Simulator Sickness Questionnaire (Kennedy et al., 1993) described in Chapters 1 and 2 ascertains whether participants experienced excessive adverse symptoms.

Table 4-6 presents the mean and standard deviation for participants' responses to the SSQ for Experiment II.

Table 4-6. Simulator Sickness Questionnaire (SSQ) results for Experiment II.

SSQ		Experiment II		
		N	Mean	S.D.
Nausea		40	32.20	23.93
Oculo-motor		40	51.17	29.32
Disorientation		40	55.33	44.63
Total		40	290.30	207.33

4.5 Experiment III: Method

4.5.1 Participants and Procedure

Participants ($n = 40$), apparatus, tasks, and procedures were the same for Experiments II and III. Of the 40 participants in Experiment III, 14 were male and 26 female. Mean age and IPD (\pm SD) of participants were 21.65 years (\pm 4.475) and 62.65 mm (\pm 4.294), respectively.

Please also refer to Section 2.1.2: Participants.

4.5.2 Design

Just as with Experiment II, the stimuli were simple stereoscopic hinges. We compared the perceived 3D shape obtained psychophysically with the predictions based on a ray tracing model, recorded the viewing comfort of each experimental condition, and assessed these in relation to the tolerable limits of parallax at different IAs using a hinge angle estimation task.

The investigation in Experiment III again used a stereo hinge placed in front of (out of) the screen plane (negative parallax). The hinge was kept at a fixed depth as its angle varied, its width changed. Five hinge angles were rendered for each of five camera separations in Figure 4-13.

Experiment III - Changing Object Width

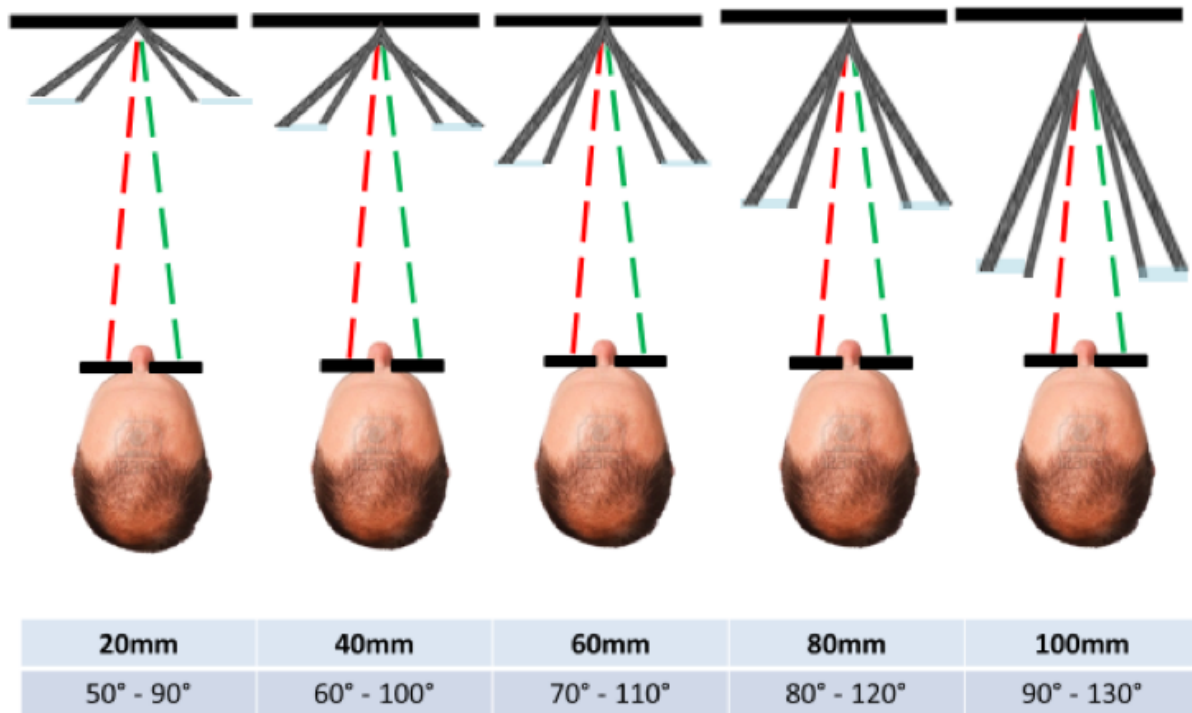


Figure 4-13. Experimental parameters for presenting stereo hinge stimuli for Experiment III, showing the various combinations of the five camera separations (20-100 mm) and the hinge angles (50°-130°).

The top row in Figure 4-14 illustrates the five hinge angles used at each camera separation (20-100 mm). The various combinations of the five hinge angles and the camera separations that they were presented in are graphically summarised in the bottom row of Figure 4-13. The screen disparity at the edges of the hinge stimuli is constant within each camera separation. The hinge object was widened to change the rendered angle. The bottom row of Figure 4-14 illustrates how the hinge is predicted to appear based on ray-tracing.

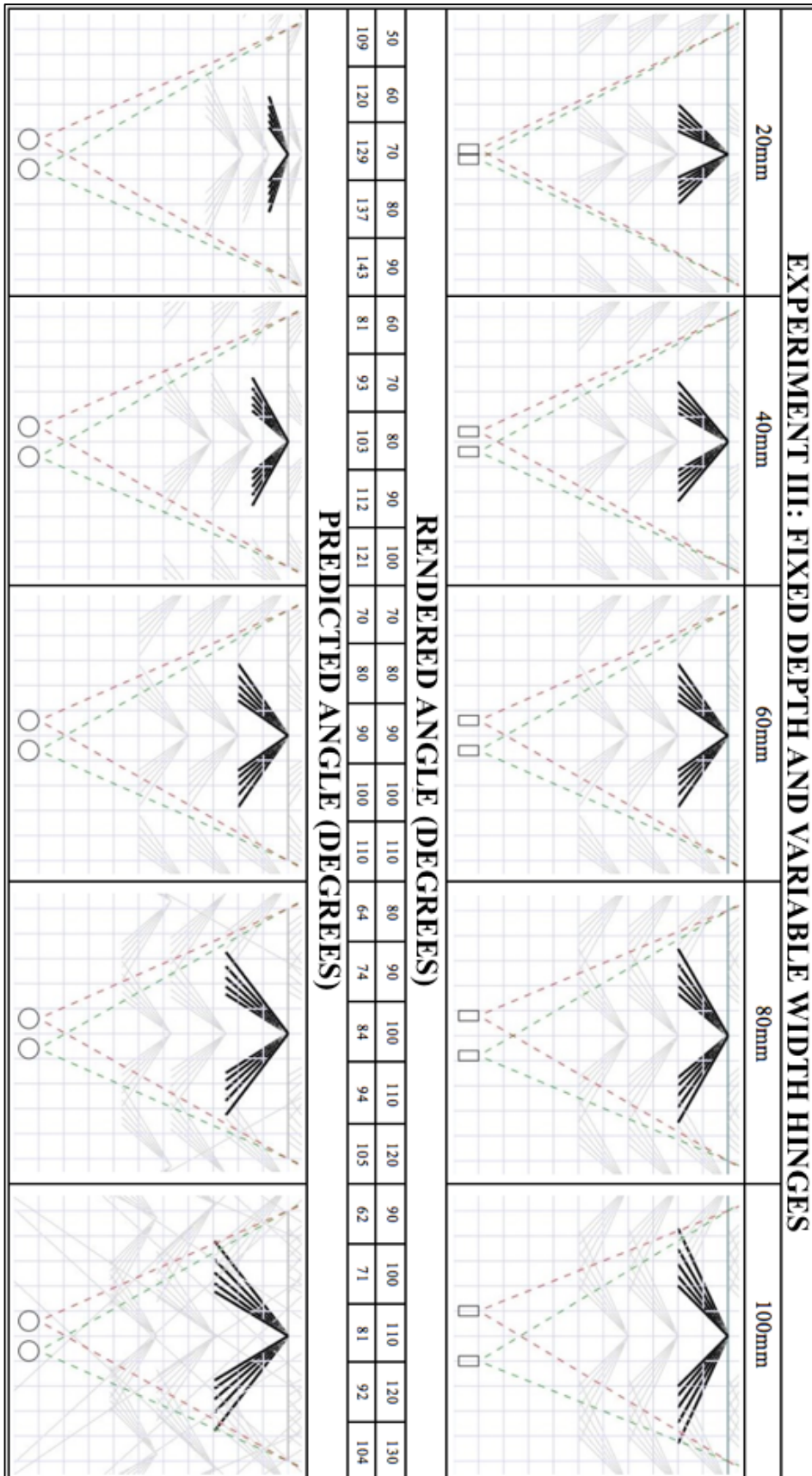


Figure 4-14. Experimental parameters for presenting stereo hinge stimuli for Experiment III, showing the various combinations of the five camera separations (20-100 mm), the rendered hinge angles (50°-130°), the predicted angles, and the perceived shape.

In Figure 4-14, the bold hinges represent the experimental stimuli. The grey hinges represent the surrounding depth context defined by using the commensurate HIT parameters. This is an important point since while the angle at the screen plane may be undistorted, the angles elsewhere become more distorted. The middle row of the figure shows the camera separations used to render the various hinge angles.

4.6 Experiment III: Results

4.6.1 Perceived Distortion

An initial analysis was undertaken to ascertain whether participants were able to distinguish between different angles at each camera separation: did they see the shapes as being different from each other?

Just as in Experiment II, a mixed model was applied to PSE with camera separation. In the experiment, there was a main effect of camera separation $\chi^2(1) = 80.533$, $p < 0.001$. The models are plotted in Figure 4-15 below.

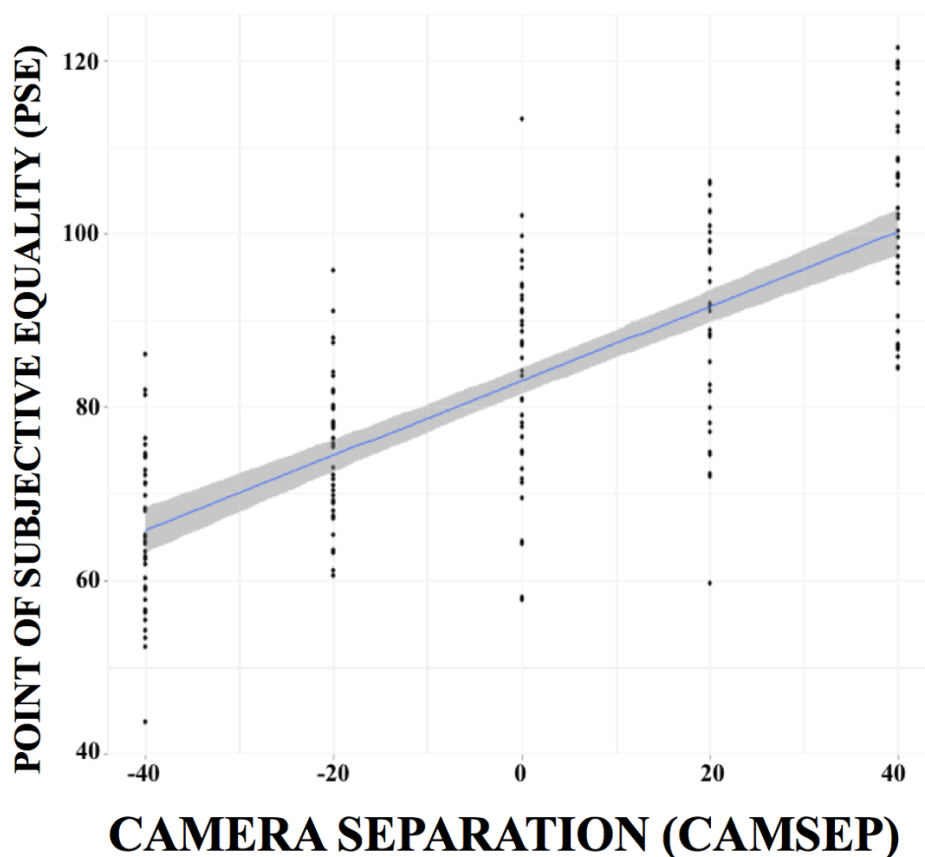


Figure 4-15. PSE curves for camera separations between 20 mm and 100 mm (60mm camera separation rebased to 0mm).

As with Experiment II, this result indicates that there is a significant main effect of camera separation for the experiment- participants were detecting differences. Can this difference be predicted by a model? And does this model need to account for participants' individual IPDs?

The first model tested assumed an IPD of 60 mm for all participants.

A mixed polynomial model was applied to PSE and compared to PSE – pred60 (the predicted value of angle for a participant with a 60-mm IPD). In Experiment III, the 60-mm IPD model correlated with the data: $r^2 = 0.5503$.

The second model was tailored to each participant's IPD (50-75 mm).

A mixed polynomial model was applied to PSE and compared to PSE – predIPD (the prediction value of angle for the participant's IPD). In Experiment III, the tailored IPD model correlated with the data: $r^2 = 0.5374$.

In the experiment, the value of r^2 obtained is very similar between the 60mm IPD model and the tailored IPD model: that is, 0.5503 vs. 0.5374. Thus, there is not a benefit of tailoring the model for individual IPDs and all ray-tracing predictions are based on an IPD of 60 mm. These findings are similar to empirical values obtained in Experiment II.

The results of the perceived angle measurements in Experiment III are summarised in Table 4-7 and depicted in Figure 4-16.

Table 4-7. Experiment III: Mean and standard deviation for point of subjective equality.

Camera Separation		Experiment III		
		N	Mean	S.D.
20mm		40	64.8°	8.9°
40mm		40	74.8°	8.2°
60mm		40	84.4°	12.3°
80mm		40	90.6°	11.6°
100mm		40	100.3°	12.1°

Distortion Data – Experiment III

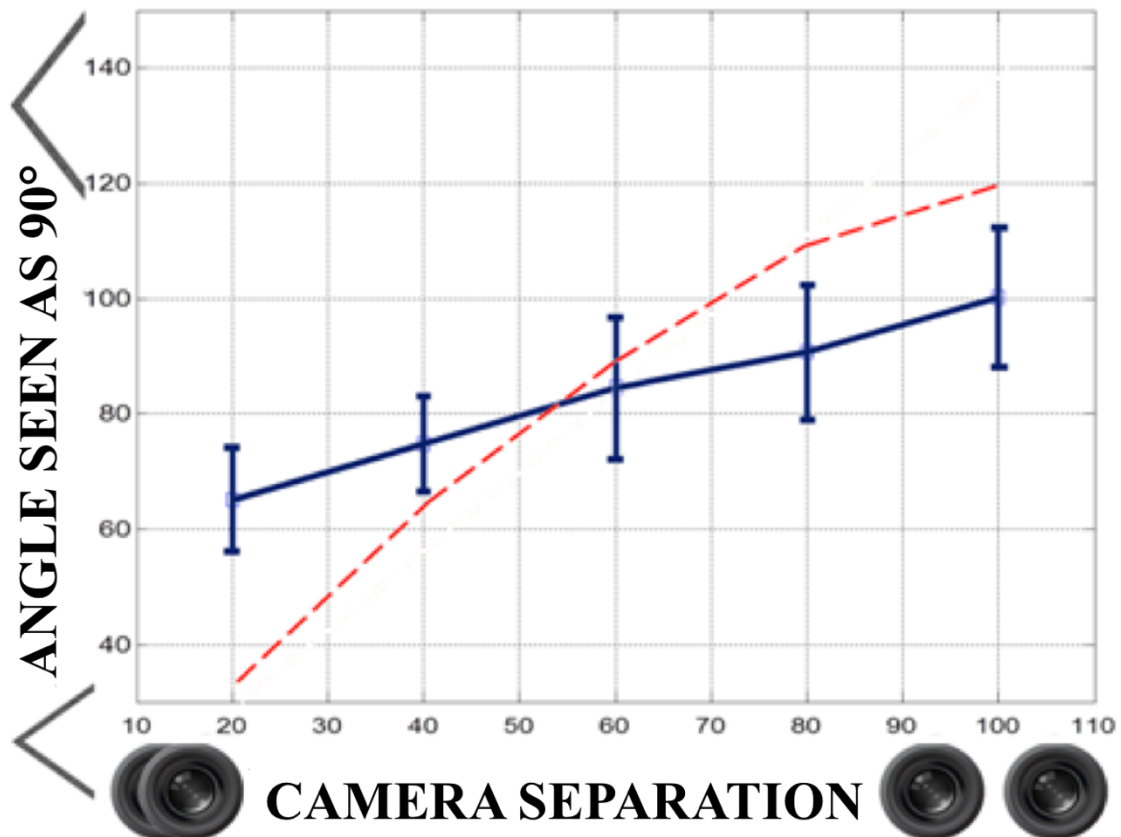


Figure 4-16. Experiment III: Distortion data for fixed-depth stimuli.

Figure 4-16 shows the PSE perceived for camera separations of 20-100mm in 20-mm steps for fixed-depth stimuli. The values predicted by ray-tracing are shown as the red-dotted line.

Experiment III shows a similar effect to Experiment II although the slope is significantly flatter than the slope of Experiment II. Increasing the width of the stimuli has caused a noticeable decrease in stereoscopic accuracy.

Repeated-measures ANOVAs (camera separation) showed a significant main effect of camera separation in the experiment: $\mu = 83.054^\circ$, $\sigma = \pm 1.402^\circ$, $F_{(1,39)} = 156.239$, $p < 0.001$, $\eta^2 = 0.880$. This confirms the result obtained in the initial analysis, i.e., pilot experiment.

Post-hoc paired samples t-tests showed significant differences between all combinations of PSEs (20-40 mm, 20-60 mm, 20-80 mm, 20-100 mm, 40-60 mm, 40-80 mm, 40-100 mm, 60-80 mm, 60-100 mm, and 80-100 mm) in Experiment III: $t_{(39)} \leq -10$, $p < 0.0001$.

A repeated-measures ANOVA (camera separation * experiment) did not find a significant between-participants difference between the PSEs for Experiment II and Experiment III: $F_{(1,76)} = 1.061, p > 0.05$.

4.6.2 Psychometric Function Slope

The data for the slope of the psychometric function are presented in Table 4-8 and depicted in Figure 4-17.

Table 4-8. Experiments III: Mean and standard deviation for psychometric function slope.

Camera Separation		Experiment III		
		N	Mean	S.D.
20mm		40	7.70	2.26
40mm		40	8.24	2.11
60mm		40	7.53	2.75
80mm		40	7.30	3.03
100mm		40	7.71	2.46

Slope Data – Experiment III

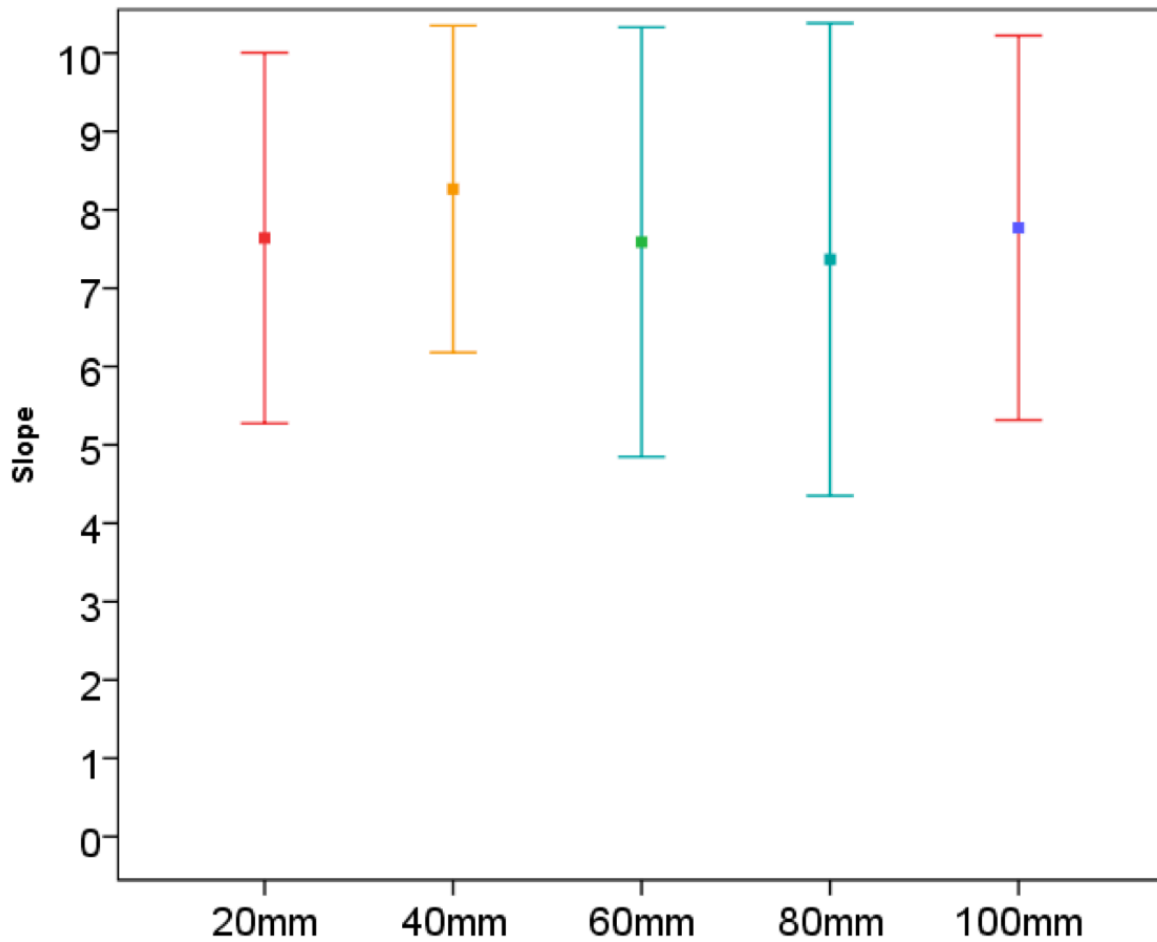


Figure 4-17. Experiment III: Slope of psychometric function for fixed-depth stimuli.

The slopes in Figure 4-17 are consistently high, a logical finding given that the task should have been harder.

Repeated-measures ANOVAs (camera separation) showed a non-significant main effect of the psychometric function slope for the experiment: $\mu = 83.054^\circ$, $\sigma = \pm 1.402^\circ$, $F_{(1,39)} = 1.002$, $p > 0.05$, $\eta^2 = 0.025$.

4.6.3 Comfort

Table 4-9 and Figure 4-18 report the comfort values at each camera separation summated for all hinge angles.

Table 4-9. Experiment III: Mean and standard deviation for comfort data.

Camera Separation		Overall Comfort Experiment III		
		N	Mean	S.D.
20mm		40	4.24	0.78
40mm		40	4.23	0.81
60mm		40	4.40	0.64
80mm		40	4.52	0.56
100mm		40	4.47	0.68

Comfort Data – Experiment III

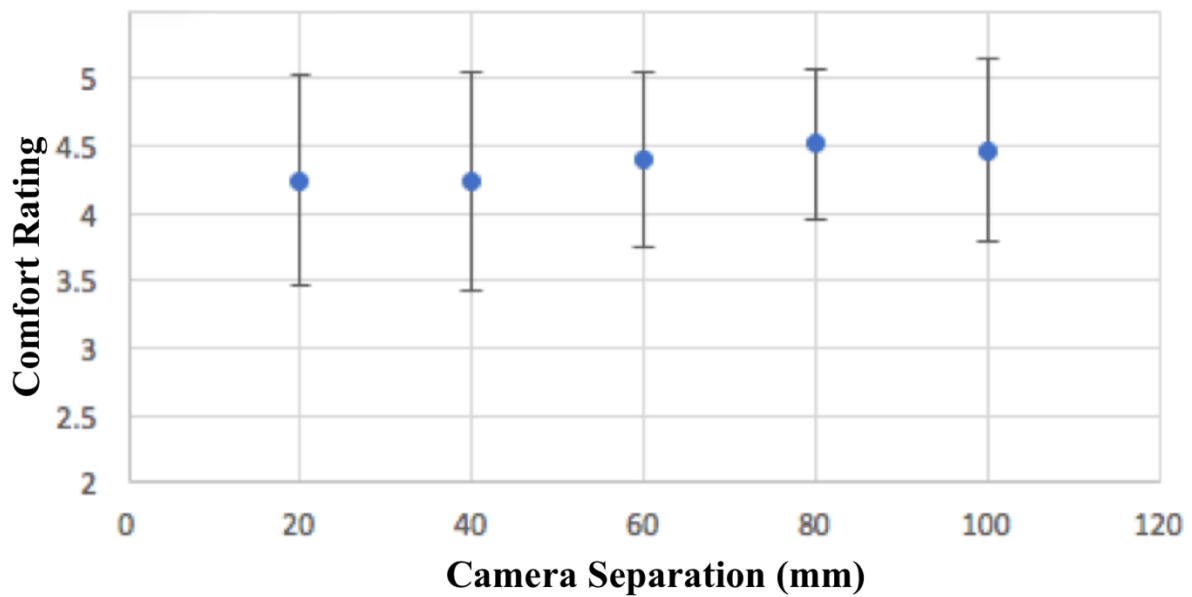


Figure 4-18. Experiment III: Overall comfort data for fixed-depth stimuli.

Figure 4-18 shows the overall comfort data plotted against camera separation for Experiment III. Like with Experiment II, the range of comfort values reported by the participants was between 3 (neither comfortable nor uncomfortable) and 5 (very comfortable); no participant reported a strong discomfort for any of the displayed stimuli. Mean values were almost 4 (out of 5) or above. Z-scores were computed but this did not meaningfully expand the effect.

Figure 4-18 shows comfort stays broadly flat across the camera separations for variable-width fixed-depth hinges. The data indicate that camera separation of itself is not a determinant of comfort with fixed-depth hinges. Next, the effect of hinge angle on comfort was analysed, and the data are plotted in Figure 4-19.

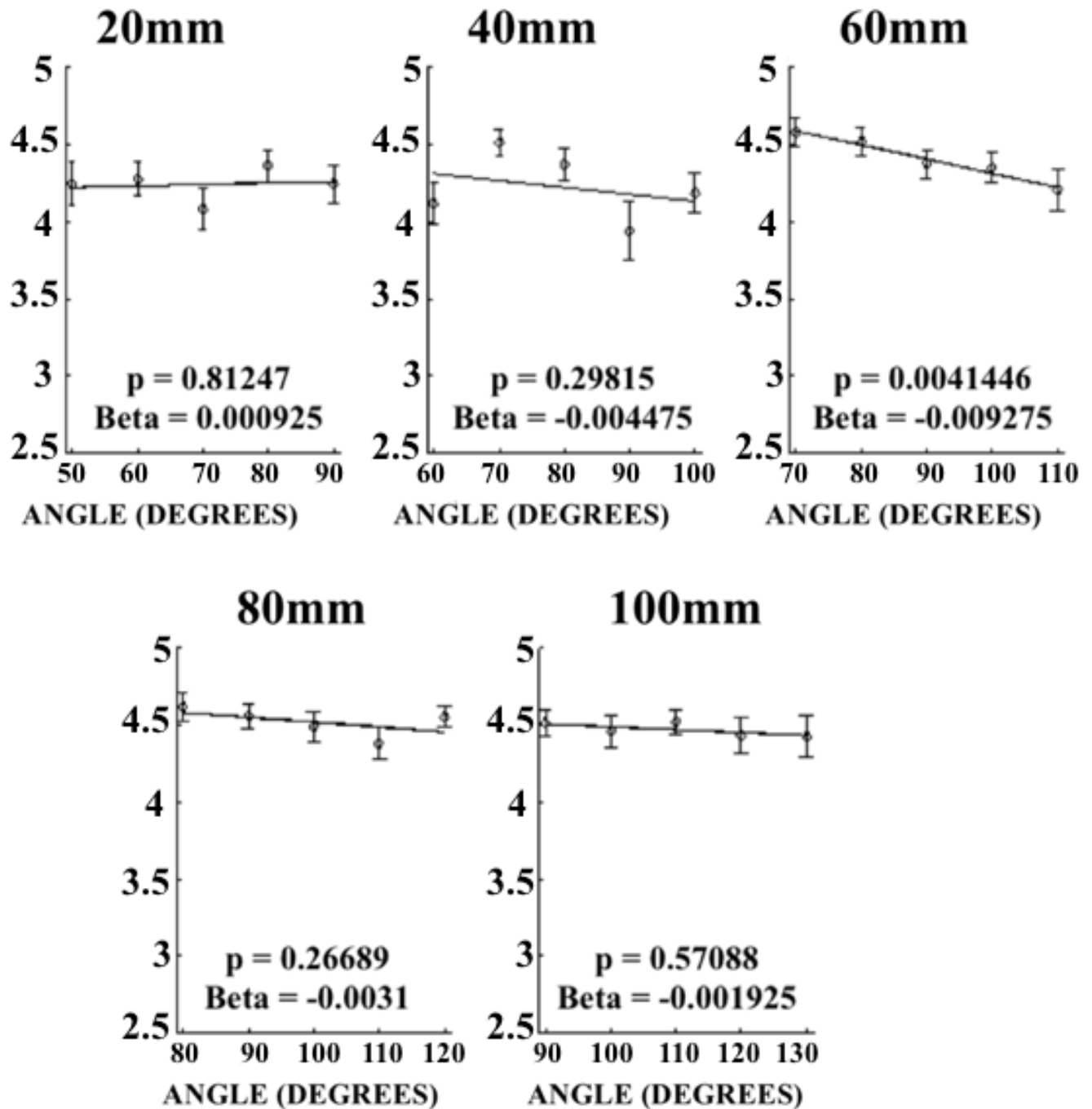


Figure 4-19. Experiment III: Comfort ratings plotted as a function of hinge angle for fixed-depth hinges.

Figure 4-19 plots the comfort ratings by hinge angle for each of the five camera separations for Experiment III. A negative association between comfort and hinge angle is present only for the camera separation of 60 mm, as in Experiment II, although the effect is less pronounced. For all other camera separations, there is no significant association between angle and comfort.

To understand better whether hinge angle, camera separation or both influenced comfort, a mixed effect model was applied to comfort data with hinge angle and camera separation. A maximal model was simplified until it converged.

For Experiment III, there is also a main effect of angle ($\chi^2(1) = 13.011, p < 0.001$) and centred camera separation ($\chi^2(1) = 55.55, p < 0.001$). However, unlike Experiment II, there is no discernible interaction of camera separation and angle ($\chi^2(1) = 1.4311, p > 0.05$).

4.6.4 Relationship between Comfort and Distortion

As with Experiment II, two hypotheses were tested.

Hypothesis H₂ stated that parallax is, firstly, not correlated with comfort and, secondly, is not correlated with distortion (i.e., angular distortion). This was tested by investigating whether comfort would be determined by the apparent departure from 90° as predicted by the ray-tracing model. For example, an angle of 50° at a 20-mm camera separation is predicted as 102°, 12° different from 90°.

In Experiment III, there was a main effect of departure from 90° ($\chi^2(1) = 15.416, p < 0.001$), contrasting Experiment II.

The second hypothesis tested, Hypothesis H₃, stated that distortion is affected by hinge placement on-screen while comfort is nuanced and was tested in two ways.

The first was by investigating whether comfort would be determined by the difference between the 2D angle rendered and the 3D angle as predicted by the ray-tracing model. For example, an angle of 50° at a 20-mm camera separation is predicted as 102°, a 62°-difference from the 50° 2D angle. A variable, distortion, was created representing this difference.

In the experiment, there was a main effect of distortion: $\chi^2(1) = 17.916, p < 0.001$.

The second means of testing Hypothesis H₃ was whether changes in the perceived shape determined comfort. A linear regression analysis was conducted, but the results were not statistically significant.

4.6.5 Screening

Pre-screening with the Wirt/Titmus Fly Stereoacuity Test confirmed that the stereoacuity measures of the participant pool were normally distributed and fell within normally accepted tolerances and boundaries, and Table 4-10 displays the mean and standard deviation for participants' stereoacuity (expressed in seconds of arc) for Experiment III.

Table 4-10. The mean and standard deviation of the study participants' stereoacuity as measured by the Wirt/Titmus Fly Test.

Fly Test		Experiment III		
		N	Mean	S.D.
Stereoacuity		40	54.75	29.78

Table 4-11 summarises the SSQ results.

Table 4-11. Simulator Sickness Questionnaire (SSQ) results for Experiments III.

SSQ		Experiment III		
		N	Mean	S.D.
Nausea		40	28.86	24.68
Oculo-motor		40	53.63	37.23
Disorientation		40	57.77	55.37
Total		40	298.54	257.81

4.7 Discussion

This section, and the figures below, re-state the experimental logic and provide a concise overview of the experimental procedure. As Figure 4-20 shows, the hinge began as a 2D image which is then duplicated.

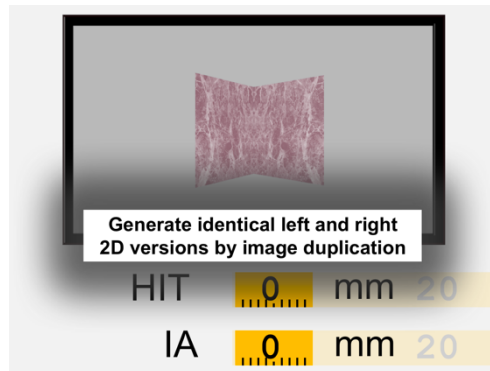


Figure 4-20. A 2D marble textured stimulus image was generated and duplicated. The HIT and IA values at each stage are shown.

Note that, in agreement with previous (see Section 1.6.4: Vergence-Accommodation Conflict: Applied Principles), HIT and IA are yoked.

After undergoing HIT, the 2D stimuli were then successfully transformed into a hinge stereo pair as illustrated in Figure 4-21: two monocularly identical left and right versions of the stimuli were transformed into a hinge stereo pair using HIT.

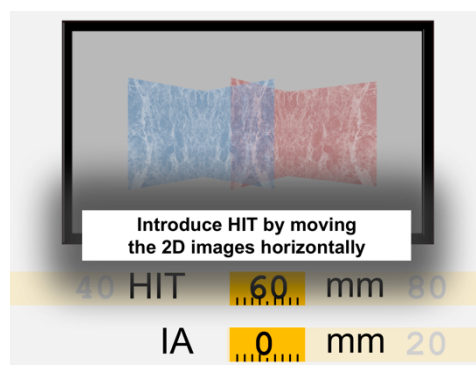


Figure 4-21. HIT was then used to transform the hinge stimulus image by moving the left and right images horizontally.

Note, crucially, that the combination of identical HIT and IA give Camera Separation (Cam Sep) (for a definition, Section 1.7.2: 3D Percept Distortions and Section 2.1.8: Psychometric Function and the Point of Subjective Equality), as shown in Figure 4-22 (the changes in the screen pictures are exaggerated for clarity).

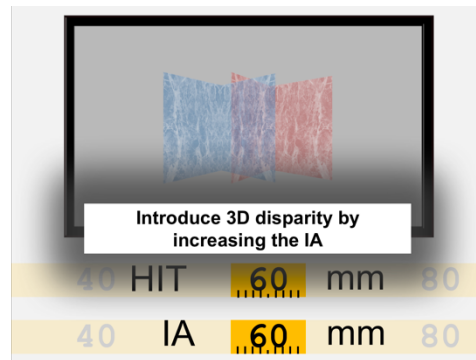


Figure 4-22. 3D disparity was then introduced by increasing the IA of the virtual stereocameras.

At this point, participants responded by reporting whether the perceived hinge angle was less than or greater than 90° using buttons on a control pad. They also responded for comfort by button press on a five-point Likert scale. Lastly, we then compared the angle perceived by an observer with angle predicted by a standard ray-tracing model.

4.7.1 Descriptive Statistics

Demographic information and IPD values are summarised in Table 4-12 below. Once again, the observers in both experiments are from different participant pools. However, the Male:Female ratio stood at ~0.54 for both experiments.

Table 4-12. Descriptive statistics for Experiments II and III.

	Experiment II	Experiment III
Age	20 years (± 2.985)	21.65 years (± 4.475)
Gender	14 Male, 26 Female	14 Male, 26 Female
IPD	52.97mm (± 5.695)	62.65mm (± 4.294)

4.7.2 Relationship between camera separation and distortion

The first main finding of these experiments is that, when rendering an angle with virtual camera separations different from 60 mm, the angle is perceived as distorted, i.e., for camera separations of 20 mm, angles look more obtuse and for camera separations of 100 mm, angles look more acute. Qualitatively these distortions are predicted by ray-tracing but the magnitude of the

observed distortions (the deviation from 90°) is smaller than predicted. The effect is more pronounced for variable-width (fixed-depth) hinges (Experiment III) than for fixed-width hinges (Experiment II).

At the camera separation level that most closely matches human eye distance (60 mm), the point of subjective equality was 90 degrees. When the camera distance was smaller than human eye distance (20 mm/40 mm), the PSE was less than 90° , and when it was larger (80 mm/100 mm), the PSE was greater than 90° . By altering the camera separation from 20 mm to 100 mm, the hinge stimulus was perceived as progressively larger. Similarly to Black et al. (2012), camera separations of 20 mm and 40 mm had a flattening effect. At the 20-mm camera separation, an angle of 68° was judged as a right angle. For the 40-mm camera separation, an angle of 74° was judged as a right angle. Note that the stimuli were not adjusted for presentation at the individual IPD which is typically between 52 and 75 mm. Preliminary data analysis (Section 3.1: Pilot Experiment) had revealed no significant effect of observer IPD on the angles perceived.

Qualitatively, these distortions (based on PSE judgements) are predicted by ray-tracing, but the magnitude of the observed distortions (the deviation from 90°) is smaller than predicted between camera separations (since the gradient of that line was steeper). To some extent, observers are able to compensate for the changes introduced by camera separations as demonstrated in the large error bars. The latter are indicative of high inter-participant variability. For smaller and large camera separations, there is a tendency to ignore the disparity information at the hinge edges and the perceived angles seem to shift towards a 90° angle. More specifically, the camera separation most closely matching human IPD was recorded at a PSE of 93° . As was expected, the PSE for both Experiments II and III replicate the findings of Banks et al. (2009). However, the PSE slope at the 60-mm camera separation for Experiment III was significantly flatter than the slope in Experiment II. Increasing the object width caused a decrease in stereoscopic accuracy, in agreement with Lee et al. (2013).

However, Banks et al.'s (2009) experiment did not investigate changing camera separations. Instead, their experimental setup generated monitor rotation and object rotation. We speculate that this could be due to observers either using monocular cues or that there is a built-in bias for right angles. The replication of Banks et al. (2009) for the 60-mm camera separation illustrates that the stereoscopic stimulus can be altered to something more realistic, like the stimulus used

in the present study, than the wire frame used in Banks et al. (op. cit.). Future experiments therefore should aim to use even more realistic stimuli or an actual scene.

The significance of the camera separation to PSE judgements contrasts with the rationale underlying the content producers' preference for use small camera separations (typically, 20mm) and wider-angle lenses (Boyle, 2012). Cameras are set to a low or very low interaxial, then the material is converged behind the screen plane. These settings are thought to be the most comfortable settings to use. However, both the prediction and experimental data show that these settings have the biggest distortive effect on what the original 2D image was trying to convey, in this instance, a right angle.

Certainly, the largest difference between prediction and perception occurred when a 20mm camera separation was used. At this parameter, the hinge angles were evaluated (i.e. 3D percept task) to be slightly more obtuse than the prediction model. However, while the predictive model is fairly accurate, the magnitude of the distortion just from this is substantial. Therefore, converging instead of reframing can be very distortive. This model demonstrates that distortion is visible even when the nodal point of the object is presented at zero disparity. Although the effect of changing HIT appears to be negligible and is advantageous to content producers since it can reduce the amount of binocular parallax information present, it must be cautioned that even small changes can have outcomes of this magnitude. Distortion data may be affected by accommodation/vergence conflict or accommodative proximity (as per Shibata et al., 2011a) or simply by the visible presence of the screen bezel.

However, the remaining inter-observer differences indicate that while participants can reliably estimate angles, their perception may be affected by additional factors beyond the scope of the model including the visible presence of screen bezel, accommodation/vergence conflict, image resolution issues and stimuli exceeding the width of their fusion zone (Liu, Bovik & Cormack, 2008). Additionally, the stimulus width of the variable width targets may have been larger than the stereoscopic overlap between their eyes given the fixation distance was only 60 cm resulting in a vergence angle of 2.286° , reducing the stereoscopic overlap from 60° at parallel to 55° .

Grüninger & Krüger's (2013) analysis of a tiled stereoscopic display setup confirmed that increasing bezel sizes distorts the perception of VR-rendered scenes. However, this distortion—a delimiting effect—causes uniquely unnatural vision for objects in positive parallax (hence the term “fishtank” stereoscopy). The bezel size of our Sony 52” 3DTV exceeds Grüninger &

Krüger (2013) threshold for satisfying results. Importantly, however, Grüninger & Krüger (2013) report no detrimental impact on task completion: in fact, they report improved task completion times. Furthermore, a non-effect of bezel width on task performance (Bi, Bae & Balakrishnan, 2010; Smith, Teather, Lass & Carette, 2015; Tan & Czerwinski, 2003; Vatavu & Mancas, 2015) and user perception (Sandin et al., 2005) is also reported in other publications. Regardless, Tan and Czerwinski (2003) note that physical discontinuities such as bezels elicit a 10% degradation in task performance *when* coupled with modulations of object depth (i.e., varying the focal point against a fixed planar location).

Another tiled-monitor publication (Wallace, Vogel, & Lank, 2014) observes that bezels wider than 0.5cm elicit perceptual errors between 4% and 7% when judging object magnitude. This is because screen bezels introduce a nearer focal plane and an obvious real-world disparity. However, the authors conceded that compensation techniques remain unresolved. It is logical to suggest the need for replicating these experiments- particularly for positive disparity- in bezel-minimised 3D TV displays. However, our 0.2” bezel is ecologically valid: bezel obsolescence has hitherto proved elusive for practical and UX reasons and consequently, replication using strikingly thinner bezels may yet prove impractical and unnecessary in light of non-consequential adoption of “bezel-less” 3D TVs.

On the other hand, vergence-accommodation conflicts may also explain the additional inter-observer differences. Human observers have globally different sensitivities to disparity and VAC. Several publications document the differences in consistency between expert and naïve observers when assessing comfort for a variety of stereoscopic stimuli. For instance, Li (2013) shows consistent results for experts compared to non-experts when assessing cause of discomfort for in-motion stereoptic stimuli. Expertise, in the sense of previous knowledge of subjective experimental methodology, is an important human factor that should be taken into account whenever inter-observer differences are observed (Heynderickx & Bech, 2002; Hands, Brotherton, Bourret & Bayart, 2005; Speranza et al., 2010; Möller & Raake, 2014; Lebreton, Raake & Barkowsky, 2016). Admittedly, our participant panel constituted entirely of naïve viewers. Vision research studies, once again, point out a multitude of variables that may affect visual perception. In turn, these factors subtly affect perception thresholds for VAC and, ultimately, distortion and self-reported comfort. The human factors include psychographic (Jumisko-Pyykkö & Häkkinen, 2008) and demographic (Quintero & Raake, 2012) variables and sensorial and cognitive styles (Jumisko-Pyykkö & Strohmeier, 2013; Serrano et al., 2017). This

variability is also observed in other publications: Gautier (2012) defends his hypothesis that disparity does not modify the inter-observer congruency (IVOC) and is consistent over time. This indicates that variability in self-reported scores, despite non-effect by disparity, is nonetheless active in subjective comfort. Interestingly, Khaustova (2015) posits that, at different screen parallax, inter-observer congruency was significantly higher with low texture complexity (i.e., with stimuli same colour as the background) than with medium and high texture complexities [i.e. checkerboard texture similar to Banks et al.'s (2009) wireframe texture], perhaps explaining the lack of radical variability for our relatively large participant panel. It is worth stating that Tidbury et al. (2015) also report substantial inter-individual differences in natural fixation point of the eyes.

Furthermore, the screen resolution of 1080 p with images made from 1920x540 halves means still only a few pixels of stereo information. The image resolution and stereo resolution are far below the 40-50 cycles per arc-degree (cpd) required to give realism (Masaoka, Emoto, Sugawara & Nojiri, 2007; Masaoka et al., 2008). As such, there are mediation cues to depth which make the scene very hard to accept given the low quality of input stimuli, hence, brutally, 3D in name alone. Also, high stimulus width would place edges beyond the foveola and macula (Liu et al, 2008), resulting in only the gradient being perceptible, not the edge disparities. Taken together, all these factors may explain the comfort values reported.

4.7.3 Relationship between disparity, distortion and comfort

Our second and most significant finding in both Experiments II and III is that comfort is mostly independent of disparity (and hinge angle). Importantly, only for the camera separation which is similar to the human average inter-pupil distance (IPD, *c.* 60 mm) is comfort dependent on the angle of the hinge: observers seem to prefer acute over obtuse angles. At all other camera separations, comfort is not related to disparity. The strong negative correlation between disparity (arcmin) and comfort and the lack of a correlation between angular distortion and comfort ratings means that changing camera separation by linking interaxial and HIT is, therefore, a distortive process making a comfortable undistorted stereoscopic image difficult to achieve. Once again, this contradicts previous research. However, it contextualises the experimental results and expands the causative explanation of viewer comfort beyond disparity alone.

The fact that we find a dependence of comfort on the stimulus angle only at this particular camera separation may indicate that observers make more efficient use of disparity information which is

consistent with the accuracy in judging the perceived angle. Yamanoue et al. (2012) found a similar pattern for their experiments when investigating the correlation between disparity and comfort.

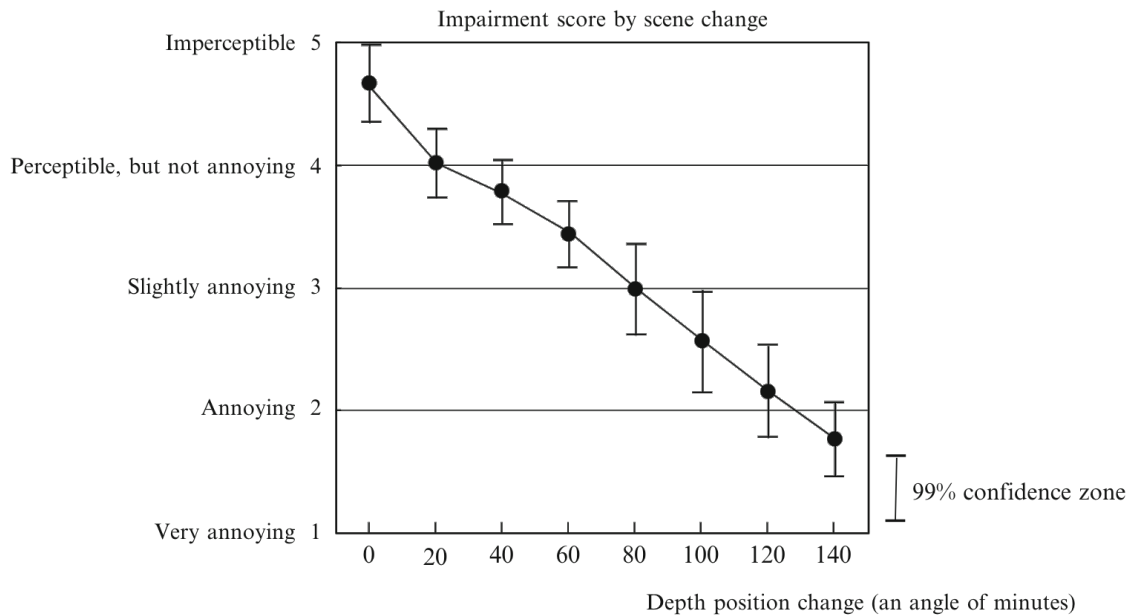


Figure 4-23 - Evaluation of impairment by changes in depth position (adapted from Yamanoue et al., 2012).

Figure 4-23 shows the results of an experiment investigating the effect of changing an image's parallax distribution on visual comfort; the depth change is evaluated against a five-point comfort impairment scale. Yamanoue et al. (2012) concluded that the tolerance limit of watching points depth-wise position change, the point where the evaluation value is 3.5 in the graph, is approximately 60 minutes of arc. However, Yamanoue et al.'s (2012) experiments used different amounts of screen disparity at different relative convergence points than the current study. The stimuli used in these experiments were objects or simplified scenes, whereas the present study employed an unnatural hinge stimulus. Their stimuli and approach suggest a logical template for future experiments.

The ANOVA statistics reflected this analysis. ANOVA results in Experiment II showed, firstly, a significant main effect of camera separation on PSE judgements, secondly, significant and consistent main effect of camera separation on comfort, and thirdly, a systematically increasing difficulty in angle discrimination as the camera separation increased. These findings suggest that as the camera separation increases, the image becomes less comfortable to view and also, that the mean difficulty in perception becomes progressively harder as the camera separation increases. The data argue that in Experiment II, comfort does seem to decrease with camera

separation, and consistently too, broadly in line with previous research (Kytö et al., 2012; Montgomery et al., 2003; Oskam et al., 2011).

One-way repeated-measures ANOVA for Experiment III showed a lower than significant main effect of camera separation on comfort compared to Experiment II, but a consistently high difficulty in the percept task as the camera separation increased (compared to the systematic increase in Experiment II). Importantly, where Experiment II showed an initially systematic relationship between disparity and camera separation that maxes out at the 80 mm-100 mm range, Experiment III reports no variation in disparity in each camera separation and the function slopes are all approximately 8, higher than all but for the 80-100mm.

Importantly, Experiment III showed that comfort stayed broadly flat for the negative (out-of-screen) parallax. Indeed, no observer reported a strong discomfort for any of the displayed stimuli. Under a maximal analysis model, both camera separation and angle were found to have individual effects. However, this interaction was far subdued when compared to Experiment II. Experiment III does not show an interaction between camera separation and angle and its impact on disparity. When plotted against the overall screen disparity, comfort ratings for Experiment III show no regression present. This indicates that stimulus width counters the amount of disparity present in each scene for fixed-depth stimuli (Lee et al., 2013).

Black et al. (2012) found that obtuse hinge angles caused a decrease in comfort at the 60mm camera separation. This study had not looked specifically at the effect of acute and obtuse angles and comfort, and instead looked more generally at the link effect of differing camera separations on comfort. However, these findings were used as a basis to predict that camera separation would affect comfort. Nonetheless, it was found that there was no significant effect of camera separation and comfort at any of the camera separations tested which was unexpected based on Black et al.'s (2012) findings. For this reason, the correlation between comfort ratings during the experiment and the SSQ conducted after the experiment was analysed.

Firstly, oculomotor sickness was paired with the participants' overall individual comfort score. To do this, the individual mean scores across the five camera separations were averaged to produce one score. No correlation was found between these two variables. Secondly, the total SSQ score was paired with participants' overall individual comfort score. Similarly, the results showed no correlation between these variables. The individual mean comfort score for all participants is between 3 (neutral) and 5 (very comfortable) apart from one score where the value

is 2.96- this can be rounded to 3 and would be placed in the neutral comfort group. This suggests that adverse effects of 3D were not related to how comfortable the image is to view, i.e., any discomfort measured was not due to cyber- or motion-sickness.

These results are unexpected because if participants have a high total SSQ score, it would suggest they were experiencing some discomfort. However, they did not state this on the computer task during the experiment. This may be due to the five-point comfort rating scale being unclear. Participants were asked to judge how comfortable the angle they had just seen was on a five-point Likert scale where 1 is very uncomfortable, 2 is uncomfortable, 3 is neutral, 4 is comfortable, and 5 is very comfortable. However, when presented with the comfort rating page, participants only saw the numerical value without the corresponding labels. Therefore, they had to rely on their memory to remember the scale and its corresponding labels which may have caused the lack of variation in the comfort scores attributed to the camera separations. Vlad, Ladret, & Guerin (2013) have used five-point scales for comfort but have presented participants with the corresponding coding. For example, the numerical value -2 is placed with “C—“, a code for very uncomfortable. In this way, it is clear to participants what each numerical value corresponds to at all times. Nevertheless, participants responded using a narrow range: the SSQ responses were indicated along a narrow four-point Likert scale, where 0 indicated no negative symptoms and 3 indicated severe symptoms. Narrowing the range of the scale was a deliberate choice and reflected concerns about undesired response variability observed in the field (Barkowsky et al., 2013; Corriveau, Gojmerac, Hughes & Stelmach, 1999; Huynh-Thu, Garcia, Speranza, Corriveau, & Raake, 2011; Jones & McManus, 1986; Lambooi, IJsselsteijn, Bouwhuis & Heynderickx, 2011).

Additionally, qualitative data was gained from participants about why they gave a particular score for the image they were judging. This reinforced the results gained from the five-point scale as it confirms that participants understood the scale. Additionally, Speranza et al. (2006) also used a written scale and found visual comfort ranged from uncomfortable to comfortable on a scale consisting of Very Comfortable-Comfortable-Mildly, Uncomfortable-Uncomfortable-Extremely Uncomfortable. A range of the values on the scale was used, so perhaps a written scale may be useful for future experiments.

It is clear that there are some issues with the rating scale as although some participants scored highly on oculomotor sickness and consequently scored highly on the individual mean comfort score, they did not give a score which reflected this (such as 2- uncomfortable or 1- very

uncomfortable). The primary type of discomfort expected were the oculomotor items on the SSQ because, as stated previously, numerous studies have found that S3D causes the same oculomotor symptoms as detailed in Chapter 1. Due to this rating issue, it is likely that the mean comfort values may have been biased to a higher value, due to the comfort value selection screen displaying the value “5” each time participants were required to respond. Future studies may wish to employ alternative methods of collecting comfort data. An example would be randomising the comfort value displayed each time a selection is necessary to avoid biasing the comfort values.

Moreover, the SSQ was originally developed to study symptoms induced by aviation simulator displays (Jumisko-Pyykko et al., 2010). The SSQ has been applied to several fields outside the aviation research community (Jumisko-Pyykko et al., 2010) such as static and dynamic environments (Jaeger & Mourant, 2001), head-mounted display use (Hakkinen, JVuori & Paakka, 2002) and near-eye display (Polonen & Hakkinen, 2009). However, it does measure factors which are not present in static 3D. Therefore, it may not be an entirely representative measure of adverse side effects from this study.

Furthermore, for both Experiments II and III, the ratio of male to female observers was 0.538, showing more female than male participants. It bears repeating, however, that the observers in both experiments—and for all experiments in this study for that matter—were from different participant pools. Häkkinen, Liinasuo, Takatalo, and Nyman (2006) hypothesise that females score more highly on the SSQ than males. If an SSQ were to be used again as a variable, the experiment should have the same number of male and female participants in order to balance this.

That said, it must be noted that the SSQ was not administered before the experiment. In this way, although it is unlikely that all participants would have been feeling unwell prior to the computer task, there is no way to disprove discomfort without SSQ pre-testing. Therefore, in future, an SSQ would be carried out prior to and on completion of the computer task to ensure the symptoms reported were due to the task and were unrelated to any other factors i.e. pre-test vs post-test scoring.

Hypothesis H₂ was supported and Hypothesis H₃ was partially supported by these experiments.

CHAPTER 5 – EXPERIMENTAL: POSITIVE PARALLAX

The purpose of Experiment IV was to repeat Experiment II using hinge images rendered behind-the-screen (positive parallax) rather than in-front-of-the-screen (negative parallax) as presented in Experiment II. Such into-the-screen disparities are more relevant for commercial 3D content—indeed, the majority of S3D content is located behind the screen plane. The objective was to assess whether there were any significant differences in the perceived distortion and comfort compared to Experiment II.

More specifically, Experiment IV was conducted to investigate the fourth Hypothesis H_4 , that is, the vergence-accommodation conflict is more pronounced out of the screen than into the screen. To avoid confusion, it is worth restating that negative disparity (out-of-the-screen) is known in the industry as negative parallax and positive disparity (into-the-screen) is typically referred to as positive parallax in the industry.

As with the previous two experiments, we assessed perceived distortion and viewing comfort for 20-mm to 100-mm camera separations using five different hinge angles for each camera separation.

5.1 Review

Industry practice recommends reduced exposure to stereo content in front of the screen (i.e. with negative parallax). Mendiburu (2012) opines that positive parallax is more fusible. Shibata et al. (2011a) demonstrated that negative parallax produces discomfort while positive parallax has little to no such capability at a short accommodation distance; of the two parallax manipulations, positive disparity is meant to be the more forgiving end. The authors also demonstrate that, as the accommodation distance becomes smaller, so too does the zone of comfortable fusion, echoing industry practice to limit parallax ranges and utilise positive disparity over into-the-screen content.

Perhaps unsurprisingly, commercial scenes contain more into-the-screen parallax than out-of-screen disparity. An analysis of parallax values for eight 3D films shows positive parallax, on average, ~22% higher than negative parallax (Voronov et al., 2012). A follow-up analysis of the full-length parallax values for these eight and another two 3D films showed positive parallax ~19% higher than negative parallax (Voronov et al., 2013). These values are from a sample of

ten 3D films, less than 10% of the total number of stereo 3D films analysed by the MSU Video Group. Therefore, it is entirely conceivable that positive parallax could be several magnitudes higher. Nonetheless, vergence-accommodation conflicts still occur even for behind-the-screen objects. The extent of these conflicts, however, is not entirely well established.

This experiment tests hypothesis H₄: The vergence-accommodation conflict is more pronounced out of the screen than into the screen.

5.2 Method

The design, equipment, stereo capture system, stimuli, procedure, and method of analysis for participant data ($n = 40$) was the same for Experiment IV as it was for both Experiments II and III as indicated in Chapter 4, with the sole exception that the hinge angles were rendered behind-the-screen, as shown in Figure 5-1.

Importantly, the mean age and IPD (\pm SD) of participants was 19.72 years (\pm 1.486) and 53.45mm (\pm 3.975), respectively. This participant pool consisted of 14 male and 26 female observers, a gender ratio similar to pools in Experiments II and III. The decision to keep the gender ratio similar across these experiments was primarily because a gender split had been observed in other disparity studies as highlighted in Section 4.7: Discussion (Häkkinen et al., 2006; Read & Bohr, 2014; Thomas, 2010).

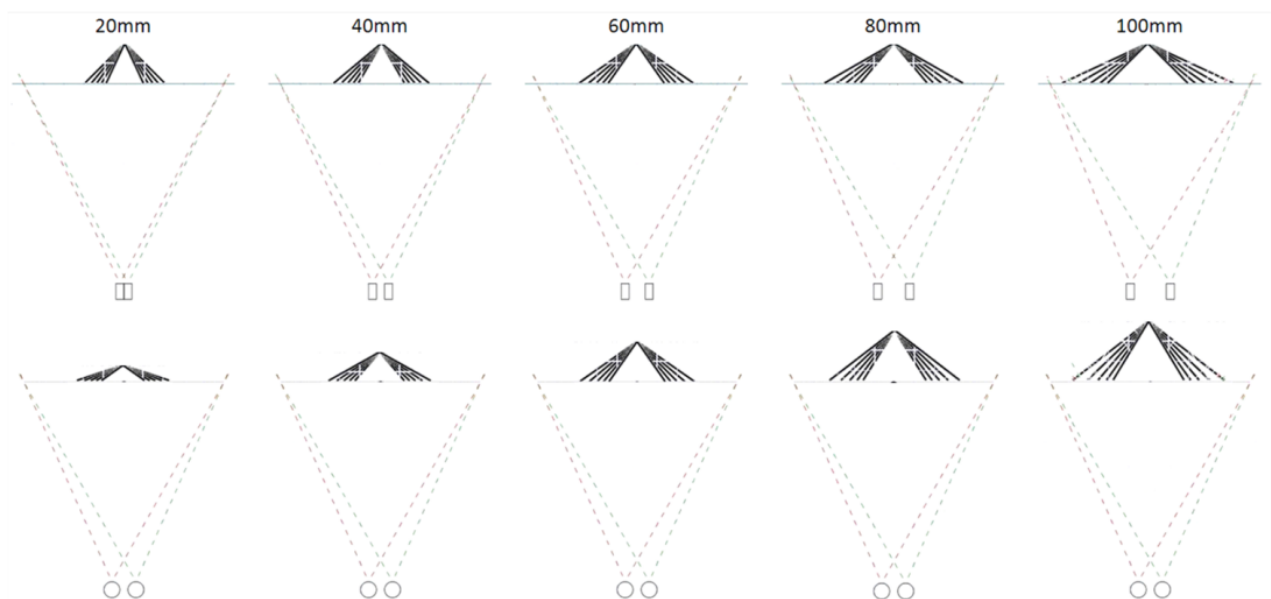


Figure 5-1. Experiment IV: Hinge angles (rendered and predicted).

In Figure 5-1, the top row illustrates the five hinge angles used at each camera separation (20mm-100mm). The hinge angle was varied by widening the hinge while keeping the depth of the rendered hinge object constant. The bottom row of Figure 5-1 illustrates how the hinge is predicted to appear based on ray-tracing.

5.3 Results

5.3.1 Perceived Distortion

Like with the previous experiments, a mixed model was applied to PSE with camera separation. There was a main effect of camera separation $\chi^2(1) = , p < 0.001$. The perceived hinge angles were flatter than the prediction line.

Table 5-1 and Figure 5-2 below summarise and depict, respectively, the results of the perceived angle (PSE) measurements in Experiment IV.

Table 5-1. Experiment IV: Mean and standard deviation for point of subjective equality.

Camera Separation		Perceived Angle	
	N	Mean	S.D.
20mm	40	65.2°	9.0°
40mm	40	74.8°	8.2°
60mm	40	84.8°	12.5°
80mm	40	90.8°	11.8°
100mm	40	100.7°	12.0°

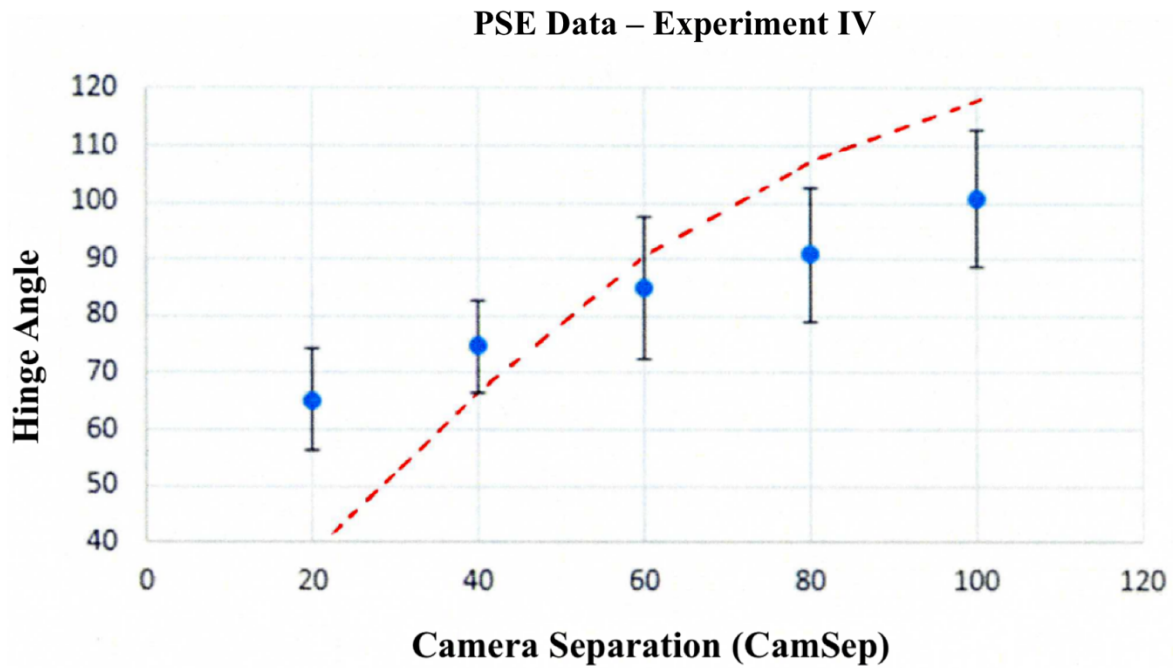


Figure 5-2. Experiment IV: Perceived angles compared with predicted.

Figure 5-2 shows the points of subjective equality (PSE) (i.e., the angles perceived as a right angle) for camera separations of 20-100mm in 20-mm steps for fixed-depth stimuli rendered behind-the screen (Experiment IV). The red-dotted line shows the values predicted by the ray-tracing model.

Qualitatively, the change in perceived angle follows what is expected from ray tracing. However, the magnitude of change in the perceived angle is significantly smaller than predicted by the ray-tracing model.

5.3.2 Psychometric Function Slope

Table 5-2 and Figure 5-3 summarise and depict, respectively, the data for the slope of the psychometric function in Experiment IV.

Table 5-2. Experiment IV: Mean and standard deviation for point of subjective equality.

Camera Separation	Slope		
	N	Mean	S.D.
20mm	40	7.60	2.34
40mm	40	8.54	2.78
60mm	40	7.80	3.22
80mm	40	7.84	3.90
100mm	40	7.67	2.45

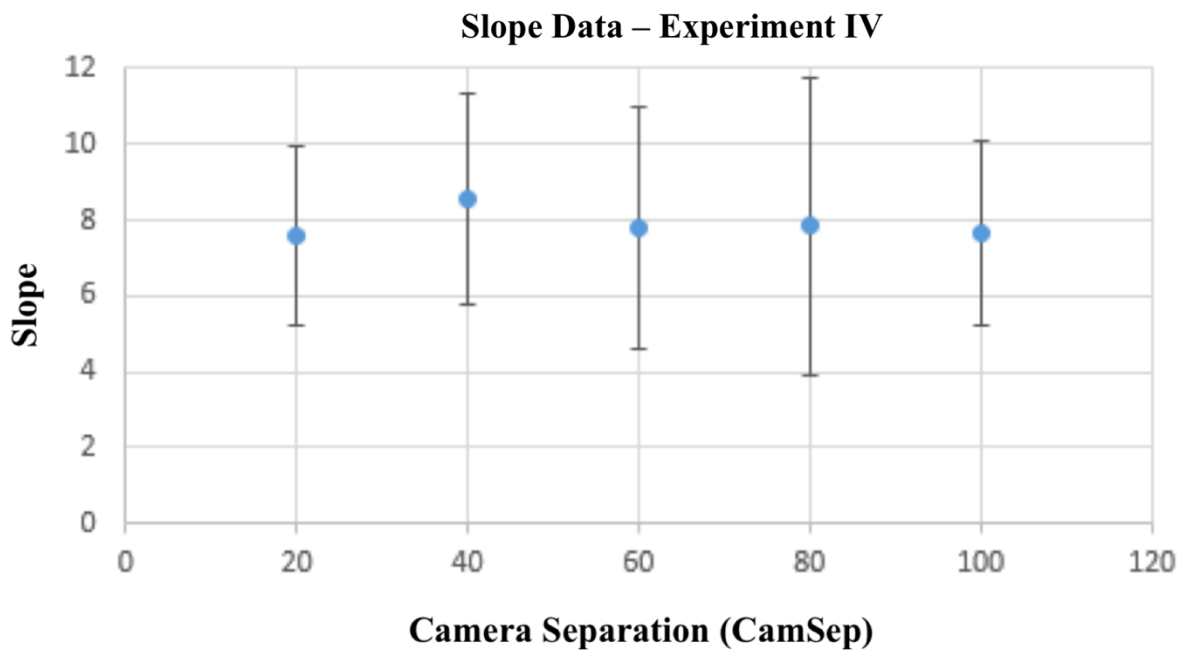


Figure 5-3. Experiment IV: slope of psychometric function.

There was no difference in slope across the range of camera separations.

5.3.3 Comfort

Table 5-3 and Figure 5-4 report the overall comfort values at each camera separation for Experiment IV.

Table 5-3. Experiment IV: Mean and standard deviation for comfort data.

Camera Separation	Overall Comfort		
	N	Mean	S.D.
20mm	40	3.89	0.76
40mm	40	3.99	0.70
60mm	40	3.99	0.74
80mm	40	4.04	0.76
100mm	40	3.86	0.95

Comfort Data - Experiment IV

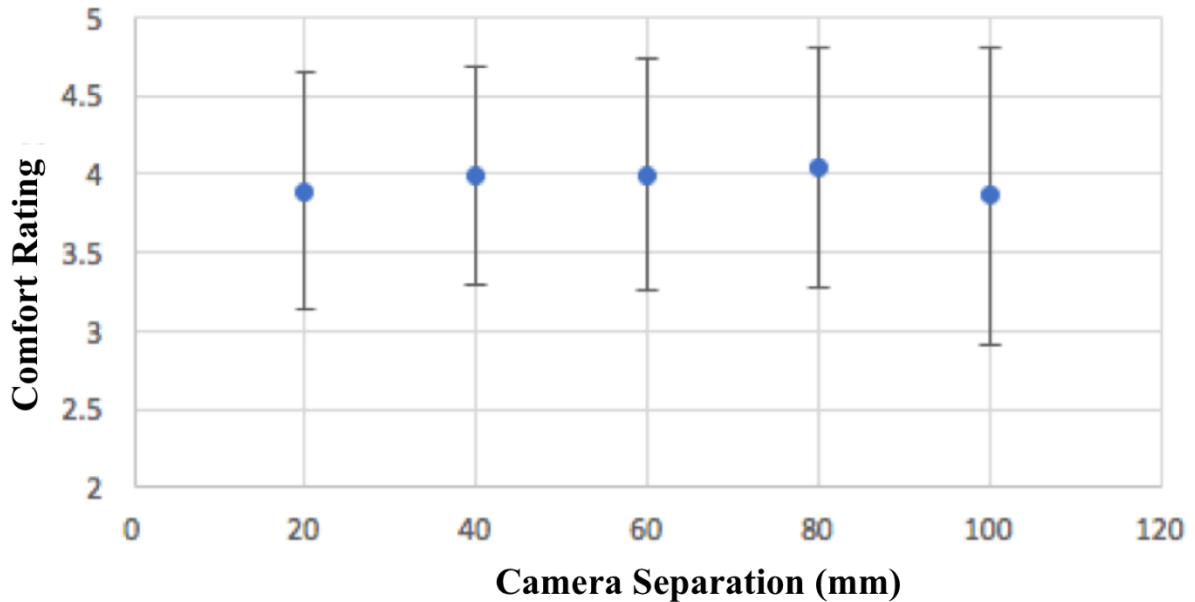


Figure 5-4. Experiment IV: Overall comfort data for fixed-depth stimuli rendered behind the screen.

Overall, the Comfort data is flat across the range of Camera Separations.

Next, the effect of hinge angle on comfort was analysed. The data are shown in Table 5-4.

Table 5-4. Experiment IV: Mean and standard deviation for comfort data at each hinge angle at each camera separation.

Cam. Sep. 20mm			Cam. Sep. 40mm			Cam. Sep. 60mm		
Hinge	Comfort		Hinge	Comfort		Hinge	Comfort	
Angle	Mean	S.D.	Angle	Mean	S.D.	Angle	Mean	S.D.
50°	3.76	0.92	60°	3.96	0.72	70°	4.00	0.74
60°	3.93	0.70	70°	3.95	0.79	80°	4.07	0.69
70°	3.89	0.77	80°	4.03	0.65	90°	3.97	0.71
80°	3.91	0.70	90°	3.97	0.69	100°	3.94	0.79
90°	3.94	0.68	100°	4.04	0.65	110°	3.98	0.78

Cam. Sep. 80mm			Cam. Sep. 100mm		
Hinge	Comfort		Hinge	Comfort	
Angle	Mean	S.D.	Angle	Mean	S.D.
80°	4.11	0.81	90°	4.03	0.80
90°	4.13	0.63	100°	3.96	0.77
100°	3.90	0.80	110°	3.87	0.86
110°	3.99	0.72	120°	3.93	0.89
120°	4.06	0.81	130°	3.53	1.33

There is no effect of hinge angle on comfort for any of the camera separations studied. Z-scores were computed for this data, but again, there was no statistical benefit of doing so.

Note that, as with Experiments II and III, most comfort responses between 3 and 5 show no strong discomfort reported by participants.

5.4 Discussion

Experiments II and III used stimuli with out-of-the-screen disparities in the same way that Banks et al. (2009) did. In commercial applications, objects tend to be rendered behind the screen plane. Experiment IV repeated Experiment III for into-the-screen disparities which are more relevant for commercial 3D content.

Overall, the results obtained for perceived angle, slope of psychometric function and comfort for behind-the-screen hinges (Experiment IV) were very similar to those obtained for in-front-of-the-screen images (Experiment III).

It should be noted, however, that this experiment used simplified (i.e. merely stretched), computer-generated hinge angles of no specified scale that were not real objects. It is inherently hard to distort a hinge. This is an important difference, since the distortive effect of 3D manipulation on real objects may well be different from ambiguous hinges (Enright, 1984; Horwood & Riddell, 2012). Does the texture give cues in the same way that, for example, a grid might have given? Nonetheless, the hinge was not subjectively perceived as distorted since the texture mapping is uniform (Sheffer & De Sturler, 2002; Vangorp et al., 2013). This suggests that the texture can be altered from a wireframe to a more realistic texture, without any effect of distortion. Hence, the selected stimulus could be distorted in pure isolation.

Moreover, participants did reliably estimate the angle of the hinge even though it has no strong intrinsic properties. Future experiments could aim to investigate the outcome of using an actual scene rather than computer-generated imagery. Although research has suggested that this does not make a difference, such studies did not control for the acquisition parameters of the scene (Yamanoue et al., 2012). Also, the majority of stereoscopic imagery is (1) moving, not stationary and (2) located in behind the screen plane, not in front. Therefore, it is important to repeat this study for moving stimuli at all depth planes to ensure more accurate mapping of the results.

Additionally, hinges have properties which means they are not familiar to ordinary observers, hence, there is no correct answer to angle perception. Similarly, while observers can recognise a 90 angle in context, many right angles presented out of context would indeed look obtuse or acute. Therefore, to understand the perceived distortion of objects, it is important to present a variety of objects where there is a “correct” answer as to whether the object looks flattened or stretched. Observers should also be able to adjust the object so that they can “dial” it in. Binary choices only extrapolate a response.

That said, Experiment IV showed that, firstly, comfort increased with disparity and decreased with hinge angle. This negative correlation between comfort and hinge was especially pronounced at the 100-mm separation. Secondly, a similar pattern to Experiments II and III is observed such that angles appear obtuse at small camera separations and angles appear acute at large camera separations. Thirdly, the change in perceived angle also follows what is expected from ray tracing although the magnitude of change in perceived angle is smaller than predicted by the ray-tracing model.

Hypothesis H₄ is supported, the results re-affirmed a perceptual bias between into the screen stimuli, which were judged as flatter than out of the screen stimuli, which were perceived more veridically.

CHAPTER 6 – EXPERIMENTAL: OFF-AXIS VIEWING

The purpose of Experiment V was to investigate the relationship between viewer comfort and oblique viewing for stereoscopic stimuli. We hypothesise that comfort rather than distortion is affected by viewer position, i.e., hypothesis H₅.

6.1 Review

Research on the experience of multiple viewers of video content is plentiful, both from a 2D and stereoscopic perspective. The field comprises a disparate assembly of thematic concerns and technical choices- hence, we will restrict this introduction to viewer comfort research.

Eye-tracking data shows that viewers process stereoscopic content differently. Going from 2D to the 3D condition, Häkkinen et al. (2010) report that commercial stereo scenes evoke more eye movements: observers ($n = 20$) experienced longer fixation time lags and saccadic movements when viewing complex stereoscopic structures. An earlier investigation had found longer rates of fixation, fixation durations, and saccadic movements for various 3D conditions compared to 2D image presentation (Jansen, Onat & König, 2009). These studies imply that the fixation points for stereo content, whether in motion or static, are more widely distributed, a finding confirmed by Czúni & Kiss (2012). These points of interest (Holliman, 2004; Huynh-Thu, Barkowsky & Le Callet, 2011; Huynh-Thu & Schiatti, 2011; Wexler & Ouarti, 2008) and the manner in which viewers process them inform the design of stereoscopic displays especially of the cinematic variety.

The natural extension of these studies is an analysis of viewer comfort not only from a typically frontoparallel position, but also from oblique viewing positions. Viewers also process stereo content differently from 2D when viewing positions are physically offset. Viewing distances and viewer position are important determinants of viewer comfort. Experiment I shows that comfort increases with distance due to a higher threshold for vergence-accommodation conflicts. On the other hand, position displacement places a perceptual burden for stereoscopic viewing: off-axis viewing distorts perspective projection (Banks et al., 2009).

Compensation mechanisms exist when viewing content from an off-axis perspective. Banks et al. (2009) argue that compensation is especially evident during off-axis viewing for 2D content and absent for 3D viewing (presence of compensation means that viewers can perceive stereo

scenes correctly; its absence leads to perceptual distortions). (For a review of the compensation theory, refer to Busey, Brady, and Cutting, 1990 and Todorović, 2008, and to the discussion section below). More specifically, Banks et al. (2009) report that observers reported veridical stereo hinge angles, but could not compensate for oblique viewing, consistent with earlier findings (Vishwanath et al., 2005). However, there is an element of ambiguity as to the extent of perceptual invariance at off-axis angles and the extent to which said distortions could be accounted for by the stereo viewing geometric model described by Woods et al. (1993).

Burton et al. (2012) show perceptual distortions for off-axis viewing of virtual stimuli that are smaller than predicted by a ray-tracing model, contrasting Banks et al. (op. cit.). However, the researchers contend that departures from the latter study, in particular, regarding the model predictions, may be due to the presence of monocular cues: awareness of monocular cues to depth may alleviate distortions in stereo stimuli (Butler & Kring, 1987; Polanyi, 1970; Yang & Kubovy, 1999). This concession also seemed to apply to our studies as discussed in Chapters 4 and 7 (see also discussion section below) and is repeated in a follow-up study (Pollock et al., 2012) and elsewhere (Saunders & Backus, 2007). However, Ponto, Gleicher, Radwin, and Shin (2013) describe a perceptual calibration technique that validates the stereo geometric model: their technique uses a ray-tracing model to correctly calibrate comfortable viewing parameters in the design of a CAVE system. Interestingly, Burton et al. (2012) find no significant relationship between the viewing distance and perceptual distortions, closely mirroring our findings in Experiment I [see also Tibau, Willems, Van Den Bergh, and Wagemans (2001) for a similar observation regarding the relationship, or lack thereof, between the viewing distance and perception distortion]. These contrasting findings are re-stated in numerous publications with distortions and compensation outcomes demonstrated for different situations. In sum, extant literature indicates one of several scenarios:

- 1) that when users who are laterally displaced from the centre of projection (CoP) view 2D images binocularly, they compensate for the oblique viewing position and report reasonable veridicality (Banks et al., 2009; Banks, Rose, Vishwanath & Girshick, 2005; Cutting, 1986; 1987; Farber & Rosinski, 1978; Goldstein, 1988; Haber, 1980; Pirenne, 1970; Rosinski et al., 1980; Vishwanath et al., 2005; Yang & Kubovy 1999);

- 2) when viewing 2D images binocularly, observers experience distortion with little, if any, compensation mechanics (Ellis, Smith & McGreevy, 1987; Goldstein, 1987; Koenderink, van Doorn, Kappers & Todd, 2004; Niall & Macnamara, 1989; Todorović, 2008);

3) binocular viewing of stereo content elicits distortion and marginal (or absent) compensation (Banks et al., 2009; Kelly et al., 2013; Kim et al., 2012; Koenderink, van Doorn, Kappers & Todd, 2004; Leiser, Bereby & Melkman, 1995; Yang et al., 2011); and

4) when viewing stereoscopic content from oblique viewpoints, viewers do not experience any noticeable or uncomfortable perceptual distortions as the compensation mechanism operative when watching 2D content extends impressively to stereo 3D (Hands & Read, 2013; Hands, Smulders & Read, 2015).

For some of these studies, viewer discomfort is implied with non-compensated perceptual distortion. Other studies, however, make a direct connection between off-axis viewing and comfort. Biometric data shows that S3D content elicits visual fatigue- for instance, Wang et al. (2016) use an assortment of objective and subjective scoring methods to establish that a 3D movie causes visual fatigue more serious than for a 2D movie and a host of biometric studies exist towards this end (Chen et al., 2015; Frey, Appriou, Lotte & Hachet, 2016; Jeong et al., 2015; Lamboojij et al., 2009; Malik et al., 2015; Park & Mun, 2015). Eye-tracking studies show that 3D content has higher discomfort when compared to 2D content (Iatsun, Larabi & Fernandez-Maloigne, 2014) and more visual fatigue indicators (Iatsun, Larabi & Fernandez-Maloigne, 2013). It is perhaps unsurprising that a related study reports visual discomfort, or its various proxies, during off-axis viewing (Aznar-Casanova, Romeo, Gómez & Enrile, 2017).

That these results present contrasting insights is an understatement: vision science publications employing different procedures and stimuli show that lateral displacement for the S3D condition produces a variety of often contradicting distortion outcomes with comfort studies showing universally that, despite the ambiguity, off-axis viewing elicits fatigue. Furthermore, little effort has focused on the issue of how acquisition and presentation factors affect the coherence of off-axis viewing. The relevance of reconciling these contradictions is significant. This is the imperative that Experiment V is intended to respond.

Experiments II, III, and IV reported in the preceding chapters were conducted with observers looking directly at the screen. Significant perceived distortions were observed for camera separations different from 60mm. Experiment V, on the other hand, will investigate the effect of off-axis viewing, to model situations where the viewer is not centred on the screen such as in a typical cinema (Banks et al., 2011; Hands & Read, 2014).

In this multi-viewer experiment (to model cinema seating such as in Figure 6-1 below), with off-axis viewing the following phenomena are expected: (I) hinge angle perception would be distorted, (II) discriminating between hinge angles would be more difficult, and (III) comfort would decrease.

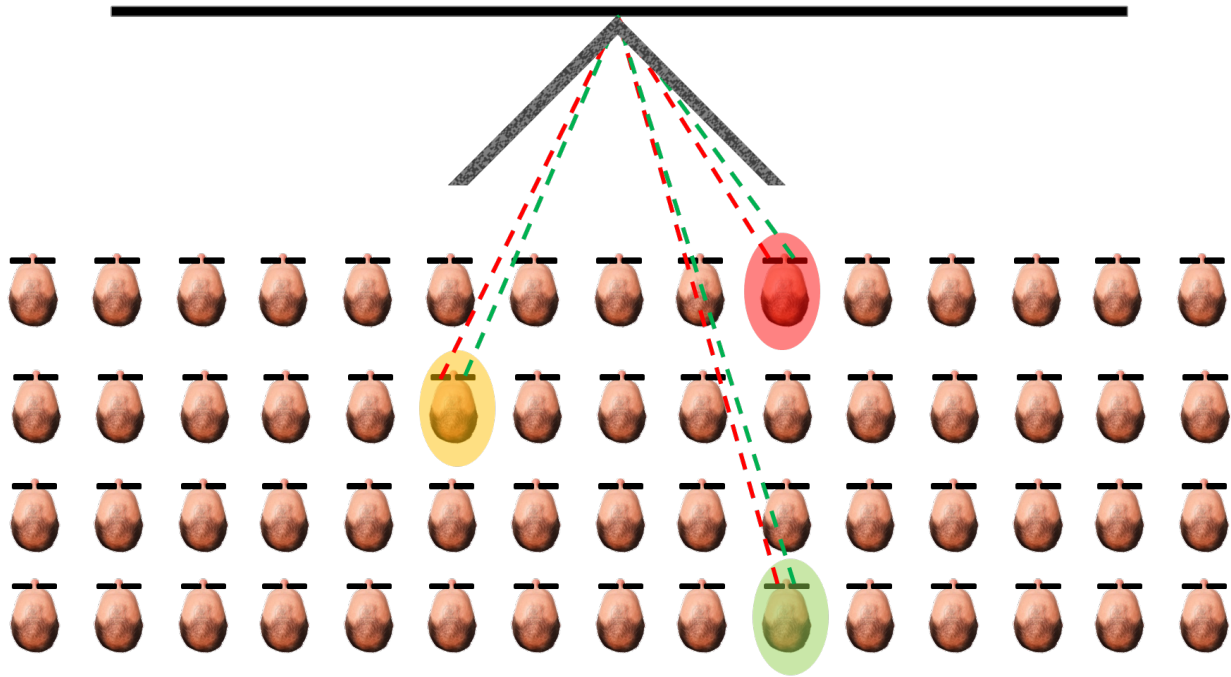


Figure 6-1. Illustration of the notional comfort levels in a 3D cinema.

This experiment tests hypothesis H_5 : Distortion is not affected by viewer position, but instead, comfort is affected.

6.2 Method

6.2.1 Participants

Taking part in the study were 24 students (18-29 years of age) from the University of Liverpool, including 15 males and 9 females. Opportunity sampling method was used. Once again, it bears repeating that the participant pools were different across all the experiments in this study including Experiment V.

9 of the participants were first-year psychology students who participated in the experiment according to EPR (Experiment Participation Requirement) scheme. They were rewarded with EPR points. The other 15 participants were the researcher's friends who volunteered to

participate in the study and were given no material rewards. All the participants had normal or corrected vision and stereo acuity better than 100 seconds of arc according to the Stereo Fly Test.

6.2.2 Apparatus

The apparatus and materials used are as denoted in Chapter 4, including the choice of the 3D monitor, marble textured hinge, four-point Likert Scale, and the post-exposure Simulator Sickness Questionnaire (Kennedy et al., 1993).

6.2.3 Design

A mixed design was used in the study. Each participant was tested in three viewing positions as shown in Figure 6-2. Half of them were tested in the positions of 0° , 22.5° left, and 45° right to the centre of the screen. The other half were tested in the positions of 0° , 22.5° right, and 45° left.

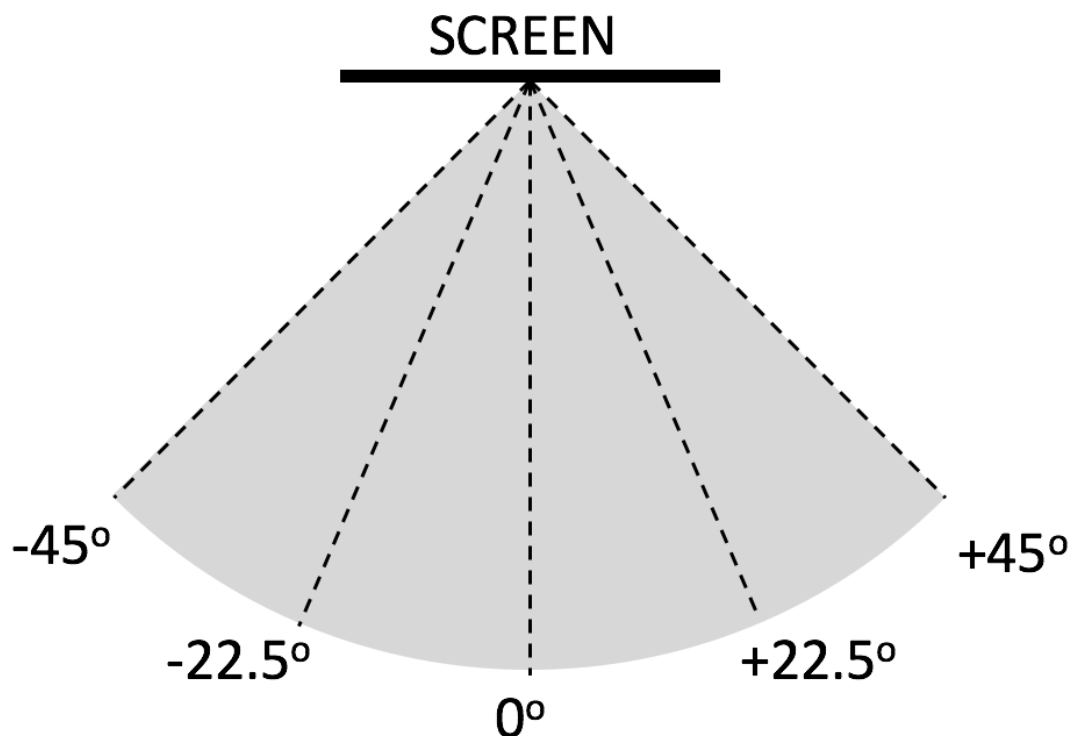


Figure 6-2. Diagrammatic representation of viewing positions relative to the observation screen.

The order of the viewing position was counter-balanced. There were twelve (12) possible orders with 0° being the first viewing position 1/3 of the time, the second 1/3 of the time, and the third

1/3 of the time with the four permutations to fit around these three conditions: 22.5°L, 45°R; 22.5°R, 45°L; 45°L, 22.5°R; and 45°R, 22.5°L. The 12 orders were assigned to 12 different participants. As there were 24 participants in the experiment, each possible order was applied twice (see Figure 6-3).

The independent variables in the study were the camera separation (20 mm, 40 mm, 60 mm, 80 mm, and 100 mm) and the viewing position (0°, 22.5°, and 45° relative to the centre of the screen). The dependent variables were perceived distortion (mean angle perceived as 90°) and level of comfort on a five-point Likert scale.

The disparity at the edges of the hinge configurations was kept constant and the angle co-varied with the physical screen width of the rendered hinge stimuli. All the images of hinge configurations were behind the screen plane (Figure 6-4). How the angles of the hinge stimuli would be perceived at different viewing positions was predicted by ray-tracing (Figure 6-5).

Participant	Block 1	Block 2	Block 3
1	0C	22.5L	45R
2	0C	22.5R	45L
3	0C	45L	22.5R
4	0C	45R	22.5L
5	0C	22.5L	45R
6	0C	22.5R	45L
7	0C	45L	22.5R
8	0C	45R	22.5L
9	22.5L	0C	45R
10	22.5R	0C	45L
11	45L	0C	22.5R
12	45R	0C	22.5L
13	22.5L	0C	45R
14	22.5R	0C	45L
15	45L	0C	22.5R
16	45R	0C	22.5L
17	22.5L	45R	0C
18	22.5R	45L	0C
19	45L	22.5R	0C
20	45R	22.5L	0C
21	22.5L	45R	0C
22	22.5R	45L	0C
23	45L	22.5R	0C
24	45R	22.5L	0C

Figure 6-3. The counterbalanced sessions showing the three different experimental sessions and the total number of applications.

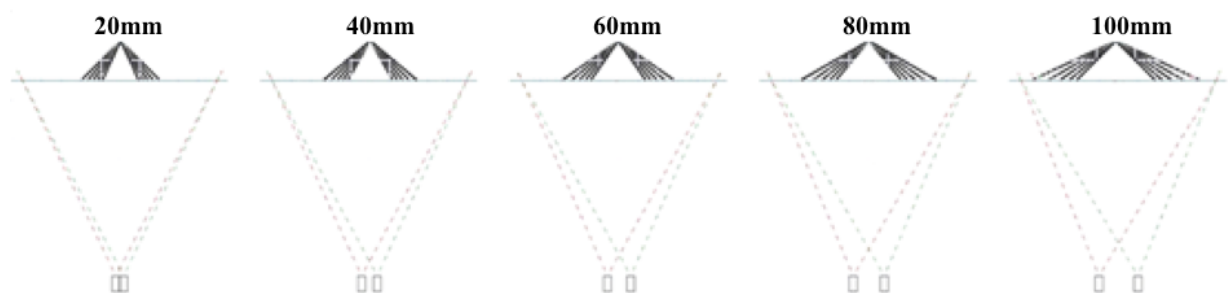


Figure 6-4. Experiment V: The five camera separations and hinge angles presented.

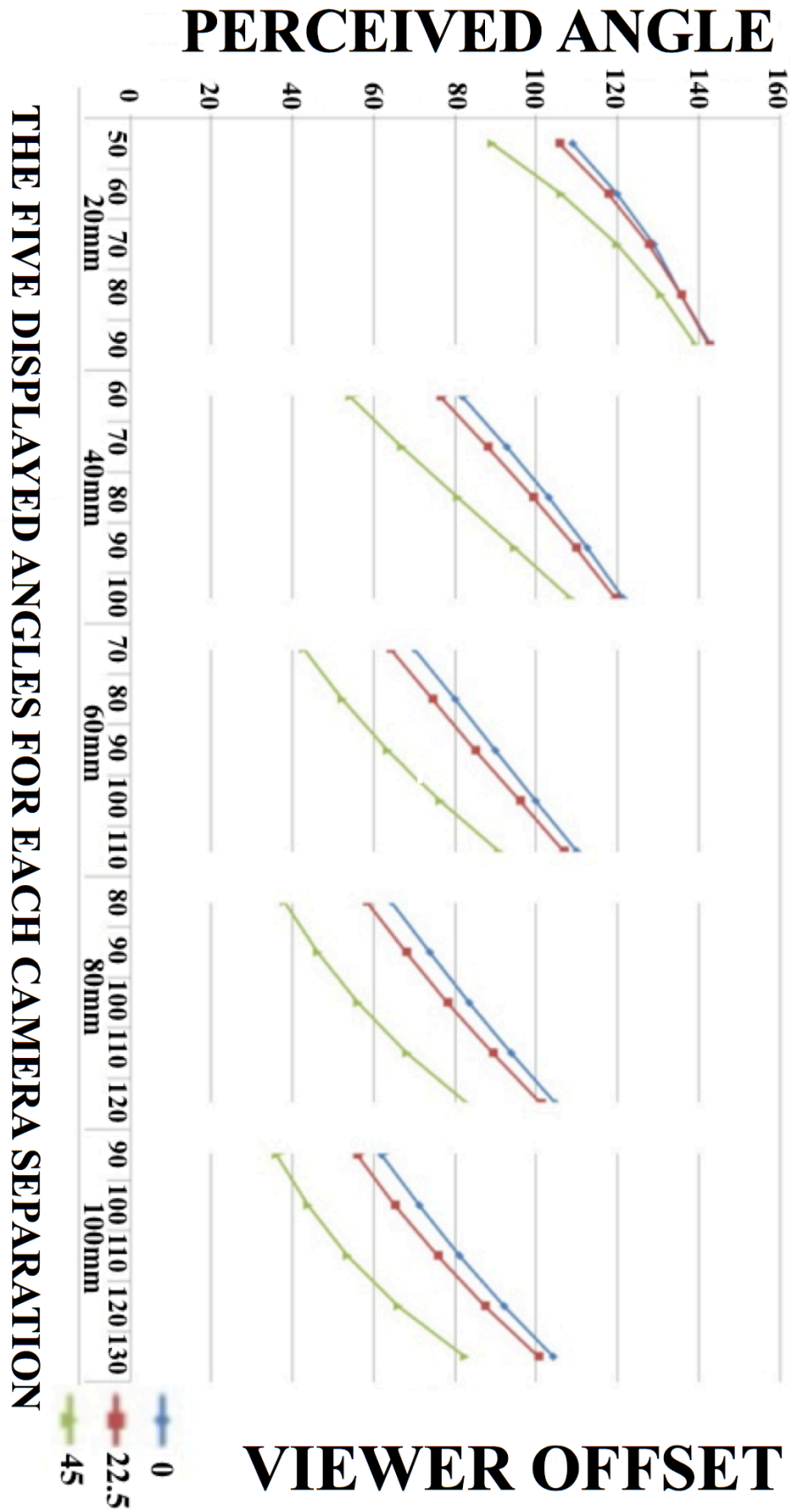


Figure 6-5. Experiment V: Ray-tracing predictions on how the angles of the hinge stimuli would be perceived at different viewing positions.

The figure above illustrates distortion predictions for each of the three horizontal viewing angles. The green line shows the predictions for the 45° angle, red denotes the trend for the 22.5° angle, and the blue line for the frontoparallel position (0°). The figure shows that the 22.5° angle is a reasonably distortion-tolerant viewing condition while the 45° angle is predicted to be a distortive viewing position. Furthermore, the figure shows that doubling the viewer offset angle produces a greater than double difference predicted distortion.

6.2.4 Procedure

Participants were taken into the visual perception lab and given the information sheet and the consent form. After signing the consent form, they did the Stereo Fly Test. Participants who scored above the threshold (100 seconds of arc) would be considered as eligible for the experiment.

The experiment consisted of three sessions, within each of which participants were tested in one of the three viewing positions (0°, 22.5°L, 45°R or 0°, 22.5°R, 45°L) based on the viewing order they were assigned. The viewing positions were marked on the floor by tags and were 60cm away from the 3D monitor. The procedure was the same for each session.

Participants were first given oral instructions on the experiment. They were then invited to a viewing position and asked to be seated at an eye height that was in the vertical centre of the screen by adjusting the height of the chair, the chin rest, or both. Subsequently, participants were told to put on the 3D glasses and shown a sequence of 250 hinge images with 25 different hinge stimuli being shown ten (10) times. The oral instructions for the procedure for hinge estimation and comfort rating are as denoted in Chapter 4.

6.3 Results

6.3.1 Perceived Distortion

Once again, as with the previous experiments, a mixed model was applied to PSE with camera separation. There was a main effect of camera separation $\chi^2(1) = , p < 0.001$. There was no main effect of off-axis viewing ($p > 0.05$) for viewing angles of up to 45°.

Table 6-1 and Figure 6-6 depict the mean angle seen as 90° by the 24 participants at each camera separation, for each viewing position. Contrary to expectations, the viewing position does not have any consistent significant effect on perceived distortion, except for the smallest camera separation (20 mm).

Table 6-1. Experiment V: Mean and Standard Deviation for Point of Subjective Equality for each viewing angle.

Cam. Sep.	N	0° View		22.5° View		45° View	
		Mean	S.D.	Mean	S.D.	Mean	S.D.
20mm	24	58.7°	18.2°	52.5°	19.8°	51.1°	22.8°
40mm	24	60.4°	18.7°	65.1°	8.2°	59.9°	17.7°
60mm	24	74.4°	13.7°	75.1°	12.6°	68.7°	18.7°
80mm	24	76.1°	19.4°	82.3°	10.9°	73.7°	24.3°
100mm	24	86.4°	22.2°	91.6°	12.9°	85.6°	21.9°

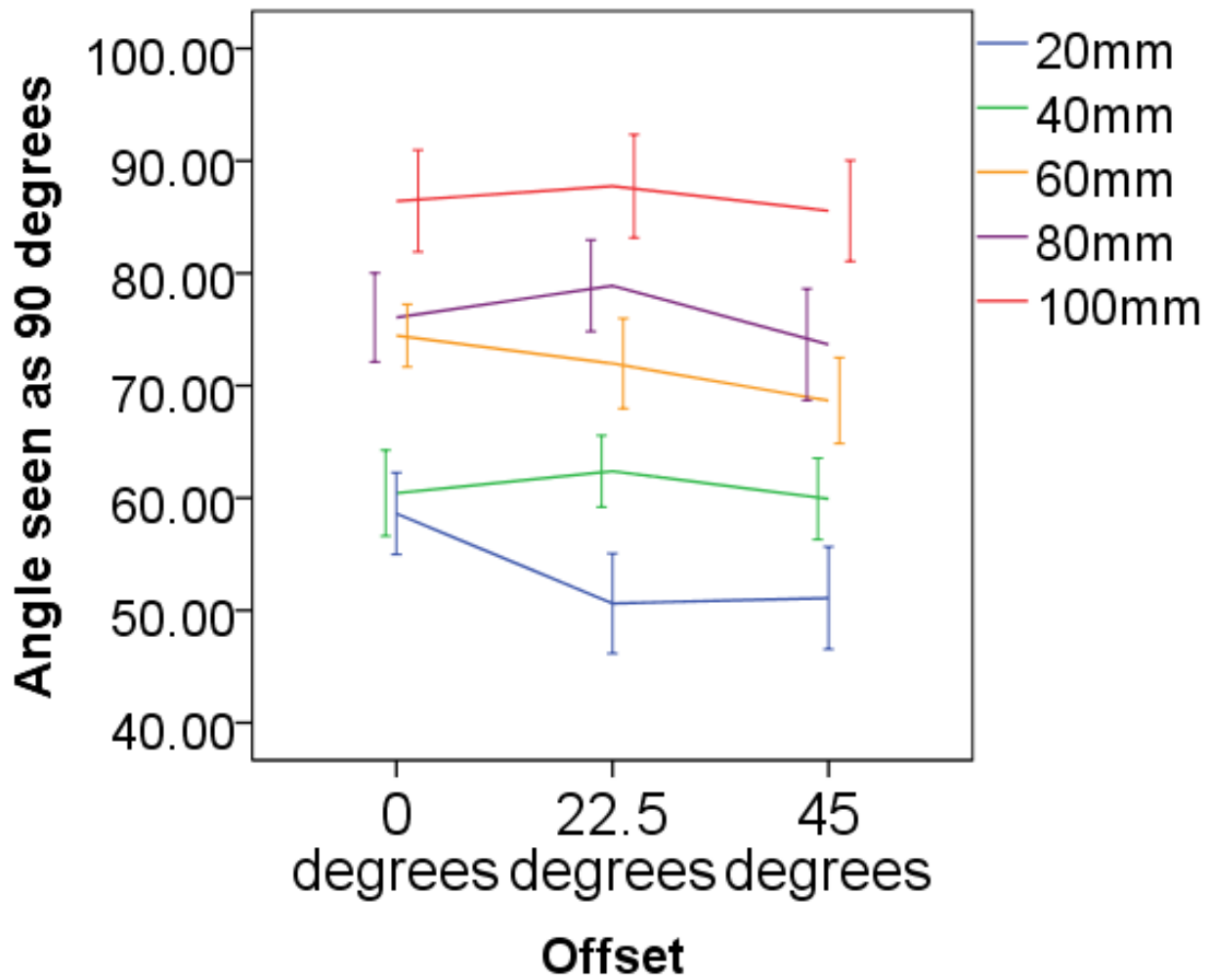
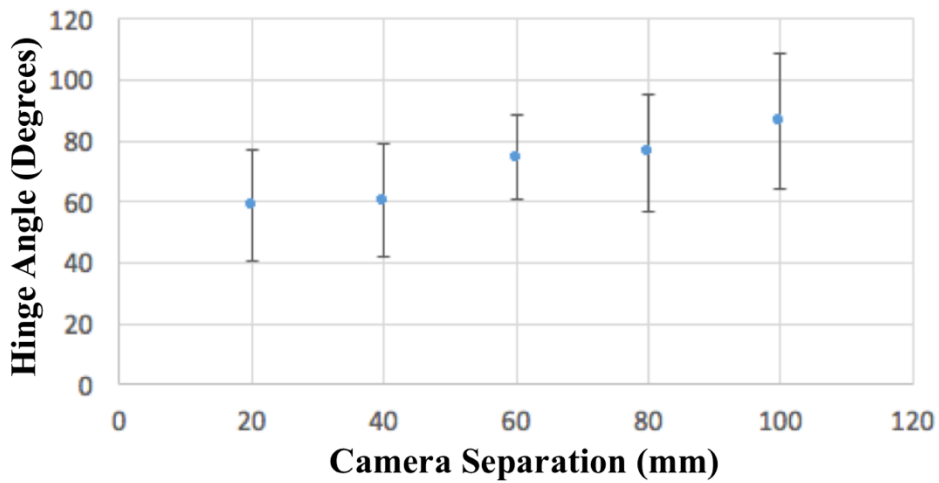


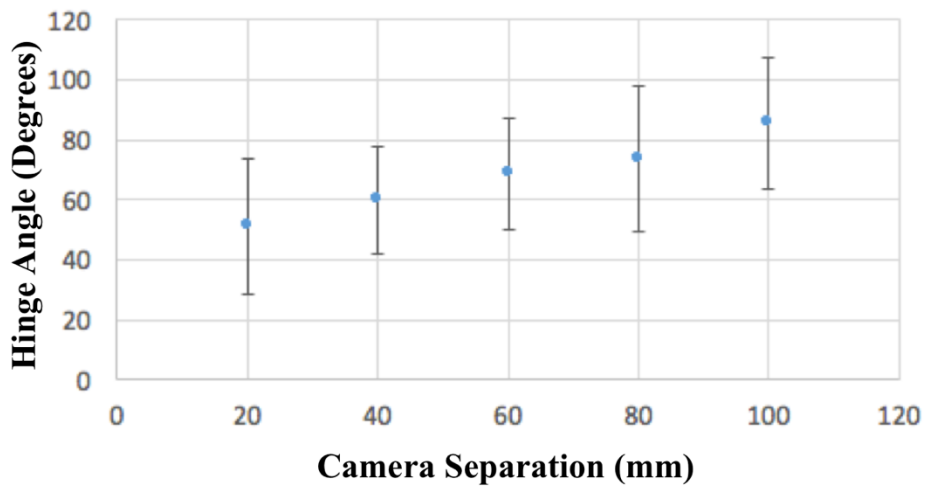
Figure 6-6. Experiment V: The mean angle seen as 90° by camera separation for each viewing position.

Figure 6-7 plots the distortion data (points of subjective equality) for each of the viewing angles and again reflects that there is no significant difference between the perceived angles at the different viewing angles for angles of up to 45°.

PSE Data for the Hinge Angles - 0 Degrees Viewer Angle



PSE Data for the Hinge Angles – 45 Degrees Viewer Angle



PSE Data for the Hinge Angles – 22.5 Degrees Viewer Angle

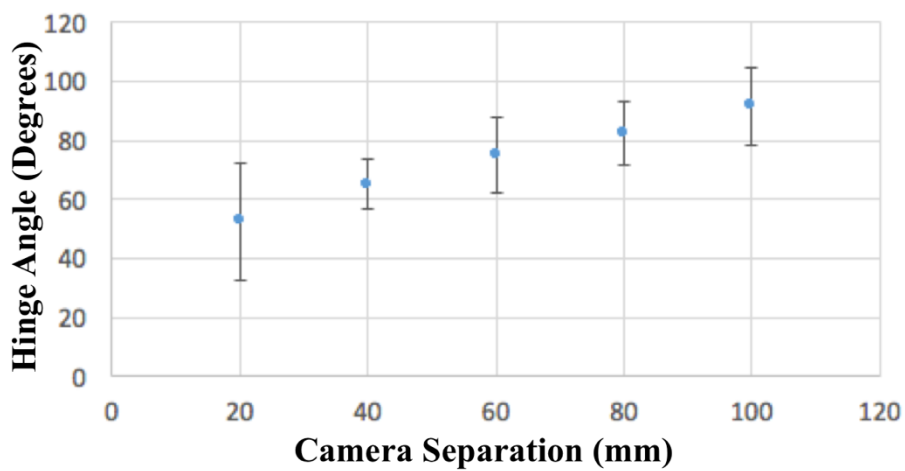


Figure 6-7. Experiment V: Distortion data at each of the viewing angles.

6.3.2 Psychometric Function Slope

Figure 6-8 plots function slope against camera separation for the three viewing angles.

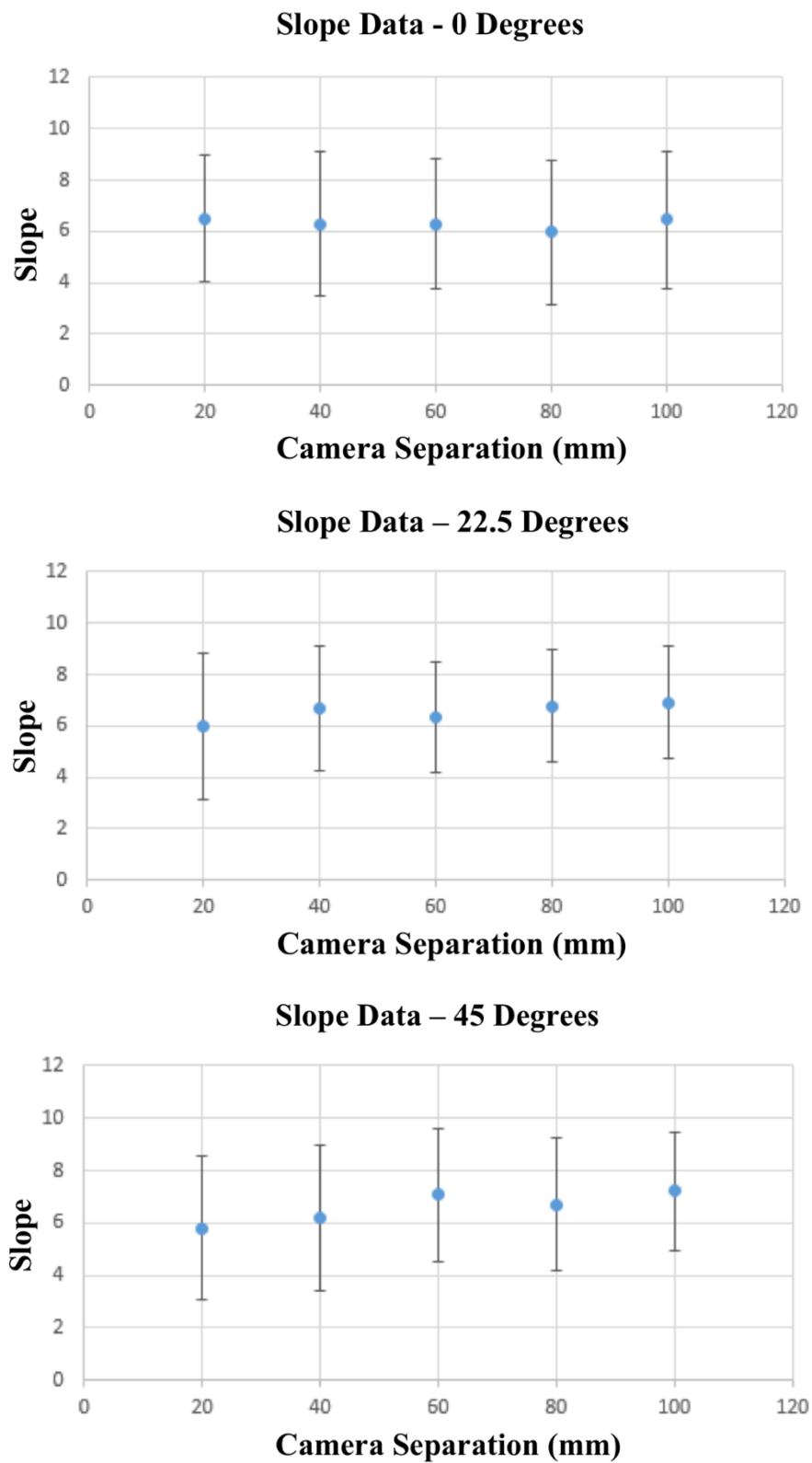


Figure 6-8. Experiment V: Psychometric Function Slope data for the three viewing angles.

Compared with the straight-on view (0°), there is a modest increase in slope with camera separation at the oblique viewing angles. Again, contrary to expectation, the participants found it a bit easier to discriminate between the hinge angles with off-axis viewing for angles of up to 45°.

6.3.3 Comfort

Table 6-2 reports the overall comfort values at each camera separation for each viewing angle.

Table 6-2. Experiment V: Mean and Standard Deviation for overall Comfort for each viewing angle.

Comfort	N	0° View		22.5° View		45° View	
		Mean	S.D.	Mean	S.D.	Mean	S.D.
Cam. Sep.							
20mm	24	3.53	1.02	3.61	1.11	3.48	1.20
40mm	24	3.62	1.04	3.49	1.05	3.34	1.17
60mm	24	3.63	1.00	3.52	1.22	3.48	1.11
80mm	24	3.66	1.10	3.64	1.16	3.28	1.20
100mm	24	3.73	1.12	3.46	1.17	3.27	1.05
Overall	120	3.63	1.06	3.54	1.14	3.37	1.15

Table 6-2 and Figure 6-9 below depict data for the Comfort data for each camera separation for each of the three viewing angles (0, 22.5, and 45 degrees).

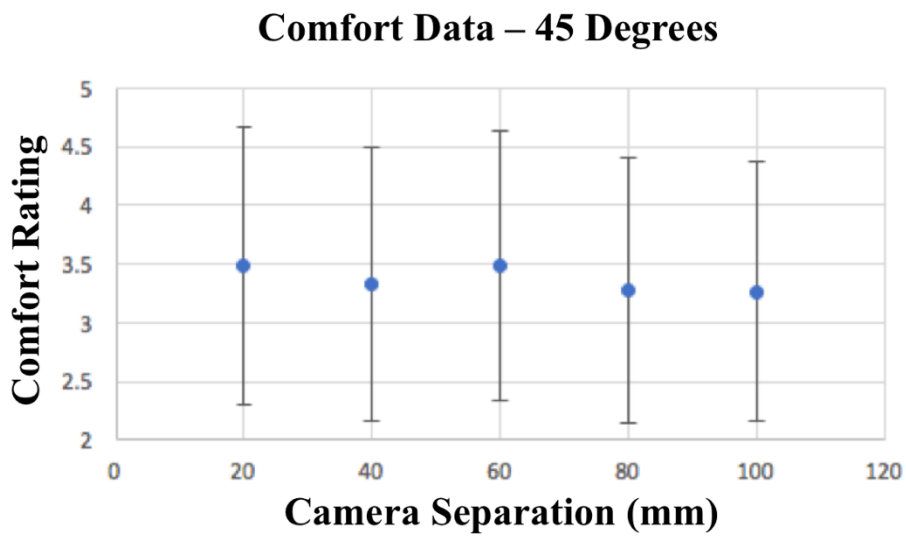
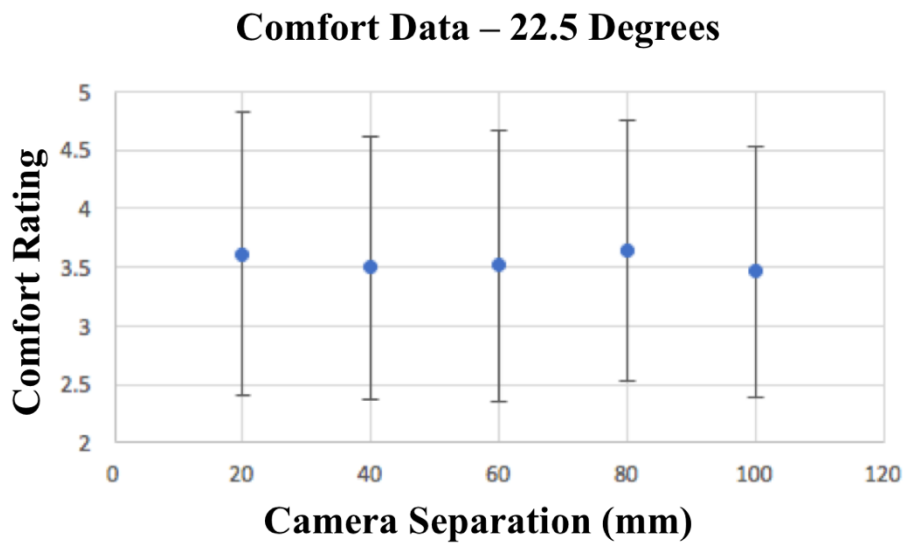
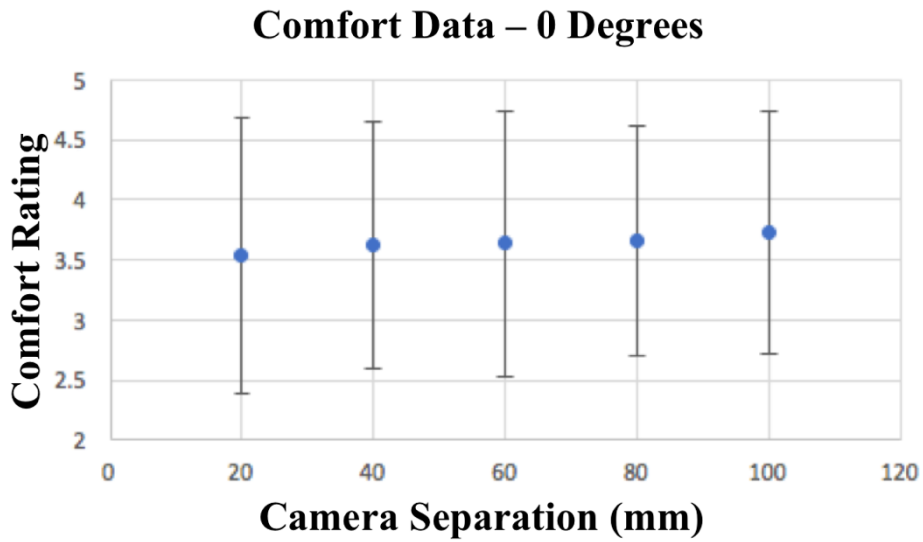


Figure 6-9. Mean level of comfort for each camera separations on each viewing position.

Overall, there is no difference between comfort values at the three viewing angles, neither is there any effect of Camera Separation on comfort at any of the experiment's viewing angles.

6.4 Discussion

Contrary to expectation, there was no consistent significant effect on perceived distortion by off-axis viewing for angles of up to 45° off-centre. Only at the 20mm camera separation was a noticeable reduction in the angle perceived as the viewing angle increased. The overall lack of significant interaction between the three viewing angles and distortion is in agreement with Hands et al. (2015).

Where Banks et al. (2005) and Vishwanath et al. (2005) report greater distortion at the frontoparallel position at a wide geometric field of view (>45°), we found that distortion is overall unaffected by the viewing angles used in Experiment V, leading to perceptual invariance. Additionally, Thompson et al. (2011) also argue against this limited perceptual effect of off-axis viewing. However, they hypothesise that cues from other sources enable preservation of perceptual constancy for 3D content, in line with our finding on sustained perceptual constancy for angles of up to 45°. Burton et al. (2012) also reports a marked effect of lateral displacement on both distortion and comfort. Interestingly, Banks et al. (2009) find that while viewers were unable to compensate for off-axis viewing, they nonetheless were able to report a right angle without bias. However, it is worth noting that Banks et al.'s (2009) simulated lateral displacement from the centre of projection (CoP) through monitor rotation as opposed to displacing the viewer. A similar approach was used for Banks et al. (2005). It is probable that this methodological decision preserved the influence of monocular cues or that of familiarity cues, i.e. built-in bias for right angles.

As with the previous experiments, a flattening of the relationship between perceived angle and camera separation, as compared with that predicted by ray-tracing, was observed.

Also, contrary to expectation, no increase in difficulty of angle discrimination, as measured by the slope of the psychometric function, was observed with off-axis viewing for the selected range of viewing angles, nor did the comfort data show any effect noted relative to off-axis viewing.

Yang et al. (2011) reported that in cinema settings, younger research participants (13-23 years old) experienced the greatest dizziness at the 45°L position, although no interaction was observed for the other seating positions (i.e., 22.5°L, central position, 22.5°R, and 45°R). Furthermore,

these younger participants also reported greatest nausea at the 45°L, 22.5°L, and 45°R viewing positions, although greater nausea symptoms were observed in the central position after 3D viewing. On a related note, participants at the 22.5°L and central position experienced a greater sense of object motion. However, the central position elicited a greater sense of involvement in the movie.

While our study agrees with Yang et al. (2011) that the central position affords greatest immersion—in our case, because of a marginal interaction between viewing position and distortion—we disagree with their finding that the central position elicits the least viewer comfort. However, our findings affirm that viewing distance enhances viewer comfort for stereoscopic perception (Experiment I). Importantly, the central position represents the frontoparallel position that reflects HIT when it matched to the IPD.

There are several probable reasons for these observations as highlighted here. Firstly, compared to Banks et al. (2009), our study utilised a longer viewing distance (about 33% longer) which made the stimuli presented that more orthographic (Hands, Smulders & Read, 2015), a condition with perceptual connotations (Hagen & Elliot, 1976). This may have enhanced the participants' visual ability to achieve off-axis compensation and, consequently, improved veridicality. Secondly, we selected a generic marble texture in contrast to Banks et al.'s (2009) wireframe texture. This selection successfully ensured that our stimuli hinge had less visible crosstalk which lent itself to boosted stereoscopic fusion. Vatolin (2011) confirms that texture selection can complicate 3D vision.

Several hypotheses have been forwarded to explain perceptual invariance including compensatory hypotheses such as pictorial and surface compensation (Vishwanath et al., 2005). Ultimately, compensation mechanics yield perceptually invariant images despite geometric distortions in the retinal image. Of the two hypotheses provided above, pictorial-compensation is particular importance as it delivers both geometrically and perceptually correct compensation for all viewing conditions (Vishwanath et al., 2005). (For a more definitive overview of these and other hypotheses, see vision science literature: Banks et al., 2005; Busey et al., 1990; Kubovy, 1988; Perkins, 1973; Pirenne, 1970; Sedgwick, 1991; Todorović, 2005; 2008; 2009; Vangorp et al., 2013| Zorin & Barr, 1995).

According to this method, the centre of projection is recovered from the geometric information that forms a projection's vanishing point. When reconstructed for camera calibration, this

particular compensation method also requires assessment of the viewing distance and stimuli orientation (Caprile & Torre, 1990). Hagen (1976) observes that this compensation method is operative only when pictorial surface qualities are visible. In our case, the presence of a visible picture quality (i.e. texture) is theorised to have enhanced the ability to compensate for viewer horizontal displacement. However, this process is computationally intensive, requiring significant cortical processing which accounts for the drop-off in viewer comfort. That said, Banks et al. (2005) propose an improved theory underlying perceptual invariance during oblique viewing. This theory offers that S3D viewers utilise local surface slant to reduce noticeable distortions. However, the authors argue that at wider displacements (particularly those exceeding 45°, which is close to one of our viewing positions), viewers would experience the most distortion. Our data shows that said distortion is basically unaffected by viewing position. This result is also noted in Vishwanath et al. (2005), where seven viewing positions (-45°, -30°, -15°, 0°, 15°, 30°, and 45°) were tested: the authors found consistent invariance especially when the viewing angle was < 45°. Notably, as with other studies already reviewed here, the authors did not investigate the effect of typical acquisition factors, choosing instead to elicit displacement by rotating the screen.

Nonetheless, Morita & Ando (2012) report statistically significant changes in the oculomotor subscore of the SSQ instrument when participants viewed stereoscopic content at the only oblique position tested (40° position). In our experiments (Experiments II and III), a noticeable flattening of responses is noted when acquisition FOV is unmatched with observer AOV. Also, horizontal offset will result in a distorted field of view and scaling, leading to non-veridical perception. Considering that oculomotor cues are related to the observer, it lends credence to the interaction between convergence, and accommodation (Reichelt, 2010) and viewer comfort at oblique viewing positions. Indeed, horizontal offsets not only reduce immersion, but also elicit perceptually uncomfortable visuo-ocular responses (Yang et al., 2011). Vangorp et al. (2013) dispute this approach, arguing that the response to off-axis viewing is a function of distance, a non-observer factor, from the stimuli. Several other authors make similar arguments (Adams 1972; Lumsden, 1983; Todorović, 2009; Cooper et al., 2012; Hands et al., 2015). Regardless, Banks et al.'s (2009) findings validate the observer-centric retinal approach in explaining viewer compensation—or, in their case, the lack thereof—during oblique viewing. Granted, Banks et al. (2009) compared the participant perception of non-stereoscopic and 3D stimuli. However, only two participants were exposed to this experimental setup.

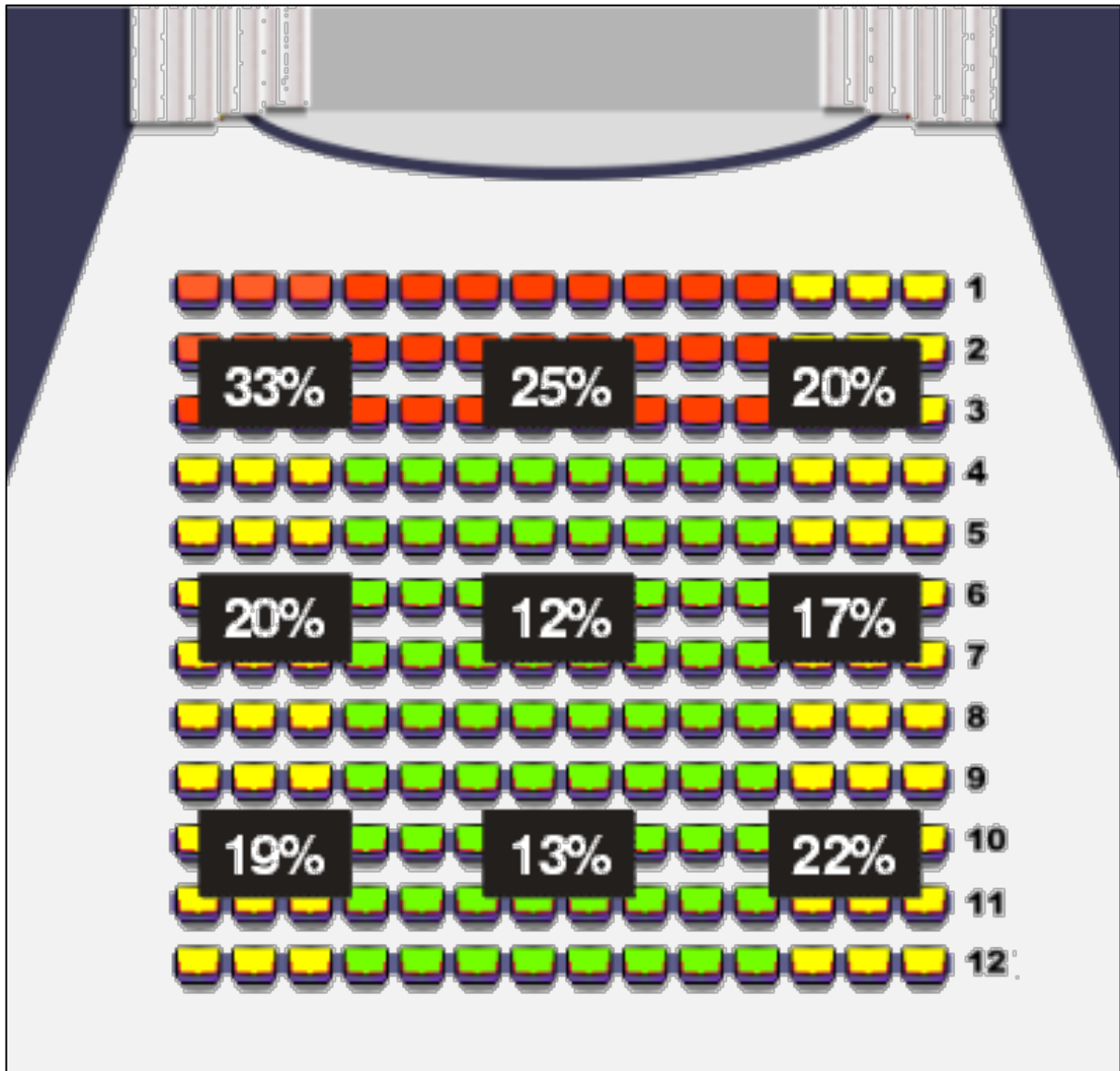


Figure 6-10. The percentage of moviegoers that self-reported visual discomfort by seating position after watching a 3D film (adapted from Ruppel, 2010).

Figure 6-10 shows that visual discomfort was, on average, more frequently reported upon leftward displacement from the CoP: on average, 24% of viewers reported visual discomfort when seating at positions displaced to the left. Other than for the top left position, all other positions displaced to the left were associated with the highest occurrences of visual discomfort. Ruppel (2010) does not provide the viewing angles corresponding to each delay nor could we obtain the literature substrate from which the angles were derived (Thomas, 2010) due to translation issues (the source material is in German). However, the author notes that more female participants (21%) than male viewers (16%) reported visual discomfort. This still does not explain the differences in discomfort across seemingly similar displacement angles as depicted in Figure 6-10.

Results from Yang et al. (2011; 2012) may provide an explanation. Yang et al. (2011) demonstrate, for instance, that younger viewers (13-34 years) report the greatest discomfort when the viewing angle was displaced to the left during 3D viewing. More specifically, the youngest viewers (13-23 years) reported greater dizziness when displaced to the farthest angle in the left (i.e. 45° to the left at a viewing distance of 3.38 metres). Slightly older participants (24-34 years) reported greater dizziness when slightly displaced to the left (i.e., 22.5° at the same viewing distance). It is possible, therefore, that Ruppel's (2010) participants skewed to this age bracket as well, accounting for the differences in comfort scores for equal left-right displacements.

Using the same dataset, Yang et al. (2012) also show that seating positions displaced to the right delivered a lower sense of immersion than the front-parallel position. The study shows that a position 22.5° to the right, 4.8 metres away from the screen (what essentially amounts to the top right position in Figure 6-10) produced stronger visual discomfort symptoms during 3D viewing vs 2D viewing (save for a similarly displaced position but at a closer distance, 3.38 metres away from the display). Also relevant is that, of the nine seating positions evaluated for specific discomfort symptoms when watching stereo content, post hoc analysis found the only significant difference between a central position on a second row and the farthest position to the right on the third row (Zeri & Livi, 2015). The symptoms in question included blur, double vision, headache, dizziness and nausea. These findings mirror that summarised in Figure 6-10 that the top right position presents significant distortion.

Our experiment (Experiment V) shows a contradicting result: there is no main effect of off-axis viewing on perceived distortion at our fixed viewing distance (60 cm). This data was for a participant pool of 62.5% male and 37.5% female observers with a range of 18 to 29 years of age. It is possible, however, that the demographics may have little utility in this discussion. Yang et al. (2011; 2012) and Zeri & Levi (2015) have markedly different participant demographics when age is taken into consideration: the former's pool has an average of 36.6 years with 77.8% of the 203 participants above 24 years old. On the other hand, Zeri & Levi's (2015) pool has a mean age of 24.4 years. Despite these differences, the two studies find that viewers report significant discomfort when viewing from a laterally displaced position [Zeri & Levi (2015) specify both the discomfort symptoms and the positions in question].

However, it is important to bear in mind that, with a real scene, subjective measures of viewing may be different from the objective measures of observing content. For instance, Yamanoue et

al. (2012) found a decrease in the comfort rating despite an objectionably acceptable level of 3D in the experimental stimuli. This is because a real scene contains numerous individual monocular depth cues, and also the fact it is a scene (familiarity cues) (Enright, 1984). Viewers tend to choose visual perceptions that is familiar to them despite the optical constraint of off-axis viewing: distorted objects are often too unfamiliar and improbable to register as possible subjects. In our experiment, however, we find that viewers could ignore the extra fusional effort required to tolerate oblique viewing, contrary to previous research (Greene, 1983). Greene (1983) finds that displacement from the CoP for anaglyphic stimuli produces distortions that are more noticeable. Instead, our research finds the opposite to be true: there is no significant effect of off-axis viewing on distortion.

Overall, it is important to determine the causative parameters of stereoscopic discomfort robustly. It has been presented elsewhere (Holliman et al., 2006; Valentic, 2011) that simply adjusting HIT such that it distributes parallax symmetrically about the fusion zone can reduce discomfort. Also, presenting the convergence point such that infinity matches IPD (easier in cinema) results in an approximate correction for all observers, not just for those sitting front-row centre.

In the previous experiments, it has been demonstrated that reliable comfort data reported elsewhere can be disrupted simply by changing target eccentricity. This is logical since the convergence point is, by definition, at zero disparity. Therefore, a large disparity close to this point will be more affective. While these experiments have indicated a correlation between eccentricity, supporting il-Lee (Jung, Lee, Sohn & Ro, 2012; Lee et al., 2013), the effect is not as clear-cut as elsewhere. It may come down to what the true extent of the image being fused, crosstalk in display as to whether the large disparity is attended to when it is off-centre (i.e. oblique viewing). Also, the convergence of the viewer's eyes is not controlled.

In Experiment V, the same observers repeated three trials, which may have introduced a generic visual fatigue element, regardless of the counterbalanced order. Due to the limited sample size available from not running the experiment in a cinema environment with a larger group of participants, this study was limited in this regard.

Hypothesis H₅ is partially supported, with perceived distortion not being affected by oblique viewing. However, there was no significant difference in perceived comfort either which was contrary to the prediction.

CHAPTER 7 – DISCUSSION

The previous chapters in this thesis introduced the literature substrate underlying, the methodology used, and empirical results of an investigation into the relationship between stereo acquisition factors and viewer comfort of static stereoscopic images.

This chapter aims to present an interpretative discussion and final examination of the main findings. As such, the chapter is organised into, firstly, a review of the hypotheses, secondly, an accounting of the empirical results, and lastly, concluding remarks. This chapter also details the implications for future research and concedes limitations of the investigative methodology and findings. The subsequent chapter will explore the applications of these findings, relating our findings back to the original research motivation (i.e. improving the generation of 3D content for cinemas).

7.1 Hypotheses and Results

This research addresses the question of how acquisition parameters affect human factors when viewing stereoscopic 3D stimuli. The research investigated answers this question through several experiments on visual discomfort after viewing stereoscopic stimuli in the form of hinges. Specific hypotheses were formulated and evaluated through five experiments. The hypotheses are as presented in Section 1.10: Hypothesis Statement.

Experiment I showed that the different screen distances had no effect on the angle perceived as 90°, discriminating hinge angles became difficult at closer distances, and that viewer comfort increased as the distances increased. This finding is consistent with the experimental hypothesis H_1 .

Experiment II (fixed-width, variable depth) also showed no relationship between comfort and distortion hence verifying that disparity (parallax) has no predictive power. This finding presents empirical evidence to support hypothesis H_2 . However, Experiment III (fixed-depth, variable-width) reports a relationship between viewer comfort and perceived distortion. Nonetheless, while the magnitudes of these observed distortions are predicted by a ray-tracing model, the predictions are mostly flat. This consistently flattening relationship is reported in all other experiments and led us to conclude that comfort is mostly independent of disparity, partially supporting hypothesis H_2 .

Hypothesis H₃ is supported by the psychophysical values reported in Experiments II and III. Indeed, there was a main effect of distortion on comfort as determined by the difference between the 2D angle rendered and the 3D angle predicted by the ray-tracing model. Crucially, however, for both experiments, viewer comfort was not determined by changes in the perceived shape.

Experiment IV presented stereo stimuli into the screen (into the screen also refers to “behind the screen”, “at positive parallax”, or “at positive disparity”). Stimuli were presented at a fixed depth and variable width, similar to Experiment III. While we hypothesised that the vergence-accommodation conflict is more pronounced out of the screen than into the screen (i.e., hypothesis H₄), we found that stereo stimuli presented into-the-screen were judged less veridically (i.e., flatter) than those presented out of the screen. This finding introduces a new dynamic that challenges the industry practice of the wholesale limiting of parallax.

Experiment V directly tested hypothesis H₅, i.e., distortion is not affected by viewer position, but instead, comfort is affected. On the one hand, the experiment supported our assumption that oblique viewing does not have any significant effect on perceived distortion, except for the smallest Camera Separation (20 mm): essentially, hinge angles were judged as being the same regardless of viewing angle (up to 45°). This finding is consistent with the first section of our hypothesis. However, contrary to expectation, oblique viewing, to the extent administered in our experiment, has no noticeable impact on the viewers’ comfort, at odds with the second component of hypothesis H₅. Once again, this contrarian finding challenges industry conventions.

The data also show that comfort data are simple for fixed width stimuli but more complex when stimulus width is changed. It appears there are competing factors to determine the comfort of a stereoscopic image. Decreasing horizontal disparity and increasing target width increase perceived comfort. In previous stereoscopic image studies, the screen is considered to be homogenous, with disparity considered to be of equal magnitude regardless of spatial position.

7.2 Performance of the Predictive Model

Under optimal conditions, we have demonstrated that there is little-perceived distortion, demonstrating the robustness of correct rendering to compensate for viewing distance. Importantly, the distortion data behaves in line with prediction, although significantly flatter, across our experiments. These results reveal that perception maps well onto prediction broadly and that prediction provides a large component of the correct estimation of 3D distortion.

Notably, however, Experiment V reveals a perceptual constancy in off-axis viewer conditions for multiple viewers which is not reflected by a typical ray-tracing model.

Burton et al. (2012) and Kelly et al. (2013) also report that perceptual distortions were smaller than predicted when using a ray-intersection model. Woods et al.'s (1993) and Held & Banks' (2008) demonstration of the utility of a similar ray-intersection approach have proved influential. However, it is Banks et al.'s (2009) publication that evaluated the predictive utility of this geometrical model when investigating perceptual distortions in stereoscopic 3D viewing. The authors successfully establish that the perceptual errors from off-axis viewing were statistically identical to the predictions from the ray-intersection model (Banks et al.'s, 2009; Pollock et al., 2012). Vishwanath et al. (2005) and Burton et al. (2012) confirm the relative accuracy of this (epipolar) geometric approach to model perceptual distortion. Where perceptual distortions were shallower than predicted by a standard ray-intersection model, Pollock et al. (2012) argue that the unavailability of monocular depth cues might account for the departures. Unfortunately, there is little evidence on perceptual models for human factors when HIT and camera interaxial are adjusted.

The distribution of distortion data in our experiments, despite inter-observer differences, shows that there is a convincing case for using prediction models. However, these models may need to include a factor to compensate for the flattening effect of 3D displays instead of real objects. There is likely a trade-off of observing a projected stereoscopic CGI image instead of looking at a) a real object or B) a stereoscopic photograph. However, caution must be expressed when correlating the angle judgement data for hinges to the perception of distortion of objects or faces. While it is quantifiable, it is not necessarily the same question. Indeed, extant research is divided into studies, firstly, where parallax values are presented with non-controlled video scenes and, secondly, with angle judgement data of controlled hinges. There is a clear case to do rigorous studies with controlled video scenes and use objects with known shape properties. Nonetheless, the current mathematical prediction model is useful because, for straightforward objects, the parallax can predict the comfort and the distortion can almost predict the distortion.

Also, there was a significant main effect of camera separation on perceived distortion (angle). However, a comparison between PSE and IPD models revealed that there was no discernible benefit of tailoring the model for individual IPD. Kim, Lee, & Billinghurst (2015) disagree, noting that adaptive IPD adjustment for all participants ($n = 12$) produced the highest comfort rating. However, the researchers admitted to expanding the participant base. Ide & Sikora (2010)

elaborate the mathematical logic underlying this adaptive approach. However, the authors' concept is not accompanied by psychophysical data. Our research has already established the limitations of extending insights on ideal parallax tolerance to real-world scenarios (Experiment V), especially without accounting for viewer responses.

Furthermore, where Kim et al. (2015) report that adaptively reducing the IPD did not degrade stereoscopic immersion, our study shows that smaller observer IPD correlates with more discomfort and vice versa. This is mainly because, at a smaller IPD, the effective parallax will occupy more of the observer's visual field. In addition to disagreeing with Shibata et al. (2013) who find no difference in veridicality between in-front-the-screen and behind-the-screen content, our research also disagrees regarding IPD. Shibata et al. (2013) report that greater IPD is correlated with more severe visual fatigue, markedly different from our findings on the correlation between observer IPD and mean comfort values.

Furthermore, while Lipton (1997) demonstrates how IA and IPD affect scaling, the ray-tracing geometric model that we have constructed shows that this scale distortion does not result in shape distortion provided the camera separation is set to match the IPD. This is more so, as in our experimental conditions, if the acquisition field of view (FOV) is matched to the angle of view (AOV). Our finding is in agreement with extant findings on the orthostereoscopic condition (Bickerstaff, 2012) and AOV matching (Bereby-Meyer et al., 1999; Read & Bohr, 2014).

As previously noted, the individual effects of camera separation and angle and their interaction with the perceptual deviations from a right angle were smaller than predicted based on disparity information alone. This finding extends prediction beyond disparity alone. Allison and Wilcox (2015) agree, noting that for realistic stereoscopic footage, the effect of IA on depth estimates across different experimental setups was much less than predicted from the geometry of stereopsis. As in our case, the authors also argue that the shortfall may be due to the preserved effect of monocular depth cues.

Once again, however, this extension beyond disparity alone contrasts previous research. For instance, Wöpking (1995) proposes disparity-based guidelines to alleviate visual fatigue. Vatolin et al. (2013) and Voronov et al. (2013) also identify a relationship between the disparity budget for commercial video content and viewer comfort. Lambooij et al. (2011) describe the relationship between visual comfort and disparity and, consequently, propose a disparity-based disparity prediction model. McVeigh et al. (1996), Didyk et al. (2011), Sohn et al. (2011), and

Jung et al. (2013) also propose various disparity-based prediction models. However, Chen, Zhou, Sun, and Bovik's (2016) recent scholarship show opportunities for improving the accuracy of disparity-based prediction models.

More relatedly, Park, Lee, and Bovik (2014) empirically prove the statistical superiority of extending perceptual prediction beyond disparity distribution only. They do so by extracting vergence conflicts from disparity and accommodation conflicts from physiological optics and foveation. Du, Masia, Hu & Gutierrez's (2013) predictive model of visual comfort also extends the metric beyond disparity and also takes into account motion combinations and luminance frequencies. The predicted scores fit very closely to viewer comfort. Guan, Lai, Chen, Chou, and Chuang (2016) also propose an extended predictive model that accounts for screen width and viewing distance variation that is more intuitive and is already field-tested.

7.3 Cinematographic Equivalence

In these experiments, the virtual camera Field of View (FOV) was matched to observer Angle of View (AOV) at 45 horizontal degrees. Changing the camera FOV systematically affects how the hinge angle appears. When the camera FOV is increased such that it is a wide-angle lens, maintaining the observer AOV, the hinge angle appears more acute. Likewise, if the camera FOV is decreased so that it is a telephoto lens, again maintaining the observer AOV, this causes the hinge angle to appear more obtuse.

Figure 7-1 illustrates the range of camera FOVs that are required to generate the angles used in the experimental series. Existing production guidelines to stereoscopic 3D (3D Consortium Guidelines Safety Committee, 2004; Boyle, 2012; Coppin, 2011; McNally, 2013; Zone, 2012) give an accepted range of focal lengths as between 20 mm and 40 mm on a cine sensor.

CHANGE IN FOCAL LENGTH ON A CINE SENSOR BY DOLLY ZOOM

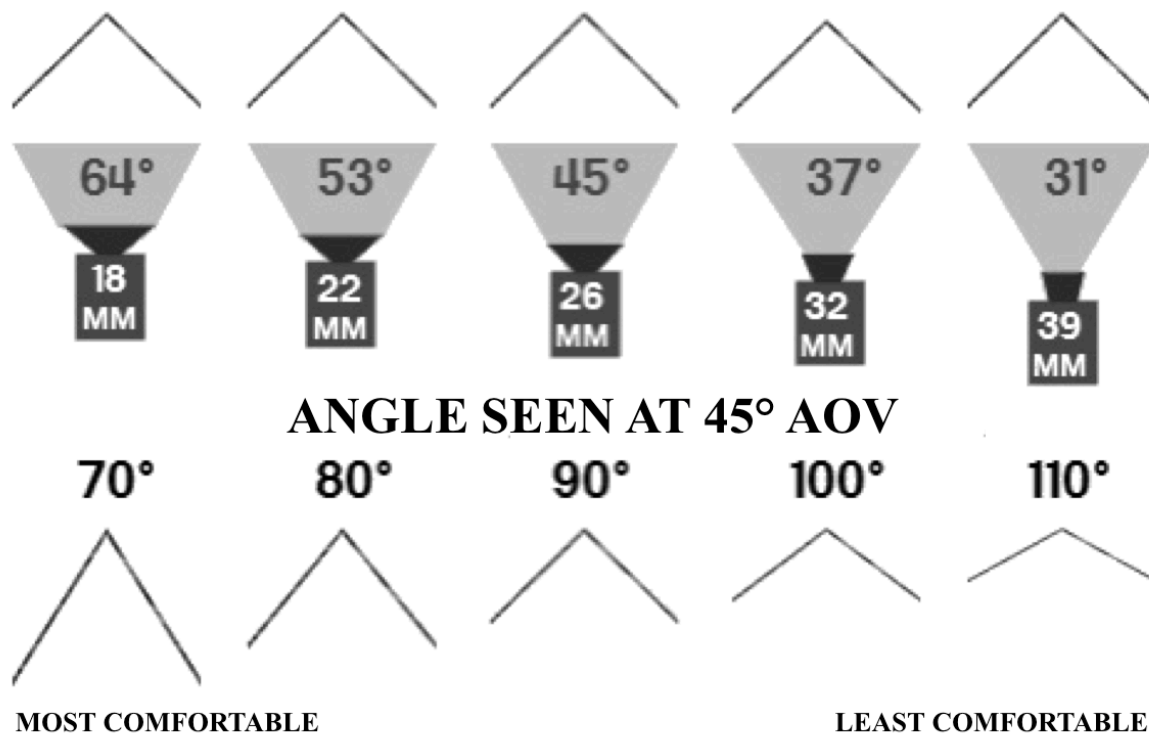


Figure 7-1. Range of camera focal lengths utilised in this experimental series.

In Figure 7-1, the bottom row shows the range of angles presented at the 60mm camera separation in the experiments, all generated using a standard lens (26-mm focal length, 45° FOV). In the top row, all five angles are 90°. The focal length and camera-hinge distance are changed simultaneously to keep the hinge at the same apparent size on the screen. The rendered angle changes systematically as shown on the bottom row. A 18-mm wide angle lens (64° FOV) produces an apparent 70° angle, and a 39-mm telephoto lens (31° FOV) produces an apparent 110° angle.

7.4 Limitations

7.4.1 Hinge Stimuli

A potential shortcoming of these experiments is that the stimuli were rendered at pre-specified virtual camera separations, one of them (60 mm) being close to the average inter-pupillary distance (IPD). The stimuli were not adjusted for presentation at the individual IPD which is typically between 52 and 75 mm. Read & Bohr (2014) report a slight gender effect (due to average female IPD being 0.96x male IPD): of the 132 female participants that were exposed to

S3D content, 30% recorded reported adverse effects compared to 17% of the 100 male observers. Except for Experiment V (62.5% were female), the participant pools in the other experiments had more female observers than male: 65% were female in Experiments II, III, and IV compared to 52.5% in Experiment I. Regardless, our findings did not show any gender split such as the one observed by Read & Bohr (2014) i.e. our findings were non-significant here. Since the deviations are fairly small, we do not expect gender to influence our data and intend to address this issue in subsequent experiments.

The results reported here indicate a lack of a ground truth after the experiments. Banks et al.'s (2009) results found reliable parity where a 90° angle presented at human eye camera separation, in life size, and frontoparallel on a screen was perceived with a PSE of almost exactly 90°. The results of the first two experiments presented here showed that a 90° angle at a 60mm camera separation had a PSE of approximately 75° in both cases. It is possible that the results could be affected by a rendering error.

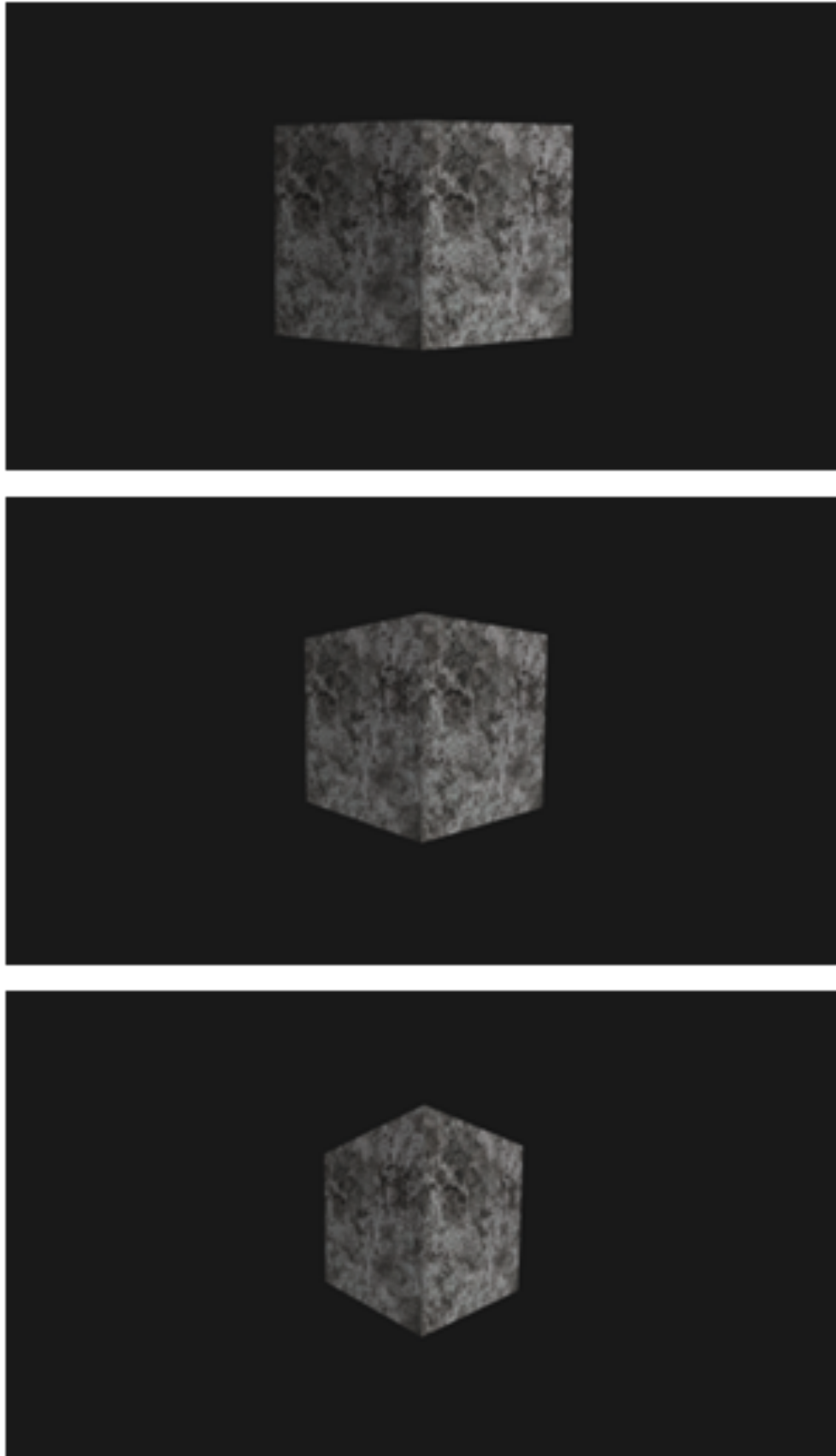


Figure 7-2. Stereo hinge perception at different fields of view. FOV = 35 degrees (Above); FOV = 45 degrees (Middle); FOV = 55 degrees (Below).

Other limitations are evident. First, the hinge object has idiosyncratic properties in that it is not a disparity defined gradient generated by a random-dot pattern. Harris et al. (2008) have used this approach and still observed a bias, perhaps due to mediating effects of accommodation vergence breakage. Corriveau et al. (2011) report accommodation and vergence linkage applied to the hinge task where the placement of the virtual target in negative disparity results in a different demand than observing a real target. It is not clarified whether this is due to context, or if the experiment was strictly controlled. Shibata and Banks used a red-textured grid to define the hinge. This was rendered in CGI. However, with currently available commercial screen technology, such high contrast patterns do not perform well.

Other choices for the stimulus were an object such as a tennis ball which would have object constancy. In that case, the participant's understanding of the shape of the object would potentially override disparity-defined shape information about the object. The other option would be a face; however, this would likely be compounded by additional face processing and subject to bistable illusions (i.e., hollow face illusion) (Króliczak, Heard, Goodale & Gregory, 2006).

The current stimuli were rendered in order to subtend a constant horizontal angle of view. It was considered that by keeping object depth constant but changing the horizontal width of the hinge to change the angle presented would result in an obvious monocular cue to width to the participant.

7.4.2 SSQ

The Simulator Sickness Questionnaire was used to record dizziness, disorientation, and nausea in participants. Overall, participants responded low on this scale. Whilst it is an established measure, SSQ was originally intended for helicopter pilots where there would be a large field of view, moving stimuli, and also, potentially a motion platform. Therefore, more streamlined measures of stereoscopic viewing eyestrain and discomfort adopted by Corriveau et al. (2011), Vienne et al. (2011) and Yamanoue et al. (2012) contain more appropriate questions relating to the content presented.

7.4.3 Familiarity

It is important to note that this is but part of a multi-stage process to evaluate the effect of stereo acquisition factors on distortion and comfort. Humans are familiar with seeing 90° angles, but it

should be evident that the judgement of the angle as 90° is only a product of context. Therefore, presenting an angle out of context is a different question.



Figure 7-3. In real-life, we seldom see a right angle in such an isolated context.

The proposed next stage would be to use a library of common household objects to test this finding. Real-world objects may elicit unpredictably different perceptual responses compared to artificial stimuli (Bishop, 1996; Horwood & Riddell, 2012). Instead of measuring whether the angle is greater than or less than 90° , the task would be to judge whether the object is stretched or flattened relative to its correct shape. Conceivably the same problem may arise that an object presented at a far viewing distance in isolation would appear to be unnaturally distorted, whereas this is just an artefact of the normal human visual field. For instance, a teacup on a table may appear ellipsoidal whereas the context of the table would give the context information for its correct shape to be determined. However, our pre-existing knowledge of the shape may provide a statistical difference between the abstract hinge objects which have no “correct” answer- for instance, a 45° hinge is no less objectionable than a 90° hinge. Whereas a tennis ball elongated to the shape of a rugby ball is potentially an easier question to answer. The “real object approach” certainly introduces shape constancy.

7.4.4 Applicability of Findings to Off-axis Viewing

Stereoscopic acquisition and presentation parameters were manipulated across two positions off-centre in Experiment V, 22.5° and 45° in both directions, i.e., right—and left—ward. The experiment revealed persistent perceptual constancy for off-axis viewing even at the farthest viewing angle tested, i.e., 45°. Only at the 20-mm camera separation was a noticeable reduction in the angle perceived as the viewing angle increased.

However, due to the limited number of lateral displacements (two on either sides), these findings may have minimal applicability in commercial cinemas. Nonetheless, they are entirely applicable in computer gaming applications.

7.5 Implications for Future Research

7.5.1 Objective Measurement of Viewer Comfort

Although the research presented here has provided versatile and empirical insights into the delivery of comfortable S3D content, it could be expanded in several directions. For instance, it would be interesting and perhaps informative to include biofeedback data as part of a predictive toolset for the comfort of watching stereo 3D content.

Furthermore, there is a clear opportunity to use real stereo footage. Indeed, presenting footage that has been live (on-the-fly) or post-converted to optimal stereographic settings will enable the vision science research community to empirically and veridically demonstrate that correct object size relations (see Rushton, 2005) are the most important determinant of comfortable stereoscopic content. By using the 3DVB2 framework (Gobbetti, 1993; Veltkamp & Blake, 2012) for on-the-fly parallax correction in conjunction with disparity analysis software (Lazaros, Sirakoulis & Gasteratos, 2008; Kim, 2007) to determine acquisition settings, this should enable the end display parallax to reflect an orthostereoscopic acquisition system, regardless of the original settings. Through the 3DVB2 standard, it should be a straightforward measure to enable live interaxial repurposing and thereby ensure a consistent orthostereoscopic geometry appropriate to the capture lens. In this way, even footage that was captured with poor stereographic quality can be presented in a more appreciable format. Comparative experiments and previously defined biometric feedback could then measure viewer comfort, and robustly measure whether this technique improves the 3D experience.

In the experiments reported here, a fixation target and the stimulus image were presented converged at the screen plane. There are two factors which may be an issue here. First, the eyes may not be converged exactly at the screen plane, but slightly in front of or behind it, using the fusion zone to fuse the hinge in stereo. Second, there are large individual differences between where viewer's natural resting point for their eyes is. The issue of where exactly the eyes are looking at can be problematic, since observers may demonstrate the same stereoacuity but be under different amounts of eyestrain at a particular fixation distance. Unless the target is placed at an observer's normal fixation distance, it is difficult to objectively compare between observers. There is limited normative data available, none of which is very current.

Hoffman and Sebald (2007) performed an eye tracking experiment using the hollow face illusion. Vergence distance was calibrated, and participants fixated on where they perceived the tip of the nose to be. Somewhat surprisingly, participants fixated on the illusory nose (the disparity information specified the opposite). What is even more surprising is that the binocular information received by the retinas simply did not correspond to where the eyes were pointed. This can suggest that, in fact, the vergence angle of the eyes is independent of the placement of disparity information in space. Vienne et al. (2011) used an eye tracker to measure the viewer's eye movements. They reported lower amplitude microsaccades for larger amounts of disparity. Oculomotor fatigue was difficult to isolate within the general context of fatigue.

The use of a face-mounted binocular eye tracker is proposed for future experiments. This would allow measures of binocular fatigue (PERCLOS, blink duration, and blink frequency), accommodation (pupil dilation), and vergence (symmetrical pupil displacement).

On a related note, various fatigue monitoring technologies (FMT) have been proposed. However, the methodology of their application and evaluation is woefully inadequate or has subdued accuracy. For instance, PERCLOS (percentage of eyelid closure) has been certified as an empirical measure, but seems very simplistic (Sommer & Golz, 2010) and seemingly cannot systematically and precisely model viewer fatigue. Indeed, the visual fatigue literature is populated by very basic methodology. Future research would be valuable if it could establish parameters and conditions that precisely measure and avoid visual deterioration.

As was initially noted from the outset, this study does not investigate cue combination models. Admittedly, this may be a limitation in itself. Instead, the focus of this study was to use a robust stimulus to investigate the effect of manipulating acquisition parameters. While this task is

reliable, future research will focus on using simpler disparity-based stimuli to measure the fusion zone across different viewer distances. Several authors (Landy et al., 1995; Grove et al., 2006; Wismeijer, Erkelens, van Ee, & Wexler, 2010) have devoted considerable energies to researching cue combination models. For an exhaustive review see Howard (2012).

This research has also produced several other questions for future inquiry. First, are rich scenes (such as those typically found in stereoscopic content) susceptible to the same magnitude of distortion as abstract objects in an empirical setting? Or do the known scene properties hinder the perception of distortion? Second, are linearly predicted results from previous accounts reliable when distortions commensurate with everyday viewing are introduced? The large inter-observer differences indicate that there may be mitigating orthoptic factors beyond those presented here, and that future comparisons should be done by placing the image at an equal point of unstressed fusion for all observers.

A subsequent experiment was also conducted to verify whether there is any effect of changing angle while maintaining a constant object depth on either comfort or distortion measurements. Distortion needs to be explained in the context that in this instance the hinge presented is merely stretched, but it is not subjectively perceived as distorted since the texture mapping is uniform. A potential replication could investigate using a constant texture image of known size with strong shape cues such as circles which would then be stretched and contracted to keep the image information constant. In this way, subjective distortion could be measured. The hinge angle also had linear perspective defining the ages and a texture gradient which also accounted for mediation.

7.5.2 Understanding the Disparity Budget

Studies examining the disparity budget and its impact on viewer comfort (Shibata et al., 2011a; Vatolin et al., 2013; Voronov et al., 2013; Yamanoue et al., 2012; See also Section 1.6.6: Relationship between Image Comfort and Distortion), while failing to strictly control camera separation, can be extended in one of two directions.

Firstly, the applied use-case of large-scale tests on natural content would provide useful tolerance specifications for stereoscopic camera manufacturing. A random-dot psychophysics analysis would help industry professionals to fully understand how the visual system perceives depth warping when free from all other pictorial cues. However, random-dot stereogram studies only inform themselves as the interactions with monocular cues in even simple scenes, leave alone

production-grade images, creates perception conflicts. Secondly, the researcher suggests utilising biometric feedback devices as part of a predictive toolset of viewer comfort.

7.5.3 Future Research

Plenty of studies use 3D video content, but while the display parameters are known (how much parallax and where it is distributed), the acquisition and post-processing parameters of IA, HIT and field of view (FOV) are often lost in preparation. Other studies use simplified 3D objects, but at the expense of ecological validity (confidence in finding the same result outside of the lab). Can the experience of 3D be predicted by the amount of parallax alone?

Our research suggests that when viewing simple hinge objects, the amount of distortion perceived approximately matches what can be predicted through ray-tracing. Also, the amount of parallax does not reliably predict comfort. The only time parallax is measurably related to comfort is when the HIT approximately matches the inter-pupillary distance (IPD). When viewing simple hinge objects with HIT set to approximately IPD, people rate 3D as (slightly) more comfortable. But this may be due to the choice of stimulus and is not definitive advice for content production.

The above experiments fixed viewing position centrally with a chinrest, with the display field of view matched to that of the camera. So how important is seating position? How does the use of wide angle or telephoto lenses affect the 3D viewing experience? And is there any interaction between the above factors?

Recent research has shown that off-axis viewing of 3D content on a 3DTV is fairly insensitive to viewing angle, in line with the distortions experienced when 2D at all but the most extreme viewing angles (Bank, Held & Girshick, 2009; Hands & Read, 2013). These findings beg the following questions. Firstly, what is the difference- if any- when this experiment is repeated in a cinematic environment and, secondly, does changing the acquisition factors exacerbate perceived distortion?

Future research could also include showing a range of simple 3D objects, generated from a selection of 3D acquisition parameters including IA, HIT and FOV. The presented stimulus would still be a simple object, not a movie scene. The order of presentation will be randomly interleaved to reduce second-guessing the outcome as has been demonstrated in this dissertation. Audience members would, ideally, respond using a web app on their smartphones (with paper backup), inputting their seating co-ordinates such that it will be factored to the dimensions of the

cinema and so each audience member's distance and inclination from the screen will be known. Audience members will then rate a selection of 3D scenes for distortion and comfort using sliders. The results will be processed in real time and displayed live for the audience. This experiment would provide ecologically valid insight as to whether a creative choice of HIT causes unnatural looking 3D or audiences simply do not care.

Additionally, the experiment would inform academia and stereographers if, firstly, a seating position matched to the focal length would be important for comfort and, equally important, if the amount of off-axis 3D distortion experienced by the viewer is affected by the amount of parallax presented. By engaging the audience to take part and experience an experiment using controlled 3D stimuli, this simple, quick form of data collection can be a useful tool for 3D content makers to give confidence that their audience is sitting comfortably. Also, the study could conceptualise a framework necessary for the rapid testing of viewing position in industry.

7.5.4 Open Questions

It is established in the field of stereoscopic imaging that changing the camera interaxial in isolation is only a scaling mechanism, and does not introduce distortion beyond changing the apparent size of objects. So, it is unsurprising that an abstract object such as a hinge is virtually insusceptible to changes in scale. It could be suggested that CGI movies (which tend to be received more positively than their live-action counterparts) can exploit the same ambiguity. Virtual stimuli have no true or objective scale.

Changing the camera convergence point effectively takes the infinity plane of the stereoscopic image and moves it forward, or worse, backwards. The convergence point is not susceptible to viewing distance since it does not need to commensurately increase with viewing distance to form the same visual angle on the screen, rather, the separation between the infinity point of left and right images on the screen should match the viewer's IPD. Many papers simply do not report or adequately describe the precise stereo configuration used, and the seemingly harmless act of re-converging in post-production or experiment preparation can in fact be detrimental. The other stereo factors of changed field of view (FOV) and camera interaxial: when yoked to a correct convergence point, they lead to linear deformations. When these factors are yoked to an incorrect convergence point, these linear deformations become non-linear.

As a result, content producers for different screen sizes face a dilemma. Beyond contending with the accommodation/vergence conflict on 3DTVs (where the viewing distance is within the 6m

range), observers of 3DTV content will seldom see the screen content presented at optical infinity. Typical television viewing figures place the observer at a distance of 2.7 metres from the screen, regardless of its size. For a diagonal screen size of 52", this presents a horizontal screen width of 1 metre. At a viewing distance of 1m, the observer's eyes are converged 1.718° from parallel. At a viewing distance of 2.7m, the observer's eyes are converged to 0.637° from parallel. At a viewing distance of 4m, the observer's eyes are converged to 0.430° from parallel. The infinity point is represented in both instances at the same physical location on the screen. However, at a near distance, the amount of disparity presented on the screen exceeds the observer's fusion range. This demonstrates the main manipulation in our experiments. A convergence point at the wrong distance in stereo space causes the background image to warp. In the case of a black background such as that presented here, the background is ambiguous.

This study found there was no relation between stereo acquisition parameters and comfort when acquisition parameters were controlled to present constant disparities. This is not necessarily surprising due to the absence of context present in the stimulus image. The hinge has no "correct" shape beyond the arbitrary 90° required by the task. Here, disparity was the only causative factor of decreased comfort.

However, future experiments with objects may yield different results. The key question is whether there is a relationship between perceived distortion and comfort. All studies and assessment metrics to date are based on parallax information irrespective of the content they contain. While no distortion/comfort relationship was found in this example, it does not preclude this relationship being found in future content.

The theory to substantiate this prediction is as follows. The relationship between stereo base and monocular cues is well understood and is typically parameterised as hypostereo and hyperstereo. Similarly, the convergence point can be parameterised as hypoconvergent or hyperconvergent. With a familiar object, there is a "correct" answer in terms of the configuration of stereo camera base and convergence point. Deviation from this "correct" answer would cause an elongation or contraction of the object, which would distort it from its familiar form. If this distortion is too extreme, the object will appear very flat.

So why would this cause discomfort? The main answer is the inherent depth map that is available in monocular real images. Enright (1984) observed perspective vergence, where the eyes would make a corrective vergence movement when presented with different regions of an image. For

an image presented with orthostereo information, this vergence movement would not be required since the disparity information would be in correspondence with the existing monocular image information.

Eye tracking data of objects which are presented in orthostereo and hypo and hyper stereo bases may display different eye movements. Indeed, it would be important to calibrate the eye tracker with monocular information.

So, the question can be asked again as, does a conflict between expected and perceived disparity from an image region result in a saccade which is uncomfortable? Or is the saccade made without discomfort?

7.6 Summary

The research findings can be summarised as follows. The laboratory scenario revealed greatest viewer comfort occurred when a virtual hinge was placed on the screen plane. On the other hand, the single-viewer experiments (Experiments II and III) revealed into-the-screen stereo stimuli was judged flatter while out-of-screen content (Experiment IV) was perceived more veridically.

Furthermore, Experiments II, III, and IV consistently showed no systematic correlation between the amount of screen disparity (parallax) in the stimulus and the comfort rating for individual viewers. Lastly, Experiment V reveals a perceptual constancy in off-axis viewer conditions for multiple viewers: displacing the viewer, revealed no changes to perceived distortion, task difficulty or comfort at the different viewing angles. While distortion data behaved in line with the prediction model (albeit significantly flatter) for Experiment I to IV, results for Experiment V were not reflected by a typical ray-tracing model. Essentially, the five experiments reported in this dissertation find that there is a differing bias if the stereo hinge is convex and not at the screen plane, and a robust non-biased response if the hinge is concave with the apex at the screen plane.

In summary, the relationship between parallax and viewer comfort is not a useful indicator. Psychologists have long known this- indeed, the parallax model of stereoscopic viewing was (Wheatstone, 1838) was relegated in favour of Helmholtz's (1858/1909) models of depth perception shortly after it had been proposed. Paradoxically, industry guidelines insist on a limited parallax threshold (for a discussion, see Section 1.5.5: Industry Standards for Stereoscopic Production and Chapter 8 – Principles of Application).

In totality, our experiments show the fragility of applying experiment-based prediction and provide valuable psychophysical counterpart data to current prediction models. However, these findings are not universally applicable and several methodological limitations and open questions persist. Hopefully, by providing equivalence information, acquisition factors can be replicated to resolve them.

7.6.1 Conclusion

To conclude, our research has established that HIT is the biggest predictor of distortion since IA affects the scaling of the objects. Additionally, incorrectly specified HIT results in the observer's near triad being invoked. The eye stops down to increase the depth of field, but the screen is only on one focal plane so no benefit. A convergence point at an artificially close horizon specifies incorrect geometry. And the scene is perceived as darker due to less light entering the eye. This and other findings have been translated into recommendations for stereoscopic shooting. The researcher invites their validation in production settings.

CHAPTER 8 – PRINCIPLES OF APPLICATION

This thesis has aimed to investigate the impact of stereoscopic acquisition factors on viewer comfort. For this purpose, the thesis was guided by several focal research objectives. We explored whether it was indeed possible to predict perceived (angular) distortion and, based on these, what stereo settings are necessary to maintain an acceptable and veridical stereoscopic image. Another objective was ascertaining whether, having obtained the angular distortion (angle of view, AOV), it is possible to discern the relationship between matched and mismatched viewer AOV and acquisition FOV. Relatedly, we set out to establish the psychophysical effects of HIT and screen position on distortion and the dependency between the latter and comfort at different horizontal disparities (camera separations). Ultimately, we quantified the relationship between HIT and comfort and distortion, noting that the prediction model of visual distortion broadly matched the observer perception for distortion. Another vital contribution was an investigation into the interaction between the seating position and viewing comfort and scene distortion.

In totality, the findings discussed in previous chapters formed the basis for a set of recommendations (presented below).

8.1 Contributions

These experiments were conducted using the base of Banks et al. (2009), but with a series of conditions which more typically reflected acquisition settings. Based on the experimental findings, several guidelines should be taken into consideration when filming stereoscopic content. The production of high-quality stereo 3D (S3D) content is still a difficult and expensive art (Smolic et al., 2011a). S3D production has to consider fundamentals of human 3D perception as well as capabilities and limitations of 3D displays and combine them with artistic intent (Smolic et al., 2011b). Indeed, stereoscopic image acquisition and display is a complex and unrewarding process. Current practice is structured around a post-hoc reductionist approach, removing unwanted colour conflicts, intraocular artefacts, vertical disparities, among other practices. However, many of these issues are likely to be exacerbated by a single conflict. In contrast to the findings of Harper and Latto (2001) which states that orthostereo is dependent on life-sized visual information, the ultimate hypothesis of this research is that there is considerably more flexibility in stereoscopic content than previously proposed. Distortions of field of view

and IA are permissible because they are linear. However, distortions from HIT are non-linear and exacerbate many other issues.

It is also proposed, building on the work of Enright (1984), that photographic images contain their inherent depth maps. Therefore, for a monocular image to be perceived as being three-dimensional, it should be presented orthomonoscopically, where the field of view of the original image and the observer are matched. The stereo pair should be derived such that the screen becomes a window – for example, a stereo camera rig would be framed to match the exact field of view of the screen, and converged (through parallel projection/asymmetrical viewing frusta) at the same distance as the human eyes. Achieving this requires using a correct HIT where $HIT = IPD$ thereby eliminating vertical retinal disparities and shear distortion and ensuring shape constancy from front to back.

To guide content makers, it is imperative that the above (i.e., ortho condition, where $HIT = IPD$) is always the starting point. Then, the focal length can be increased or decreased in a linear relationship with the interaxial provided the HIT specified infinity plane remains at the same point in space. So, what solutions are available to reduce this conflict? The use of dioptric prisms to change the vergence angle for television watchers such that HIT can be corrected is such one solution.

The HIT is the biggest predictor of distortion since IA affects the scale of the objects and it is only when combined with HIT that the objects become inherently distorted. Regardless, this finding may be only true for CGI stimuli with an infinite depth of field. Photographic stimuli with finite depth of field may have an additional conflict between IA and retinal blur from depth of field change (Vishwanath, 2014).

Subsequent chapter sections further relate our findings back to the original research motivation (i.e. improving the generation of 3D content for cinemas).

8.1.1 Parallax Limits

Typically, content producers begin with a fixed IA and subsequently adjust the HIT to redistribute the parallax around the screen plane, resulting in the shear distortion described above (Johnston, 1991). However, to attain a correct perspectival representation of reality, first the HIT must be set correctly, and then IA must be scaled accordingly to arrive at the parallax that is required at the screen plane (Bickerstaff, 2012).

Building upon this argument that, contrary to current orthodoxy, the forced limiting of parallax values to within the sensory fusion range creates discomfort in the viewer due to perspective vergence (Enright, 1987) and convergence field warping (Shibata et al., 2011a), it is instructive to note that no matter what parallax values the researcher used, there was no relation to comfort. Therefore, it is implied that parallax can be safely moved forwards and backwards without detrimental effects on viewer comfort. This finding has several real-world applications.

8.1.2 Implications

Industry guidelines continue to require limited parallax thresholds (Coppin, 2011; BBC, 2012). Why might this be? While parallax—which can also be screen disparity—is not an accurate threshold of viewer comfort, it serves as a coarse criterion to exclude footage that might be shot or generated amateurishly. However, the flipside of this arbitrary regulation is that content best reflecting stereoscopic 3D cannot be displayed by the very regulations designed to ensure optimum viewing quality. Ultimately, quality control must be an automatable process. So, what measures can be implemented to ensure that content is captured “correctly”?

The implications of visual distortion are manifold. First, visual information will be distorted, thereby presenting the viewers experiences different schema to their own normal perception. If they are viewing the footage in an environment where there are contextual objects visible around the screen, the disparities represented on the screen will not match the disparities of the real-world objects. This creates considerable conflict. This is even true in the cinema, where simple textured ceilings, cinema walls (even when darkened), and screen edges combine to create a powerful context and intrinsic depth map about a scene.

Cinema naturally fares the worst due to the configurational problem of the audience sitting at between 0.8x and 8x the screen height distant from the screen, translating in real terms to between 5m and 50m. Their horizontal viewing angle similarly ranges from 0° frontoparallel to an offset of up to 45° horizontally, as investigated in experiment V. Their vertical viewing angle, often in combination with the distance from the screen can also vary by up to plus or minus 20°.

So, given the stereoscopic parameters for every viewer are different in the cinema, how can the problem be solved? One technique covered in previous sections (Section 1.5.3: Issues in Stereoscopic Projection and , Section 1.5.5: Industry Standards for Stereoscopic Production, and Section 1.6.5: Relationship between Viewer Discomfort and Limiting Parallax) is for content to be captured at a low disparity such that, when presented, depth cues remain unprocessed.

Nonetheless, this solution is insufficient: distortion is never truly eliminated as two viewers in the bottom left and top right of the cinema will both experience significantly different perceptions of the same scene.

Synoptic devices have also been proposed as they allow for independent manipulation of the convergence point not only for cinematic viewing but also for 3DTV environments (the mechanics and benefits of synoptic viewing have been explored previously: Section 1.5.3: Issues in Stereoscopic Projection and Viewing, and Section 1.7: 2D and 3D Geometric Distortions: The Relationship between Angular Distortion and Comfort). This independent convergence point manipulation sans accommodative load can also be accomplished by presenting S3D content through an aperture. In addition, the orthostereo condition—replicating normal human vision—has also been utilised to this end; alternatively, lenses with a wide field of view can elicit orthostereoscopic condition.

Regardless, true immersion only comes from motion detection, which in itself does not happen in the stereoscopic fusional area, but in the scotopic peripheral vision region. Viewers to OMNIMAX cinemas or of well-calibrated head-mounted displays report a transcendent difference in measures of immersiveness and presence when their peripheral visual field is presented with content.

Examples of 3D films shot at human eye distance are rare, for the problems mentioned earlier. Human eye distance, coupled with a non-standard lens, results in stereoscopic footage with large parallaxes which are rated as being tiresome to view. However, there is good evidence that using a standard lens will prevent these types of distortions, and that a viewer sitting in the optimal position will experience a naturalistic and immersive image. This point seemingly contradicts the more immersive experience of a lens with a wider angle of view. Surely a commensurate reduction of IA is a good compromise? In fact, provided the geometry is assessed, this is true.

Bickerstaff (2012) has recently presented a set of rules which permit a seamless relationship between the capture interaxial, subject distance and field of view. The straightforward rules presented allow the confident display of material at “legal parallaxes” and enable the content creator to focus on creativity with the content of the shot instead of the mathematical relationship between lens choice (field of view), interaxial (disparity) and subject distance. This system works robustly. However, presence measures indicate that the optimal case of human orthostereoscopic viewing to rate higher in terms of naturalness.

Vishwanath (2012) posited a further cue in addition to accommodation and vergence which is named “ocularity”. The convergence angle of the eyes is precisely linked to a multiple set of a schema to define distance not just by disparity but by “ocularity”. The terms miosis and mydriasis are nominally used to describe abnormal pupil expansion or contraction due to injury or trauma. However, they can also be used to describe pupil expansion in the normal range, and form part of the near triad of accommodation, vergence and iris, a schematic well known to orthoptists. Ironically, there is a FIZ unit (focus, interaxial and zoom) used in the cinema industry which achieves some of the same techniques. But crucially, the functions of such devices are not slaved together, and are manipulated arbitrarily and independently, which consistently introduces unpleasant viewing artefacts.

There is a known linkage between vertical disparities (Gillam, Chambers, & Lawergren, 1988; Rogers & Bradshaw, 1995) and the distance. If horizontal disparities are an arbitrary scale which can be assigned to anything (Lipton, 1997) then vertical disparities are the waypoint elements which serve to calibrate the system.

However, disparity alone is not a sufficient depth cue. Instead, ocularity, the predicted drop-off in focus or increase in blur with distance, serves as a powerful differentiator between even the most immersive stereoscopic displays and reality. Also, ocularity can be used interchangeably with miosis and mydriasis when describing the eyes’ depth of field. Indeed, just like vergence is the mechanism and convergence and divergence are the two states at either end, ocularity is the pupil expansion mechanism and miosis is contracted and mydriasis expanded.

Depth of field control is computationally expensive to implement, requiring multiple renders of each pixel. Interpolative methods are deemed as cosmetically unsatisfying. In photography, depth of field is a popular creative tool. However, there is a problem that the iris of most extant camera systems is not slaved to the camera's ISO value or ASA. Consequently, the perceived lighting of the image changes as the lens is stopped down or opened up. This is not the case for the eye. Therefore, it is currently not simulated adequately either in photography or in CGI. While the most advanced and powerful rendering systems can easily produce convincing depth of field effects, there is not a consistent logic and rule set which permits it to function as a rule.

Work by MacKenzie and Watt (2010) and Watt et al. (2005) on multiple accommodation plane displays demonstrate both the power of the focus cues in depth perception but also highlights the brightness. The system in question uses three beam splitters resulting in light transmission of

50%, 25% and 12.5% excluding decay from light loss/leakage (MacKenzie & Watt; 2010). So, there can be up to a fourfold difference in the front and rear images in such displays, which are also not helped by being cumbersome.

Plenoptic photography such as the recent Lytro system would seem to be an ideal solution to all things at this point, permitting capture of all levels of depth of field from front to back (Ng et al., 2005; Harris, 2012; Wetzstein et al., 2012; Tao, Hadap, Malik & Ramamoorthi, 2013; Venkataraman et al., 2013). The solution to the problem by “brute force” is intriguing; however, the multiple images generated by the Lytro device would need to be accessed by the metadata to permit seamless integration (Levoy & Hanrahan, 1996; Levin, Freeman & Durand, 2008; Dansereau, 2013). So, it seems that the solution does not require plenoptic capture, but simply an expanded ruleset integrating HIT, iris, and the ASA into a single framework, complementing the other triplet of interaxial, field of view, and subject distance.

The most immersive displays are those with the highest angle of view (up to 200° horizontal and 100° vertical) that mirrors the natural perspective (Lantz, 1997; Reddy, 2001; Bourke, 2008; Steinicke et al., 2011; Warren & Wertheim, 2014). These usually take the form of head-mounted displays. However, current display optics prevent the Weber fraction for pixel discrimination to be reached. Contrary to the claims of Apple Inc., who cite a Retina display as being indistinguishable to the human eye of 326 PPI at 12" (Beaudot, 2010; Seidel, 2015; LaValle, 2016), the Weber fraction is in fact 75 nanometres, or up to 250% more pixel density than even these displays. HMD optics would require a viewer distance of only 4 inches, so the display would require a pixel density which would likely exceed 600 dpi.

Regardless, the quale of the visual experience of advanced display optics impresses many viewers, since the capture settings become both of those elements of human vision which are only used in compromised isolation in conventional cinema. These elements are: 1) a large field of view and 2) a typical human eye distance for the camera IA.

But how does this optimal setting reconcile itself with the fact that orthostereoscopic perception tends to require footage shot with a standard lens at human interaxial, or immersive perception requires footage shot with an ultra-wide lens at very small interaxial? The answer is straightforward: the field of view of the screen size must match the field of view of the capturing lens. However, the difference between these two must be compensated by the IA. It is this

compensation which is the downfall of much footage since, while it is correctly calibrated, it is, in fact, a distortion of a distortion to produce a “correct” image.

Similarly, if orthostereoscopic footage is viewed at more than the correct viewing distance, Z-axis extension is the result. This can equally produce apparent distortions in content. So, it is important to reconcile which of these distortions cause viewer discomfort and whether there is a relationship between fidelity and viewer comfort. Much of the evidence from the industry states that there is no relationship between “naturalness” and viewer comfort. The reasons cited are that for hypostereoscopic disparities, humans are accustomed from being a child with a smaller IPD and are more familiar with that kind of schema. Naturally, no human has an interocular distance of greater than 80mm, so hyperstereoscopic disparities would be presenting content which has never been seen. However, is the unnaturalness alien? Or can well calibrated hyperstereoscopic content obeiscent of the same rules as other display geometries still be fine?

The question of viewer comfort is complex and can be subdivided into viewer fatigue and comfort. Fatigue can be measured by a range of questionnaires, biometric techniques EOG, eye tracking among other instruments and also simple measures such as blink duration, PERCLOS (percentage of eye closure), blink frequency and saccade lag. Viewer comfort tends to be measured by questionnaires and other self-report tasks. These issues have been explored in Chapter 2. However, much of the literature does not heed the more fundamental differences between standard human vision and artificial stereoscopic content.

In standard human vision, we are typically exposed to parallaxes- more specifically, disparities between our left and right eyes of up to 20%. Converging on near-field objects (usual minimum distance of 17cm) can produce a total divergence of the background, causing diplopia, such as a 100% disparity between left and right. In normal vision, however, this is fine.

When expressed as a function of accommodation and vergence, the demands placed on our eyes are very slight compared to the available range. In fact, our eyes are only required to make an alteration of typically 0.5 dioptres in a standard stereoscopic display whereas in the real world this might be up to 10.0. In vergence terms, the visual angle tends only to be 1°, whereas up to 10° of convergence are effortlessly managed in standard viewing.

So why is there such an incongruence between our theoretical range of ability and actual performance in stereoscopic displays?

Two common factors come into play. First, the lack of calibration from vertical disparities causes the viewer to be presented with incomplete scaling information. Orthostereoscopic presentation can mediate this, but even then, the unique role of vertical disparities has been well reported. However, the flat reality of stereoscopic content generation is that vertical disparities are unacceptable, especially when presenting content to multiple viewers at diverse angles. This point is unanswerable, given that it is well reported that non-egocentric vertical disparities do cause eyestrain (Gillam et al., 1988; Rogers & Bradshaw, 1995). Furthermore, all non-optimal viewpoints also do cause measurable distortions according to Banks et al. (2009). So, what might be the best compromise? This is difficult, and without multiple viewpoint displays, holography or infinite viewpoint imaging there will be a distortion. It is worth noting that vertical disparities that are generated from non-orthostereoscopic content are far more difficult to fuse than those generated from orthostereoscopic content. The logic for the above is straightforward enough. A naturalistic context will allow the viewer's brain to evoke standard world schema. However, a non-naturalistic context will create an unnatural percept which is difficult to resolve, and a vertical non-conformity will always be quickly identified as a source of oculomotor stress and discomfort.

Second, the lack of ocularity in standard displays is a large problem. There is intriguing age data which suggests that domestic 3DTVs are favoured by persons over 45 years old (presbyopic), whose accommodation vergence linkage has started to decay (Yang et al., 2011). Given the TV is within their accommodation/vergence range, they are more likely to have “forgiving” eye movements to prevent visual discomfort from incongruent disparity scaling. However, the reverse is true for cinema screens, which tend to be beyond the measurable accommodation/vergence range. Their eyes are more prone to range finding which produces unpleasant focusing problems. The reverse tends to be true for young people.

The answer adopted by the cinema is to use very shallow depth of field to simulate ocularity, with the knowledge that the shallower the depth of field is, the more distant the object is being presented in stereoscopic space. Therefore, even with a small interaxial, the distant object can be far away. The other solution is to use a very high depth of field with a perfectly calibrated IA or field of view or HIT to subject relationship.

Studies (Ruppel, 2010; Fitter, 2013; Mitchell, 2014; Knapp & Hennig-Thurau, 2015) show that audiences are disappointed by the “conservative” nature of current 3D releases and suggest a divergent set of problems merely from those of viewer comfort and parallax avoidance. Indeed,

it has been posited that explicitly avoiding double imaging by default excludes footage from being naturalistic, simply because diplopia constantly exists in standard human vision.

With such inherent compromises and difficulties, is there a possible solution that will allow 3D to be naturalistic, visually interesting, and not cause eye strain? It is important to note that assuming a baseline of naturalistic vision as optimal may also be incorrect. Viewers using a synoptic device are often surprised to see that the traditional 17-cm fusional limit of the eyes is eliminated and that they can fuse an object as close as 1 cm without any discomfort (provided their accommodation is corrected to this distance). Similarly, the art of hyperstereoscopic photography can produce astonishing results giving insightful new perspectives, and when practised following parameters controlling the height in visual field, the resultant image can be described as calibrated to orthostereoscopic with the correct combination of telephoto lens and larger IA. More pertinent to cinema and current practice, hypostereoscopic photography can also be calibrated by using the correct combination of wide angle lens and a smaller IA.

Furthermore, the range of devices available for content viewers is large. Therefore, the best recommendations must be hierarchical. Indeed, for some devices, the range of viewing conditions means that there is no optimal stereoscopic setting for all people which is within stipulated industry boundaries. So here, in the absence of eye movement detection, known screen size among other factors, it must be conceded that a large percentage of viewers may experience a degraded stereoscopic image.

Is viewer comfort limited to stereoscopic displays? An issue which causes viewer disengagement in 2D broadcast is the interpolation between source capture rate and display frame rate. The resultant combination of interlacing, 3:2 pulldown, and reverse telecine have a detrimental effect on motion vectors in 2D imagery. The result of degraded motion vectors is a lack of immersion and for the image to induce unwanted saccades in the viewer's visual system as their eyes try to track the motion across the screen. Strategic use of interlacing at correct motion can actually give smooth apparent motion with respect to a slow progressive frame rate, but this tends to be rare. The effect of degraded motion is amplified in stereoscopic display, generically because of the added import of clear motion parallax vectors which do not contradict the binocular parallax of the depth elements. Besides, active stereoscopic displays and most processed passive displays also induce a further level of motion degradation by introducing a 20-msec difference between the left and right eyes. This is at odds with the strict guidelines for content creation which insist on perfect synchronicity to within 0.02 ms according to standardised specifications for

Genlock/Tri-Level Sync. On a 1000-line display, even 4ms corresponds to 100 lines of difference between the left and right eyes, so an acceptable threshold must be less than 1 line, which is 0.02 ms. Perceptually, it is often the case that the visual system can tolerate large asynchronicities, and is evidenced by the fact that watching much current stereoscopic content on 3DTV and in the cinema, such problems are still current in all but dual projector passive displays which are driven by parallel outputs which themselves are in sync.

Other artefacts from 2D broadcast include object size relations. It has been anecdotally observed both in production and in viewing that viewers have an inherent preference for a range of fields of view/lens choices which most closely match their viewing device. While ultra-wide-angle content looks unpleasant or at least sub-optimal on a mobile phone display, equally, telephoto close-ups of faces look unnatural and distorted on large screens. The configuration of cameras for news reports has changed: when TVs were smaller than 30-cm diagonal, often it would be the newscaster's face full screen, whereas now, a more typical setup alternates between a medium close-up and a full body of the two presenters.

Human beings are remarkably sensitive to aspect ratio changes, which was reflected in transmission difficulties in the migration between 4:3 standard ratio and 16:9 widescreen. The result was that many programs were shot in a 14:9 safe mode so that they could be letterboxed or pillarboxed accordingly, ensuring that there were no areas of interest in the peripheral regions of the screen. The same sensitivity to aspect ratio does not directly apply to stereoscopic content. While viewers may be subliminally or subtly aware that what they are viewing is unnatural or "flat", there is not the same fine metric of performance in determining what the ideal depth or "Z" aspect ratio is.

Furthermore, there appears to be a performance bias difference as previously stated between the hypostereoscopic region of 0mm zero disparity and 62-mm orthostereoscopic regions. The shape of this is complex, with micro disparities evoking good apparent depth.

8.2 Personal Reflection

Walter Murch famously declared that three-dimensional films present a "deep problem, which no amount of technical tweaking can fix" and concluded that "3D doesn't work and never will" (Ebert, 2011). Murch is as qualified as anyone to talk about 3D content production and presentation. I have immense respect for accomplished individuals like Murch and the talented individuals that I work with in the embryonic industry of stereographic production. However,

for the benefit of this debate, and given their lifeblood involves the study of 3D binocular vision, perhaps the next voice that should be heard is that of a vision scientist.

The 3D industry has achieved common knowledge on the use of proximal and perspective vergence and stays within comfortable limits of screen disparity. Tyler and Ciuffreda present exceptionally researched material on vergence and accommodation respectively. Indeed, a timely and hopefully exhaustive review of extant literature within this domain has been delivered in preceding sections. Regardless, their publications and those of countless other impeccable researchers are notoriously inaccessible to psychophysicists and innumerable other fields of professionals such as stereographers, anatomists, orthoptists, and ophthalmologists. Even more remarkably, despite an unquestionable consolidation of knowledge on matters such as parallax and presentation of convergence cues, there exist enduring gaps in industry and research knowledge on viewer comfort.

What is currently less well understood is the perceptual repercussions of the camera separations required to maintain these parallax limits. By dropping the camera interaxial down to 20mm, we are presented with a head that is visually squashed in depth, collapsing facial features into unnatural proportions. Brewster wrote extensively about this way back in the 1850s. This is perceptually stressful, because we have known size and distance relations, irrespective of viewing distance, and irrespective of screen size. The researcher does not dispute conventions for shooting stereo, but instead, describes how the brain processes visual information inconsistent with previous conditioning. As this dissertation has documented, the answer is not that well.

Additionally, reproducing horizon viewing or infinity is virtually impossible in the current viewing setup, unless you are sitting back row centre on a domed IMAX screen which fills your field of view. So, for *Avatar* (2009), this left James Cameron with two alternatives: (1) to either render mountains “faithfully”, resulting in a matte canvas, diorama effect, or (2) to introduce a stereoscopic offset so that the mountains looked three dimensional. He opted for the latter, but this is not veridical.

As for technical tweaking, it is quite simple indeed to resolve the accommodation-vergence conflict by use of eyeglasses. Prescription 3D glasses are available on the market already- several monitor manufacturers even produce polarising clip-ons for existing 3D eyeglasses.

As for vergence, it is possible to utilise prismatic configurations successfully. Viewers who have seen *The Bucket List* (2007) may remember Jack Nicholson's prism glasses for watching TV in bed. This study has argued favourably regarding synoptical viewing. Synoptical viewing enables a correction to infinity at the screen plane for accommodation and matching vergence to infinity (such that the eyes are parallel) to provide for a more relaxed visual experience.

The findings presented here question the relevance of binocular vision in perceiving stereoscopic content. Indeed, if one were to remove binocular disparity, by presenting an identical context to each eye, one would be presenting unambiguous visual information that everything in the scene is at visual infinity. This has the side effect, of making the remaining screen content much more perceptually salient both in 2D and in 3D.

Admittedly, these solutions still require eyewear, and while this does not seem like a contentious issue in industry, it is noteworthy that ground-breaking developments involving autostereoscopic displays, holographic micro-projectors, and light field stereoscopy have been reported. Regardless, for 3D content to truly recapture its appeal and momentum, it is equally important to resolve viewer discomfort upstream the stereo 3D production pipeline. This is where this study and its often un-conventional findings come into play. Until such a time that quality autostereoscopic displays are affordable and physically practical for living rooms, the findings presented here can enable the efficient and affordable production of stereo content.

No amount of motion interpolation, super-high refresh rates and image processing demonstrated to date will remove discomfort completely. Add (bad) 3D into the picture, and the viewer is burdened with the computationally intensive processing of un-focused frame-doubled, or frame-tripled staccato motion that causes significant headaches. Furthermore, due to a deficit in 2D cinema display and projection technology, 3D cinema further exposes this weakness and becomes painfully intolerable.

The collective frustration of the viewing public is hitting boiling point with the current spate of releases. Some films, however, have got it right in their selection of stereoscopic production values and there several interesting products in the wild such as *Avatar* and *Toy Story*. However, for every one of these, there appear to be two films intent on breaking the fourth wall in some of the more imaginable ways. Although *Avatar* is a personal preference, the 3D industry urgently needs another ambitious project of similar if not better immersive calibre. Such projects could

reinforce the shed novelty of 3D entertainment and spur sales of "home" 3D television sets, game consoles, and content.

Immediate and no-compromise improvements over Avatar could include consistently matching IA to IPD and innovative approaches to exploiting creative tension, looming, monocular regions, minification and gigantism, pseudoscopy, infinite depth of field, among others. However, delivering on these innovations requires providing authentic story-tellers (such as independent film-makers and game publishers) with access to affordable stereo production. The findings and recommendations presented here promise to deliver just such a pipeline.

As an advocate of the industry, I am passionate about getting 3D right. Certainly, stereo 3D is a beautiful prospect and is visually breath-taking, presenting immense advantages over mere binocular disparity. Although poor quality films exist even in HD formats, it is incumbent on industry practitioners and researchers, to translate hard-won insights into perceptually comfortable 3D and welcome strong and even belligerent opinions on the stereographic pipeline. It is too early to write off the 3D industry, and this dissertation is but a modest contribution towards making a sustained 3D boom a reality.

Moreover, stereoscopic displays have applications that extend far beyond entertainment. Applications include remote interaction (Daiber, Speicher, Gehring, Löchtfeld, & Krüger, 2014), scientific visualization (Bryson, 1996; McIntire & Liggett, 2014), medical imaging and surgical training (Nam, Park, Kim & Kim, 2012; van Beurden, IJsselsteijn & Juola, 2012; Narita et al., 2014), virtual prototyping and computer-assisted design (CAD) (Rossignac, 1997; Gîrbacia, Beraru, Talabă & Mogan, 2014), among many others. Admittedly, however, the use of stereoscopic 3D displays in providing entertainment remains the most easily recognisable, accessible, and mass-market of all the applications. Even in the other relatively speciality applications, stereoscopic displays ensure real-time interactions with material, improve spatial perception and performance, and reduce the cognitive load of understanding and memorising complex or unfamiliar details (McIntire & Liggett, 2014). These advantages are especially dependent on the unique, cost-effective, and superior ability of stereoscopic displays to faithfully recreate 3D information on objects or scene points (Banks et al., 2009; Froner, 2011; Banks et al., 2012). The uniqueness of this format and its ability to deliver immersive experiences deserves a sustained effort at ensuring superlative viewing quality.

8.3 Conclusion

This research makes another attempt to bridge the gap between practitioner and research communities' knowledge into human factors underlying viewer comfort. A review has been delivered that analyses research in the domain and several empirical studies reported clarifying the relationship between acquisition factors and off-axis viewing on scene distortion and S3D viewing comfort. The findings served as the basis for several recommendations and guidelines for cost-effective and predictably comfortable stereoscopic filming. It is this researcher's belief that these findings and the guidelines thereof contribute empirical knowledge to the domain of S3D filming.

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APPENDIX A

A.1 Practical Applications

A.1.1 Production of Stereoscopic Images

A novel contribution of this study concerns the creative use of HIT. The predictive models alone with indicators from the data show clearly that HIT is not a creative tool, should simply be yoked to IA. Bickerstaff's (2012) set of rules apply HIT first then introduce an IA. These rules work ideally for a fixed viewing position, but shift the argument towards an emphasis on IA as opposed to HIT. The corollary of this argument is that it eschews the importance of matching acquisition FOV with AOV and implicitly over-state the importance of forced limiting of parallax. Bickerstaff's (2012) recommendations advance the argument for using HIT creatively. We argue strongly that this is not the case. HIT should simply be the inverse of its own increase from changing IA and should never be used creatively. To ensure correct perspective representation of a stereoscopically-captured scene, HIT must be scaled to IA such that $HIT=IPD$. This way, editorial changes to the IA result in a constant HIT, required parallax at the screen plane (Bickerstaff, 2012) is achieved, and vertical retinal disparities, shear distortion, and under- and over-convergence eliminated.

Importantly, it is also argued that presenting the correct convergence point where HIT matches IPD eliminates the forced perspective of the stereoscopic image and enables non-effortful approximate correction for all observers, regardless of viewing position.

A.1.2 In Computer Graphics

Application of these findings in computer graphics is perhaps the most demonstrably and immediately apparent. Unlike non-stereo cameras (i.e. CGI stereo), IA and HIT values are calculated independently in stereoscopic cameras. This greatly facilitates, firstly, generating a 2D image, secondly, separating it by HIT and, thirdly, introducing an IA value. For completeness, it is again recommended that the HIT value is set and never changed. By this approach, a constant HIT yoked to IA eliminates image distortion.

A.1.3 On the Filming Set

Using a FIZ unit, yoke IA and convergence channels of the Preston motor to one predetermined arc. This setting should be instilled for the duration of the shoot. There should never be a case where these two values are not inversely correlated to produce a consistent net HIT (for instance, the infinity or horizon point of the image should always be consistent, regardless of IA).

A.1.4 Monitoring on the Film Set

It is important to use the largest possible screen to monitor on-set, given even the best 3D field monitors experience substantial crosstalk beyond 3% into-the-screen. Failure in on-set monitoring often leads to camera alignment and post-production problems (Kala, 2010; Smolic, et al., 2011b). One solution to successful field monitoring without the crosstalk is simply to set the HIT of the two cameras to zero, and use corrective prisms or a synopter device to artificially shift the HIT from zero to the IPD. This way, the scene will go from being entirely out-of-the-screen parallax to correctly scaled into-the-screen parallax.

A.1.5 In Stereoscopic Error Correction

Viewer comfort, and the associated fields of viewer eyestrain and fatigue are handled by the stereoscopic 3D industry by a principle of matching. There is a generic focus on the only difference between the two images being one of horizontal disparity, or what would be referred to by the quasi-scientific term of parallax. There is an abundance of industry packages available for automatic stereoscopic error correction (Smolic, et al., 2011b). These packages are used primarily for filming live sporting events to ensure that physical camera misalignments are corrected in software before broadcast. Such errors include horizontal and vertical misalignment, temporal sync, rotational alignment, keystoneing, trapezoidal distortion, colour artefacts between the left and right channels, and correction of excessive or insufficient “parallax” to present a comfortable stereoscopic image.

However, these corrections may be removing valuable textural data from the “other” attributes of binocularity beyond standard stereoscopic vision. These include specular disparity, binocular luster, and heightened apparent resolution through binocular summation (ocular and neural) and tend to provide an image with texture, character, and subtlety (among others) beyond merely doubling the horizontal channels. Accepting this constraint as a necessary sacrifice to ensure the compromise of broadcast 3D works, there is still an under-controlled area in 3D production.

Systems such as Binocle DisparityTagger, CelScope3D, Technicolor's Certifi3D, Fraunhofer's STAN, Sony's MPE-300 Stereo Image Processor, and 3ality Technica's stereo image processor (SIP) all control for the above phenomena (Chen, 2010; Zilly, Müller, Eisert & Kauff, 2010; Mendiburu, Pupulin & Schklair, 2011; Zilly, Müller, Kauff & Schäfer, 2011; Sony Pictures Technologies, 2012; Hübner, Stabernack & Zilly, 2013; Baumgartner, 2014). Indeed, Technicolor lists 15 attributes and 3ality surpasses them with 18 attributes. Other “offline” content analysis systems such as M3GA and GameGrade3D by the MTBS3D alliance feature a substantial checklist of capabilities (Schneider & Nikshych, 2010; Belev, 2011). However, their correction of parallax is only generated from on screen information, not the actual capture IA. Moreover, these systems measure technical parameters without providing consistently reliable data on their impact on viewer perception (Khaustova, 2015).

Why is this of importance? Simply put, capture IA is the prime determinant of object size relations, regardless of scale. A hypostereoscopic capture IA will flatten a scene into bas-relief. As a result, motion vectors will be compressed and there will be an unnatural sense of compression. The reverse problem, a hyperstereoscopic capture IA will stretch a scene, creating dwarfism. This is more pronounced than the gigantism of hypostereoscopic image capture (Harper & Latto, 2001) due to viewers being more accustomed to seeing 2D images. However, regardless of the eventual display parallax, both of these capture techniques can result in significant viewer discomfort.

So, the solution of cinematographers tends to be to reduce IA to a minimal amount such that a near field convergence point can be obtained without putting the background beyond 2%. At orthostereoscopic capture IA, the convergence point must be 3.2m away for the background to be within 2%. For a convergence point of 0.5m away, IA may need to be as low as 10-15mm.

The relationship between monocular cues and stereoscopic cues is not linear. With hyper and hypo stereoscopy, the disparity cue has an influence but only to an extent, until at IAs of 20mm and smaller the ratio between IA and geometry becomes sufficient that the visual system rejects the salience of the disparity cue, and, provided there are strong monocular cues, the scene will look deeper. Previous research by Harper & Latto (2001) has evidenced the object-scale relationship to be of vital importance. Even if the viewer is sitting further back than the correct viewing distance, the resultant Z-axis extension will look unpleasant, however the distortion will be uniform. As a result, to ensure optimal display geometry, it is important to capture this

information either through software, analysis or rendering such that footage can be evaluated on a basis of roundness.

Advanced post-processing systems such as SGO Mistika and Quantel Pablo both enable fine disparity maps, allowing near-instant reproduction of the camera acquisition stereo-geometry. While this is primarily to allow post IA shift or interpolation, there is ample resource for appropriate elements of these programs to run live along existing quality control solutions. Match-moving software such as Syntheyes permits the extraction of lens field of view, trajectory, and also capture IA distance for stereoscopic footage. By enabling encoding for capture IA, this allows for an additional measure, which is so far only alluded to in 3ality Technica's "Stereo 3D Quality" attribute. Operators tend to not be aware of the function of this parameter.

Through recent innovations by Technicolor for the 3DVB2 standard, it should be a straightforward measure to enable live IA repurposing to ensure a consistent orthostereoscopic geometry appropriate to the capture lens. In this way, even footage that was captured with poor stereographic quality can be presented in a more appreciable format.

A.1.6 Applications of Research to TV

Stereoscopic display guidelines stipulate arbitrary maximum levels of positive (into screen depth) and negative (out of screen volume) horizontal parallax for all 3D footage. These are $\frac{1}{3}\%$ for computer games, 2% for Sky 3D, and 1% for Cinema. However, previous research (Harper & Latto, 2001) has shown that horizontal parallax is not the most effective predictor of viewer comfort.

Instead, orthostereoscopic footage where the conditions are met that: a) The display screen field of view matches the camera acquisition field of view. b) The separation between the acquiring cameras is identical to the observer's interpupillary distance (IPD). So, the key determinant factor for viewer comfort is not horizontal parallax, but is the ratio of angle of view (which is determined by the camera lens selection and the viewer distance) to the human IPD, with an optimum case of a standard lens and a 63.5mm IA distance. It could be argued that stereoscopic display guidelines are predicated on an over-simplification, and that there is a distinction to be drawn between the acquisition IA/disparity and the display parallax.

These insights are valuable in the following regard. It is recommended that, using a vanishing point detection algorithm, scan every scene to ensure that the horizon point remains consistent. Do not be concerned about depth increasing too much or excessive positive parallax. This should produce a consistent image. 3D expansion can be used safely if the HIT value is correct, but probably not the default value on TV. If the TV is of poor quality, whereby excessive into-the-screen parallax would introduce ghosting/crosstalk, it is suggested that using 1° base in prisms to artificially set the viewing distance back.

A.1.7 Applications of Research to Cinema

The DCI specification for a DCP (digital cinema package) does not contain a screen size value, nor does it contain a method to adjust the left and right images relative to one another. The ideal solution would be to modify the DCI specification such that this is the case. The best solution is to use variable adjustment base in prism in tiny increments to ensure that an individual sitting 10m from the screen perceives consistently 6cm of parallax on the screen.

A.1.8 Creative Use of Focus-linked Convergence

To maximise the quality of the stereoscopic image, it is important to establish a correct baseline and seating position. Lens choice should be to match the field of view of the “average” seating position. Convergence should be set such that the infinity point of the left and right image is parallel to IPD. In the case of cinema, this may only be a fraction of a degree beyond parallel.

If the convergence point is carefully set and maintained through metadata through acquisition and post production, then IA distance can be scaled without risk of distortion. There is a considerable amount of distortion present even in optimal stereoscopic display conditions. As the convergence point is brought forward, this distortion can result in a 30° angle being perceived as 90°. This indicates that convergence-linked acquisition mechanisms are almost certain to introduce quantifiably measurable distortion into 3D content.

This approach is compatible with keeping the subject at the screen plane. By removing the HIT from the creative equation, the stereographer is free to use camera movement and IA to bring the subject to the screen plane. The logic for this being long overlooked is that stereo pairs are fusible with cross-eyed viewing, producing compelling depth even though there is substantial distortion. This leads to a false baseline where this is acceptable for moving images. Moving images contain

motion vectors which will quickly reveal the incorrect perspective, generating eyestrain and nausea. The overall steps to introducing a safe workflow are: (1) Calculate the vanishing point in every scene, (2) Set the distance between vanishing points to match HIT, and (3) Ensure that parallax does not exceed excessive values. To increase or decrease parallax, an image warp from the vanishing point is possible provided sufficient metadata is known regarding lens.

A.1.9 Practical Demonstration of this Technique

Using a modern LG 3D TV, there are two controls. First, setting the overall strength of the 3D effect. Second, setting the position of the 3D information. By setting the 3D information deeper into the screen this will produce apparent scaling. By then changing the strength of the 3D effect, if necessary, conservatively shot movies can be safely expanded. This technique has been tested with *Tron Legacy* and *Prometheus*, which were both early stereoscopic movies with high production values but low parallax values, resulting in a flattened appearance. This difference in quality is immediately noted by all who watch it.

A.2 Parallax and Specified Distance

A.2.1 Into-screen Objects

The relationship between parallax and specified distance for into-screen objects is observed to be that specified distance increases linearly with viewing distance as depicted in the figures below.

60mm IA 60mm HIT	Screen at 0.6m	Screen at 0.8m	Screen at 1.0m	Screen at 1.2m	Screen at 1.4m
+100mm	!m	!m	!m	!m	!m
+80mm	!m	!m	!m	!m	!m
+60mm	∞m	∞m	∞m	∞m	∞m
+40mm	1.8m	2.4m	3.0m	3.6m	4.2m
+20mm	0.9m	1.2m	1.5m	1.8m	2.1m
0mm	0.6m	0.8m	1.0m	1.2m	1.4m
-20mm	0.45m	0.6m	0.75m	0.9m	1.05m
-40mm	0.36m	0.48m	0.60m	0.72m	0.84m
-60mm	0.3m	0.4m	0.50m	0.6m	0.7m
-80mm	0.258m	0.344m	0.43m	0.516m	0.602m
-100mm	0.228m	0.304m	0.38m	0.456m	0.532m

Figure 8-1 - Linear relationship between parallax and specified distance for into-screen objects

This figure, based on the computed values from the predictive model, is illustrated below as follows:

PARALLAX	SPECIFIED DISTANCE	NORMAL VISION
60mm	∞ m	∞ m
50mm	6.0m	6.0m
40mm	3.0m	3.0m
30mm	2.0m	2.0m
20mm	1.5m	1.5m
10mm	1.2m	1.2m
0mm	1.0m	1.0m
	0m	0m

Figure 8-2 - Specified distance for into-screen objects at 0mm vis-a-vis normal vision

PARALLAX	SPECIFIED DISTANCE	NORMAL VISION
60mm	∞ m	∞ m
50mm	6.0m	6.0m
40mm	3.0m	3.0m
30mm	2.0m	2.0m
20mm	1.5m	1.5m
10mm	1.2m	1.2m
0mm	1.0m	1.0m
	0m	0m

Figure 8-3 - Specified distance for into-screen objects at camera separation 10mm vis-a-vis normal vision

PARALLAX	SPECIFIED DISTANCE	NORMAL VISION
60mm	∞m	∞m
50mm	6.0m	6.0m
40mm	3.0m	3.0m
30mm	2.0m	2.0m
20mm	1.5m	1.5m
10mm	1.2m	1.2m
0mm	1.0m	1.0m
	0m	0m

Figure 8-4 - Specified distance for into-screen objects at camera separation 20mm vis-a-vis normal vision

PARALLAX	SPECIFIED DISTANCE	NORMAL VISION
60mm	∞m	∞m
50mm	6.0m	6.0m
40mm	3.0m	3.0m
30mm	2.0m	2.0m
20mm	1.5m	1.5m
10mm	1.2m	1.2m
0mm	1.0m	1.0m
	0m	0m

Figure 8-5 - Specified distance for into-screen objects at camera separation 30mm vis-a-vis normal vision

PARALLAX	SPECIFIED DISTANCE	NORMAL VISION
60mm	∞ m	∞ m
50mm	6.0m	6.0m
40mm	3.0m	3.0m
30mm	2.0m	2.0m
20mm	1.5m	1.5m
10mm	1.2m	1.2m
0mm	1.0m	1.0m
	0m	0m

Figure 8-6 - Specified distance for into-screen objects at camera separation 40mm vis-a-vis normal vision

PARALLAX	SPECIFIED DISTANCE	NORMAL VISION
60mm	∞ m	∞ m
50mm	6.0m	6.0m
40mm	3.0m	3.0m
30mm	2.0m	2.0m
20mm	1.5m	1.5m
10mm	1.2m	1.2m
0mm	1.0m	1.0m
	0m	0m

Figure 8-7 - Specified distance for into-screen objects at camera separation 50mm vis-a-vis normal vision

PARALLAX	SPECIFIED DISTANCE	NORMAL VISION
60mm	∞ m	∞ m
50mm	6.0m	6.0m
40mm	3.0m	3.0m
30mm	2.0m	2.0m
20mm	1.5m	1.5m
10mm	1.2m	1.2m
0mm	1.0m	1.0m
	0m	0m

Figure 8-8 - Specified distance for into-screen objects at camera separation 60mm vis-a-vis normal vision

A.2.2 Out-of-screen Objects

As for out-of-screen objects, the relationship is such that specified distance increases linearly with IA.

60mm HIT 1m Screen PARALLAX	20mm IA	40mm IA	60mm IA	80mm IA	100mm IA
+100mm	∞m	∞m	∞m	∞m	∞m
+80mm	∞m	∞m	∞m	∞m	∞m
+60mm	∞m	∞m	∞m	∞m	∞m
+40mm	1.0m	2.0m	3.0m	4.0m	5.0m
+20mm	0.5m	1.0m	1.5m	2.0m	2.5m
0mm	0.33m	0.66m	1.0m	1.33m	1.66m
-20mm	0.25m	0.5m	0.75m	1.0m	1.25m
-40mm	0.20m	0.40m	0.60m	0.80m	1.0m
-60mm	0.17m	0.34m	0.50m	0.67m	0.83m
-80mm	0.14m	0.28m	0.43m	0.57m	0.70m
-100mm	0.13m	0.26m	0.38m	0.52m	0.65m

Figure 8-9 - Linear relationship between interracial separation and specified distance for out-of-screen objects

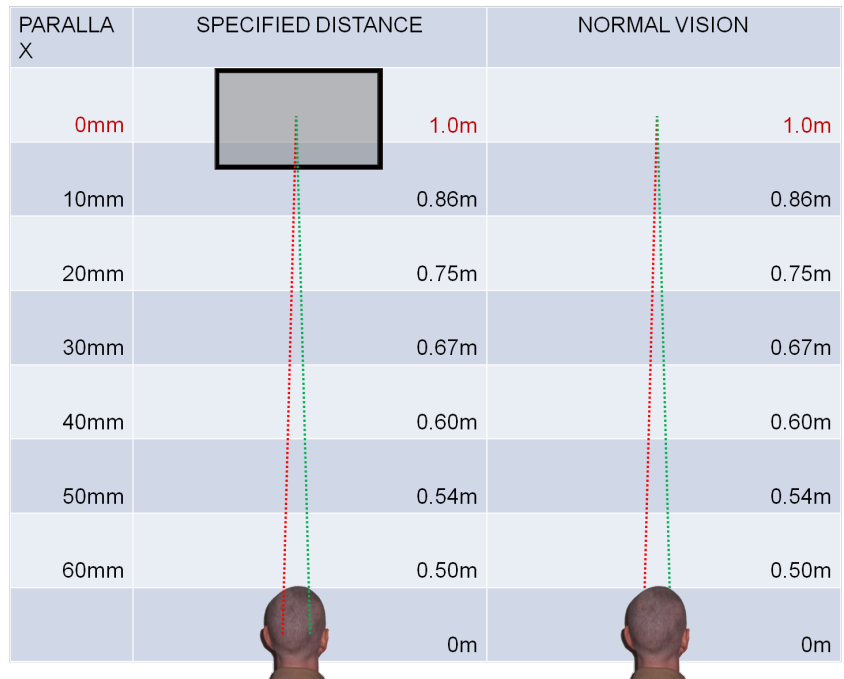
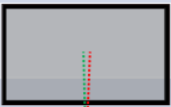


Figure 8-10 - Specified distance for out-of-screen objects at 0mm camera separation vis-a-vis normal vision

PARALLAX	SPECIFIED DISTANCE	NORMAL VISION
0mm		1.0m
10mm	0.86m	0.86m
20mm	0.75m	0.75m
30mm	0.67m	0.67m
40mm	0.60m	0.60m
50mm	0.54m	0.54m
60mm	0.50m	0.50m
	0m	0m

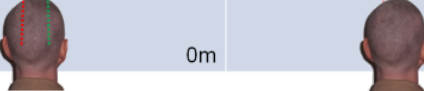
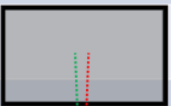


Figure 8-11 - Specified distance for out-of-screen objects at 10mm camera separation vis-a-vis normal vision

PARALLAX	SPECIFIED DISTANCE	NORMAL VISION
0mm		1.0m
10mm	0.86m	0.86m
20mm	0.75m	0.75m
30mm	0.67m	0.67m
40mm	0.60m	0.60m
50mm	0.54m	0.54m
60mm	0.50m	0.50m
	0m	0m




Figure 8-12 - Specified distance for out-of-screen objects at 20mm camera separation vis-a-vis normal vision

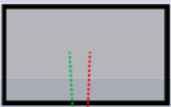
PARALLAX	SPECIFIED DISTANCE	NORMAL VISION
0mm	 1.0m	1.0m
10mm		0.86m
20mm		0.75m
30mm		0.67m
40mm		0.60m
50mm		0.54m
60mm		0.50m
	0m	0m

Figure 8-13 - Specified distance for out-of-screen objects at 30mm camera separation vis-a-vis normal vision

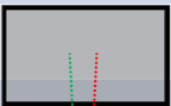
PARALLAX	SPECIFIED DISTANCE	NORMAL VISION
0mm	 1.0m	1.0m
10mm		0.86m
20mm		0.75m
30mm		0.67m
40mm		0.60m
50mm		0.54m
60mm		0.50m
	0m	0m

Figure 8-14 - Specified distance for out-of-screen objects at 40mm camera separation vis-a-vis normal vision

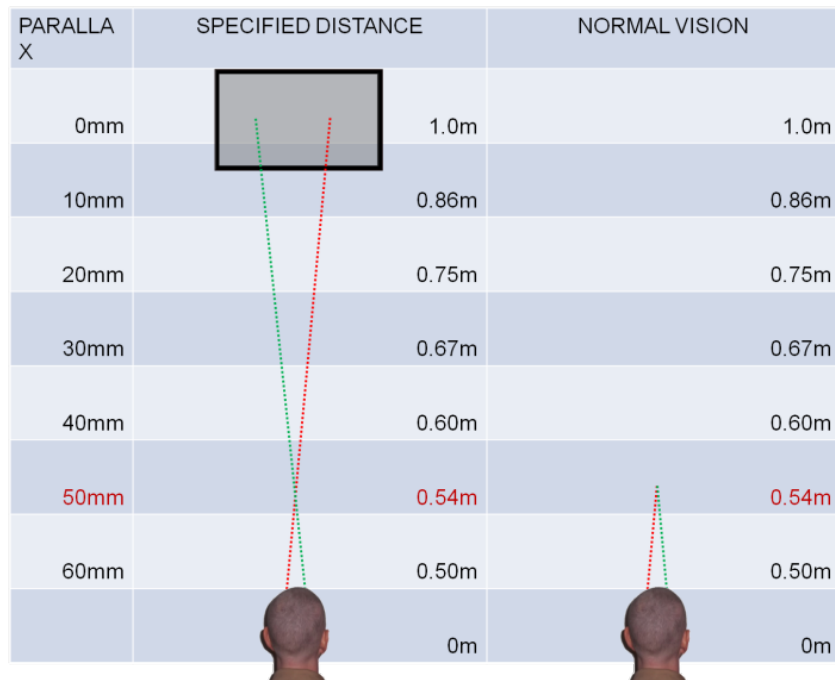


Figure 8-15 - Specified distance for out-of-screen objects at 50mm camera separation vis-a-vis normal vision

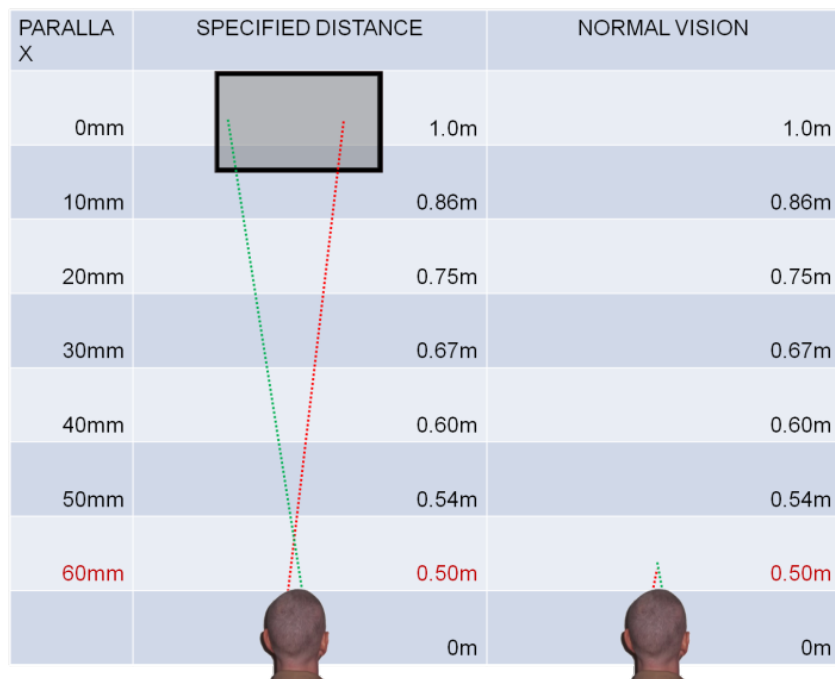


Figure 8-16 - Specified distance for out-of-screen objects at 60mm camera separation vis-a-vis normal vision

A.3 Specified Distance and Convergence

The specified distance increases non-linearly with convergence as illustrated in the figure below.

PARALLAX	IA 60mm HIT 60mm	IA 60mm HIT 60mm	IA 60mm HIT 60mm	IA 60mm HIT 60mm	IA 60mm HIT 60mm
+100mm	!m	!m	!m	!m	!m
+80mm	!m	!m	!m	!m	!m
+60mm	∞m	∞m	∞m	∞m	∞m
+40mm	3.0m	3.0m	3.0m	3.0m	3.0m
+20mm	1.5m	1.5m	1.5m	1.5m	1.5m
0mm	1.0m	1.0m	1.0m	1.0m	1.0m
-20mm	0.75m	0.75m	0.75m	0.75m	0.75m
-40mm	0.60m	0.60m	0.60m	0.60m	0.60m
-60mm	0.50m	0.50m	0.50m	0.50m	0.50m
-80mm	0.43m	0.43m	0.43m	0.43m	0.43m
-100mm	0.38m	0.38m	0.38m	0.38m	0.38m

Figure 8-17 - The non-linear relationship between specified distance and convergence

Note that at 0mm parallax, the distance remains constant at 1M. Notice also that at an IA/HIT of 60mm, the distance changes non-linearly. This is the central relationship.

Also, changing both IA and HIT results in further distortion as evidenced below.

Screen 1m PARALLA X	20mm IA 20mm HIT	40mm IA 40mm HIT	60mm IA 60mm HIT	80mm IA 80mm HIT	100mm IA 100mm HIT
+100mm	∞m	!m	!m	!m	!m
+80mm	1.0m	∞m	!m	!m	!m
+60mm	0.5m	2.0m	∞m	!m	!m
+40mm	0.33m	1.0m	3.0m	∞m	!m
+20mm	0.25m	0.66m	1.5m	4.0m	∞m
0mm	0.20m	0.5m	1.0m	2.0m	5.0m
-20mm	0.17m	0.40m	0.75m	1.33m	2.5m
-40mm	0.14m	0.34m	0.60m	1.0m	1.66m
-60mm	0.13m	0.28m	0.50m	0.80m	1.25m
-80mm	0.11m	0.26m	0.43m	0.67m	1.0m
-100mm	0.10m	0.22m	0.38m	0.57m	0.83m

Figure 8-18 - Specified distance at different IA and HIT values showing image distortions

GLOSSARY

above/below	display format for stereoscopic images where left eye is presented above right eye
ac/a ratio	the balance of how accommodative convergence drives accommodation (Acc)
acceptability	how overall a 3D image is rated. In this thesis, principally combining distortion and comfort
accommodation (Acc)	the expansion or contraction of the pupil based on focus and light levels
active shutter display	a stereoscopic 3D display which uses time sequential interleaved glasses
aerial perspective	the fog or haze that is visible in the distance, with more distal objects appearing fainter
angular field of view (AFOV)	this is the field of view that is presented to the eye, regardless of content
array capture	a bank of (usually inexpensive) cameras which can have synchronous shutter release)
artistic cues	aka monocular cues, these are the other techniques to achieve depth apart from stereopsis
aspect ratio	the difference between the width and height of an image. Common modern ratio is 16:9
asymmetrical viewing frusta	equivalent of shift photography in rendering, shifting an image horizontally against sensor
astigmatism	defect in the lens of the eye resulting in an unfocused image being cast onto retina
autostereoscopic	a 3D display that does not require shutter or filter glasses to produce a 3D effect
beam splitter	semi-silvered mirror that provides 50% transmission and 50% reflection. Used in mirror rigs

binocular cues	so-called stereo depth cues including vergence and binocular disparity
binocular lustre	difference in surface luminosity between the left eye and right eye image of a stereo pair
binocular summation	when the brain combines two images in disparity, there can be a root 2 resolution increase
blender	the most popular 3D freeware program. A rosetta stone for file formats
camera separation	arbitrary term used in this thesis to describe the combination of IA and HIT
chaotic motion	motion properties of a looming target randomly rotating in x, y, and z.
circular polariser	filters which, when orientated at 45 and 135 degrees, produces discrete image to each eye.
column interleaved	a 3D display format used in autostereoscopic displays, with left and right encoded in stripes
comfort	amalgamation of lack of eye strain, headaches and nausea resulting in positive 3D experience
convergence	motion of two horizontally separated points triangulating inwards from parallel
crosstalk	interference where left eye sees the content of the right eye and vice versa on a 3D screen
CRT	cathode ray tube - deprecated monitor format with excellent timing attributes
cue combination	the brain's processing of the combination of two or more monocular cues to depth
cue conflict	when inconsistent depth information is perceived by brain from two or more different cues
cycles per degree	used in measurement of visual acuity, describing amount of detail eye can see

depth of field	the area of acceptably sharp focus around the focal point
depth of focus	the area of back focus of a lens onto the sensor plane
digital cinema package (DCP)	industry standard structure for video and audio files required for cinematic presentation
diopthersphere	unit of measurement of an eyeglass lens, the reciprocal of the focal length
disorientation	sensation of loss of bodily alignment with what the eye can see
disparity	<i>see screen disparity</i>
distortion	general term for a deformity in shape which results in it being seen as different
divergence	the muscular movement of the eyes to move towards being parallel or wall-eyed
double image / diplopia	when the fusional capability of the eyes is exceeded, each retina perceives a different image
equirectangular	a heavily distorted spherical image format used to encode 360 panoramic image data
extinction	term to describe the level of crosstalk in stereoscopic displays, ideally this should be total
eye fatigue	state which is measurable by observing duration and percentage of eye closures
eye strain	when eyes become sore, usually manifested in dry eyes, redness and subsequent headache
eye tracker	a device to measure gaze direction, by using compound reflections of light from eye surfaces
fisheye	lens which does not have distortion correction, with a distinct circular image on a flat surface

fiz unit	Focus, IA and Zoom. In mirror rigs, the FIZ unit changes these parameters with servos
focus stacking	multiple shallow depth of field images used to create a single deeper depth of field image
frames per second (FPS)	the number of frames displayed per second (usually 24, 25, 29.997, 30 or 60)
frame rate	can reflect real number of frames per second or also perceived number of frames per second
film-type pattern retarder (FTPR)	a sheet containing finely pitched stripes of alternating circular polarised material for 3DTVs
fusional load	natural convergence/focus point of eyes where the oculomotor muscles are in equilibrium
genlock	the signal used to generate a sync pulse between two professional cameras
ghosting	intraocular light contamination due to imperfect filtering
golden ratio	1.618 : 1 aspect ratio, sometimes confused with comfortable 5:3 aspect ratio
head mounted display	a viewing device, often similar to a scuba mask, containing a screen and corrective optics
highlights	the lightest areas of an image. If these are over-exposed, there can be burn out
hinge	an object similar to a folded sheet of card, constructed of two rectangles
horizontal image translation (HIT)	HIT denotes the distance between the horizon points of the left and right images
horizon	furthest point visible in an image. Due to texture accretion, nearest horizon contains most depth
hyperopia	long-sightedness, where the lens of the eye focuses on to a point beyond the retina

hyperstereo	IA is greater than normal, causing miniaturisation or Lilliputianism
hypostereo	IA is less than normal, causing gigantism or Brodbingdangianism
immersion	a sensation of high engagement which can arise from a low or high fidelity / presence medium (for example, a book)
indicatrix	mathematical term to use a measurement of units of distortion (for instance, Tissot's indicatrix for the globe)
Interaxial (IA)	the horizontal distance between two image sensors
interocular	the horizontal distance between the two eyes
interpupillary distance (IPD)	similar to interocular, specifically relative to the distance between pupils which changes with convergence
jam sync	camera creates own master genlock signal to drive another slave camera without external source
LCD/LED monitor	current generation display technology which uses a flat or occasionally curved array of crystals or diodes
linear perspective	the depth effect created by two parallel lines which are seen in perspective to converge at a vanishing point
linear polariser	stretched polymer ions in bromide producing light extinction when two are oriented at zero and 90°
looming	the effect when an object moves rapidly towards the observer. Can be enhanced by chaotic motion
MAYA	An industry standard graphical editing environment for 3D models
mirror rig	semi silvered mirror box for two large cameras to be virtually closer than their dimensions allow

misalignment	refers to the left and right images being subject to a distortion other than horizontal disparity
motion artefacts	image inconsistencies due to rapid camera motion or poor data rate. These can conflict with stereo cues
motion parallax	the parallax movement of the front and rear elements of an image relative to one another
myopia	short sightedness
naturalness	subjective term to denote the acceptability of a stereoscopic image such that it is comfortable and undistorted
nausea	the sensation of gastrointestinal discomfort, accompanied by sweating and a clammy sensation
negative parallax	disparity behind the screen plane
occlusion	the most powerful monocular cue, when one object blocks another, can override binocular disparity
oculomotor cues	depth cues which are not in the image but are related to the observer
OpenGL	original C++ based graphical programming language to display three dimensional imagery
optical infinity	the maximum virtual distance of an observer's fusion range at which zero disparity is presented
orthostereo	stereoscopic display method where interaxial distances matches interocular
pan	a rotational horizontal camera movement
parallax (negative)	industry term to denote "out of the screen", also known as positive disparity
parallax (positive)	industry term to denote "in to the screen", also known as negative disparity

parity	an absence of disparity, viewing conditions produced by the synopter
passive display	a stereoscopic display method either using twin polarised projection or a TV with a FTPR
pixel level sync	a method of synchronising multiple cameras so they are very temporally accurate
point of zero parallax	in a stereo image, point in depth where there is no disparity between left and right
positive parallax	disparity in front of screen plane
post processing	editing, grading, colouring, conforming processes which occur when preparing captured footage
presence	sensation of being bodily or physically somewhere else
prism diopter	prismatic adjustment equivalent to one centimetre at a distance of one metre
pseudoscope	mirror/prism based device that reverses the eyes' stereo base so right is left and vice versa
pseudoscopic	when the left and right images are reversed. Can be used creatively in sparse scenes
quad buffering	a technique from professional Quadro graphics cards to draw stereoscopic frames accurately
RealD	manufacturer of circular polariser based cinema glasses
rectilinear	correction for wide angle lenses to counteract the fisheye effect accentuating vertical lines
render distance	the draw distance for computer games, performance trade off, how far into the distance is visible

resolution	the number of pixels on the screen (eg 1080P 1920x1080, UltraHD 3840x2160, 4k 4096x2160)
roundedness	measuring technique used by stereographers to determine the amount of distortion in an image
saliency	of cues to depth, which in certain conditions become more or less prominent.
scleral search coils	invasive form of eye tracking using a contact lens with copper attachment
screen disparity	the difference between the left and right images on the display screen
servo motors	a small, high powered, high torque motor favoured by the film industry
serial digital interface (SDI)	the industry standard for video signal data, identifiable by BNC connectors
side by side (SBS)	a display format where the left and right images are encoded next to each other
side by side rig	a stereoscopic capture system, usually involving a horizontal bar with two cameras
software buffering	using array data to encode the left and right image contents in software
specular disparity	the difference in colour casts between left and right images, either by light or beam splitter
squirrelling	a subsampling technique where the image sensor is moved around while zooming
simulator sickness questionnaire	an accepted tool based on the earlier MSQ which judges wellness in environments
standard lens	a lens which produces a 1:1 image on a sensor
stereo base	the horizontal distance between two image sensors

stereoacuity threshold	the finest level of difference discriminable by two eyes, usually 10 arc seconds
stereoblind	an individual who has stereoacuity above the minimum clinical threshold
stereopsis	the sensation of depth, usually but not exclusively associated with binocular disparity
stereoscope	a viewing device for still 3D images using mirrors or prisms
strabismus	misalignment between the two eyes, correctable by surgery or orthoptic exercises
strafe	a horizontal, non-rotational camera movement
sync pulse generator	an external box used to drive the genlock signal in cinema cameras
synopter	an optical device using a beam splitter and mirrors/prisms to produce zero disparity
synoptophore	orthoptic measurement device which controls multiple ocular parameters independently
telephoto	a lens with a focal length that is narrower than standard
temporal disparity	temporal difference between left and right, either from shutter glasses or capture error
texture accretion	term to that describes combination of texture density and texture gradient
texture density	the frequency of repeated elements in an image, denoting repeated distances
texture gradient	the slope of the repeated image elements, which can change with field of view
tri level sync	an industry standard for ensuring that video sources are precisely time-matched
true field of view (TFOV)	actual amount of visual field visible e.g. telescope eyepieces a segment to be bigger

uncanny valley	phenomenon where realism suddenly dips relative to fidelity of experience
Unity	a fast, visual prototyping environment suitable for virtual reality development
vanishing point	point of linear perspective origin. Can be calculated via algorithm
vergence	occulomotor movement of eye muscles causing eyes to triangulate or go parallel
version	synchronous movement of the eye muscles for looking around
veridicality	the extent to which a viewer's cognitive percept of the stereoscopic form accurately represents reality
vertical screen disparity	a misalignment between left and right images on screen from toeing in
viewing distance	the distance in depth between the viewer and the target they are looking at
vignetting	darkened, blurred edges of an image when lens edges are visible in frame
virtual reality (VR)	wide field of view, immersive environment accessed by head mounted display
warping	distortion of an image or a portion of it
wide angle	a lens with a focal length that is wider than standard
worm screw	accurate engineering mechanism to facilitate precise horizontal movements
zero aerial perspective	ideal conditions for ambiguous scale photography such as the Bolivian salt flats
zoom in	increase focal length of an image, causing a portion to be magnified
zoom out	decrease focal length of an image, causing more to be visible