EFFECTS OF LATERAL MOTION ON STEREOACUITY THRESHOLDS FOR PHYSICALLY MOVING TARGETS

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Abstract

The goal of this thesis was to determine the impact of lateral retinal motion on stereoacuity under natural viewing conditions. I found that stereoacuity thresholds remained stable when target velocities varied between 0 and 16 °/s. These results do not agree with previous literature (Ramamurthy, Bedell & Patel, 2005) which found that stereoacuity degraded at higher velocities (greater than 3 deg/s). I suggest that depth is acquired very rapidly at target onset when targets are relatively broadband and have not been distorted by motion smear. Subsequent experiments ruled out the potential effects of monocular cues, retinal smear size and inter-stimulus delay enhancing perceived depth. I conclude that artefacts introduced by the graphical displays used by Ramamurthy et al. (2005) were responsible for the observed elevation of thresholds at higher velocities.

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1. Introduction

Many human observers can use interocular displacements, or binocular disparity, of retinal images to infer the relative positions of objects in depth in a process known as stereopsis. The visual system’s ability to extract minuscule binocular disparities from retinal images is notably precise under laboratory conditions, with stationary stimuli. However, in natural environments, images of objects on the retina are rarely stable. In addition to moving objects that are not tracked with eye movements, retinal image motion is caused by movement of the observer and by their eye and/or head movements. One of the main consequences of this retinal motion is to degrade image quality by reducing the high spatial frequency components – effectively blurring edges (see Section 1.2.1). There is considerable evidence that image blur caused by motion disrupts visual processing and degrades performance on a number of tasks such as Vernier acuity (Chung, Levi & Bedell, 1996; Chung & Bedell, 1998), and letter discrimination (Chung & Bedell, 2003). It has been shown that stereopsis is also affected by blurring static stimuli (Stigmar, 1971; Westheimer & McKee, 1980). Therefore, it is reasonable to assume that increasing the lateral velocity of a retinal image will disrupt judgements of the relative depth of stereoscopic targets. In fact, prior studies have assessed the effect of lateral retinal motion on stereoacuity thresholds, (Westheimer & McKee, 1978; Ramamurthy, Bedell & Patel, 2005) and found that although there is little impact of motion on stereoacuity at slow velocities, thresholds do increase at velocities greater than approximately 3 deg/sec. However, these studies measured stereoacuity thresholds using graphics displays that may have inadvertently added artifacts. These artefacts may have made it more difficult to make relative depth judgements, and so these results may not reflect the capabilities of the visual system under more natural viewing conditions. The primary aim of this research is determine if stereoacuity is resilient to retinal motion when viewing physical stimuli which are not subject to potential display artefacts.

The earliest studies of the effect of lateral retinal motion on depth perception were performed in the early 1960s by Lit and colleagues (1960). They asked observers to match the disparity of a probe rod to that of a laterally oscillating rod. Physical rods were brightly illuminated and the mechanical apparatus provided physical depth cues. The observer was asked to fixate the probe and to adjust its disparity to match that of an oscillating rod. Consequentially, the image of the oscillating rod moved laterally across the observer's retina. Two independent variables of lateral velocity and illumination were manipulated. The lateral peak velocity of the oscillating rod ranged from 1.5°/s to 40°/s. Their data showed that the constant error in probe settings increased in relation to increasing the lateral velocity of the oscillating rod. Furthermore, the magnitude of the errors decreased as illumination levels increased, showing that the effects of motion can be counteracted by changing some properties of the stimulus (see also. Lit, 1960; Lit, 1964; Lit & Hamm, 1966; Lit, Finn & Vicars, 1972). There was no account for the source of the error due to the lack of information available at the time pertaining to how such stimuli are processed. These factors have since been identified and will be discussed in a later section (2.1 and 2.2).

In the 1970s, the widespread use of cathode-ray tube (CRT) based oscilloscopes in psychophysical experiments enabled the automated presentation of stimuli without the need for complex mechanical systems. CRTs also allowed for the isolation of cues such as perspective and accommodation that are difficult to control in real scenes. The isolation of binocular disparity can yield much about its low-level processing, but the resulting data may not be ecologically valid, given such displays may introduce additional artifacts not present when viewing physical scenes.

Westheimer and McKee (1978) used a CRT display to evaluate the effect of lateral retinal motion on stereoscopic acuity (the smallest interval in depth that observers can resolve between two targets). Their stimuli consisted of thin, vertical lines displayed stereoscopically on a CRT oscilloscope. Two lines were aligned vertically in a frontoparallel plane and separated by a small gap. After a brief fixation period, line pairs were presented for 190 milliseconds, below the latency of smooth pursuit eye movements (Westheimer, 1954). This ensured the image of the lines moved across the fovea with minimal contamination from involuntary eye movements. Both the target and reference lines moved synchronously across the retina. Observers reported the direction in depth of the target line relative to the reference line. Their data showed depth discrimination thresholds were constant at velocities between 0-2.5 °/s. They attributed averaging of disparity-signals during the presentation interval for this resilience of stereopsis to lateral motion.

Steinman, Collewijn, van der Steen and Levinson (1985) studied stereoacuity in the presence of retinal motion induced by head motion and compensatory eye movements. Observers viewed stationary photographic anaglyphs and periodically rotated their heads. Motion was done in step with a metronome to maintain a specific frequency. Eye motion was measured electronically using search coils on the observers' corneas. These measurements reveal compensatory eye movements required to maintain fixation are imperfect, leading to retinal image motion up to a maximum of 1 °/s. Even so, observers maintained comparable stereoacuity thresholds to that of stationary viewing. However, head oscillations lead to a range of retinal velocities during each trial. It was also noted that even under very aggressive head motions, binocular stimuli remained fused showing some degree of robustness to vergence velocity.

Ramamurthy, Bedell and Patel (2005) replicated and extended Westheimer and McKee's (1978) study by measuring the effect of retinal motion on stereoacuity at velocities from 0 °/s to 12 °/s. Broadband vertical line targets resembling those used by Westheimer and McKee (1978) were presented stereoscopically on a 240 Hz oscilloscope display. Motorized mirrors deflected the target image to create lateral retinal motion for 200 millisecond periods. Like Westheimer and McKee (1978), they found that thresholds were stable up to 3 °/s. However, they found thresholds rose rapidly and monotonically with increasing stimulus speed after 3 °/s. In *post hoc* control experiments, they ruled out exposure time, eye movements and retinal eccentricity as significant factors in their measurements. Ramamurthy et al. (2005) concluded that a combined effects of motion blur and smear was primarily responsible for the observed threshold elevation.

Finally, it is yet to be determined that these existing estimates of the influence of lateral retinal motion on stereoacuity accurately reflect the visual system's ability under natural, 'real depth' conditions. In recent experiments by Taylor and McKee (2010), it was found that observers performed better in acuity tasks involving static physical stimuli compared to a similar task carried out using a mirror stereoscope (graphics display). In some cases, participants could not see depth within the stereoscope, whereas they were able to with physical stimuli. It is an open question whether a similar reduction in thresholds in real as compared to virtual stimuli is observed when targets are moving laterally across an observer's retina.

1.2. Impact of lateral motion

There are two principle effects of lateral retinal motion; the attenuation of high-spatial frequency information from the target's spatial frequency spectrum, and smearing them out through retinal summation processes (Burr, 1980; Burr & Ross, 1981; Burr & Morgan, 1997). These phenomena are referred to as motion 'blur' and 'smear' in this paper, respectively. However, these two phenomenon are interrelated as they both change with respect to stimulus lateral velocity. The following sections will provide evidence for these effects in relation to retinal motion and their implications on visual processing.

1.2.1. Motion blur

'Blur' is caused by reduction of the high spatial frequency content from motion required for optimal detectability (Burr & Ross, 1981); over a large range of velocities the degree of blur changes with increasing speed. Blurring is a form of low-pass filtering that results from the temporal frequency (defined as spatial frequency x velocity) of a stimulus exceeding the temporal resolution limit of a given region of the retina (Howard & Rogers, 2012, p. 344; Watt, 1987).

Burr and Ross (1981) provide evidence for spatial frequency filtering due to lateral motion. They presented lateral moving gratings to an observer on a display with a refresh rate of 1 kHz with tight control of phosphor persistence (aftertrace). Detectability was measured by having observer report the direction the gratings were travelling, which was randomized at the beginning of each presentation. They showed that the peak contrast sensitivity of a laterally moving grating is biased to lower spatial frequencies as its velocity increases, consistent with high spatial frequency content being filtered by increasing lateral retinal velocity. In a subsequent experiment, they displayed lateral moving, evenly illuminated, 28 and 80 deg wide bars to observers and measured their detectability over a range of velocities. Bar width was adjusted by changing the viewing distance. Unlike the previous experiment, they found contrast sensitivity peaks at about the same velocity across observers, regardless of the bar size. However, overall detectability drops when the bar is wider. This shows that while high lateral velocity does filter out higher spatial frequencies from broadband targets resulting in a shift in contrast sensitivity, the velocity of peak detectability is rather invariant of target width. Filtering of high spatial frequency leading to diminished stereoacuity thresholds was also shown to occur during retinal motion induced by head motion, leading to decreased contrast sensitivity biased to low spatial frequencies (Steinman, Collewijn, van der Steen & Levinson, 1985).

In a later study, Morgan and Castet (1995) showed that lateral velocity and stimulus spatial frequency interact to influence an observer's ability to perceive depth sign. In their study, observers viewed a grating flanked by a pair of random dot stereograms (reference plane) for half a second. The lateral motion of the grating was induced via phase shifting rather than moving a target across the screen. They found that observers were able to use stereopsis to determine the depth sign of the grating relative to the random dot stereogram surfaces for velocities up to 640 °/s, if the grating did not exceed a critical temporal frequency of 30 Hz. Morgan and Castet (1995) also noted that higher spatial frequency gratings required lower lateral velocities in order to maintain accurate depth sign judgements. This further shows the dependence of lateral velocity between spatial frequency content and the efficacy of stereopsis. When viewing static stimuli, removing high spatial frequency content through low-pass filtering has been shown deteriorate the accuracy of stereopsis (Stigmar, 1971, Westheimer and McKee, 1980). Blurring resulting from motion has been shown to degrade other hyperacuity tasks such as Vernier and letter acuity (Chung, Levi and Bedell, 1996; Chung and Bedell, 2003).

1.2.2. Motion smear

Photoreceptors are capable of summation by maintaining some level of neural activity briefly after a stimulus is extinguished, which results in a persistent retinal image. Accretion of neural activity occurs if stimulation is sustained; stimulation saturates at about 120 ms where the perceived luminance of the stimulus plateaus (Burr, 1980). This temporal summation mechanism is beneficial as it increases the signal-to-noise ratio of a static retinal image. When stimulation ceases, the persistent image decays monotonically.

When an image is moved across the retina, say when an observer fixates and an object in the environment moves, the transient decay in activity of the photoreceptors results in a phenomenon known as motion smear (Burr, 1980). Motion smear is evident as visible traces of a stimulus along the axis of motion, which if sufficiently above threshold, can change the apparent width of the stimulus (Burr, 1980; Bedell, Tong & Aydin, 2010). Thus the perceived width of motion smear is dictated by the angular velocity and intensity of the stimulus. Research with static targets has shown evidence of a size-disparity correlation, where increasing the spatial scale of a stimulus has been shown to decrease depth identification accuracy at finer disparities (Smallman & MacLeod, 1994). Therefore, it is possible that changes in stimulus width due to motion smear might also serve to elevate stereoacuity thresholds.

As mentioned in Chapter 1, Ramamurthy et al (2005) measured stereoacuity for targets moving at a range of velocities and argued that the increase in motion blur at high retinal velocities compromised the visual system's ability to reliably extract depth from binocular disparity. They postulated that a shift in processing to low-frequency channels was responsible for the observed increase in thresholds as has been argued in the case of the impact of motion on Vernier and letter acuity (Chung and Bedell, 2003; Chung, Levi and Bedell, 1996). If they are correct, then moving physical targets laterally at similar velocities should also result in elevated thresholds.

1.3. Graphics display artefacts

Presenting stimuli on graphics displays is a mainstay of visual psychophysics. Graphics displays allow for stimuli to be presented without the need for complex mechanical systems. There are drawbacks to graphics displays such as oscilloscopes and computer monitors. For instance, artefacts may arise from how these displays operate, which can contaminate the stimulus image and inadvertently influence the phenomenon the experimenter is interested in measuring.

1.3.1. Frame and refresh rate

The properties engendered by the operation of graphics displays such as frame rate and phosphor persistence (pixel decay in the case of LCD monitors) can potentially disrupt fine stereoacuity for laterally moving stimuli. Computer monitors and oscilloscopes operating in raster scan mode redraw a single image on the screen several times a second in order to sustain an image. The refresh rate is the number of times per second this redraw operation occurs. While frame rate is the number of times per second the image is changed, this is usually some fraction of the refresh rate. For example, broadcast television as defined by the NTSC standard has a frame rate of about 30 frames per second (Hz), however, television sets can operate at much higher refresh rates. Motion is typically smooth at this frame rate if the image has the temporal-spatial frequency requirements to fall within an observer's window of visibility (Watson, 2010). The window of visibility defines a range of temporal-spatial frequencies that a moving stimuli must have in order to remain visible to an observer. However, if a displayed object is laterally moving at a sufficient speed, its image may appear to judder or may not be visible at all, falling outside of the window of visibility, as the sampling rate of the video or display is not sufficient to faithfully capture its motion. Therefore, for experimental apparatus, it is important that frame rates are sufficiently high as to surpass the temporal-spatial sensitivity limits of the visual system when presenting stimuli. This consideration is prudent when performing experiments examining hyperacuities such as stereopsis.

1.3.2. Phosphor persistence

Phosphor persistence results from the transient excitation decay of photo-luminescent pigments coating the inside of a CRT display. A fading yet detectable image may persist onscreen long after a stimulus is extinguished. The display must refresh itself quicker than the photo-luminescent pigment can decay in order to maintain an image on-screen. Even if phosphor luminance decays completely before the next refresh, the visual system is able to sustain some stimulation between refreshes through summation and may not perceive dark intervals between refreshes (see Section 1.2.2). However, if the refresh interval is too long, the observer may perceive flicker.

The effect of phosphor persistence on stimuli presentation is two-fold. First, the exposure time of a stimulus can inadvertently be extended (Groner, Groner, Müller, Bischof and Di Lollo, 1992). Secondly, perceptible motion trails can be produced. If smearing due to retinal persistence is present, it can be exacerbated by these motion trails. In turn, this would amplify the effect smearing may have on stereoacuity thresholds. Therefore, it is important to mitigate the effects of persistent images when conducting experiments involving retinal motion.

1.4. Purpose of experiments

As outlined above, there are multiple ways that displays may interfere and degrade relative depth information provided via stereopsis independent of blur and smear arising from the function of the visual system. Previous researchers have shown that thresholds are stable up to approximately 2.5 °/s (Westheimer & McKee, 1978; Ramamurthy et al., 2005) but increase dramatically at higher velocities. Ramamurthy et al. (2005) argue that this monotonic increase in thresholds is due to the increasing magnitude of retinal blur and smearing. However, since they used an oscilloscope display, it is not clear whether their results reflect properties of the visual system, or their apparatus. The aim of the experiments described in this paper is to assess the effect of lateral retinal motion on stereoacuity using physical stimuli; free of the artefacts mentioned in Section 1.3 (Graphics display artefacts) to measure stereoacuity thresholds for laterally moving targets.

2. General Methods

2.1. Stimuli

For the experiments presented in this thesis, similar physical versions of the line stimuli used by Westheimer and McKee (1978) and Ramamurthy et al. (2005) were crafted using monochromatic, yellow-green (peak 656 nm wavelength), 1 by 2cm rectangular light bars. These bars contain an array of LEDs embedded in a translucent resin that scatters light diffusely. Applying an acetate mask reduced the light surface to thin vertical lines (3 arc minutes wide at viewing distance of 50 cm).

The LEDs were supplied constant, regulated current, gated to turn them on or off. The LEDs were controlled using a monostable pulse of required duration generated by a micro-controller, initiated by the controlling PC. The LED light bars used here toggle on/off very quickly with negligible persistence. This driving signal ensured that the luminance remained constant across the entire exposure interval regardless of velocity. Lag associated with serial communication between the PC and apparatus were factored out empirically to guarantee accurate stimulus onset timing. Care was taken to ensure that the stimulus lines were only visible while the actuators were moving at a constant velocity.

The bright, luminous targets produced afterimages that can provide depth information long after the target lines disappear (Lugtigheid, Wilcox, Allison & Howard, 2015). I avoided afterimages by adjusting the brightness of the lines prior to testing with a current limiting rheostat. Their luminance was set 4.2 $cd \cdot m^{-2}$; a level that did not produce a perceptible afterimage for any of the observers when viewed for 200 milliseconds in pilot tests.

2.2. Inducing motion and positioning in-depth: The Physical Stereo Robot (PSR)

To position the line stimuli in three-dimensions, the light bars were affixed to a purpose built Physical Stereo Robot (PSR). The PSR system (Figure 2.1) consists of a collection of high-precision robotics and computer control hardware within a light-tight enclosure. Observers viewed stimuli through an aperture at one end of the enclosure. As shown in Figure 2.2, a pair LED line stimuli described in Section 2.1 were affixed to the ends of separate optical posts. These posts were each attached to their own gantry consisting of a linear actuator for lateral motion (Macron Dynamics MGA-628), which was in turn mounted to another linear actuator for in-depth (z-axis) motion (Macron Dynamics MGA-M6S). Each actuator has a positional repeatability of +/- 0.025 mm and a positional error of 0.4 mm per metre of travel. Given the apparatus does not move more than a few centimetres in any given trial, positional error was negligible during the course of these experiments. Actuators were driven using stepper motors controlled by a Galil DMC-4050 motion controller. The precision of stimulus motion and positioning was verified by examining the output of high-resolution optical encoders attached to the driveshaft of each stepper motor. Data from these outputs were compared to theoretical calculations, which ensured the apparatus was operating within acceptable limits and was providing accurate motion to the specification of each experimental condition. The gantries were attached above and below the viewing aperture within the enclosure to manipulate the top and bottom line, respectively.

The point of fixation (Section 2.3) resided on a fronto-parallel plane 50 centimeters from the cyclopean point of the observer. Stimuli that fell on this point were at zero disparity. The lengths of the transparent slit on the acetate mask placed in front of each LED bar was adjusted to subtend an angle of ½ degree at this distance. The lines were separated by a 25 arc minute gap. Relative depth (and hence disparity) was manipulated by moving the target line in depth relative to the fixed reference line (see Figure 2.3). Using disparity instead of relative depth, provides more readily comparable data across observers. However, the required relative depth to needed achieve a certain disparity differs between observers due to varying intraocular distances. To account for this, each observer's intraocular distance was measured using a high precision pupilometer prior to testing. This measurement was used to calculate depth from disparity (Formula 2.1) where Δ is the required depth between fixation and target lines, δ is a required disparity, z is the distance to the fixation plane and i is the observer's inter-ocular distance. The two lines were always vertically aligned when moving and their direction of motion (left/right) was randomized to avoid any anticipation effects. The experiment was conducted in complete darkness to eliminate extraneous depth cues and to maximize target-background contrast. In addition, stray light from uncontrollable sources in the lab were baffled by the apparatus' viewing aperture and light absorbing cloth shell.

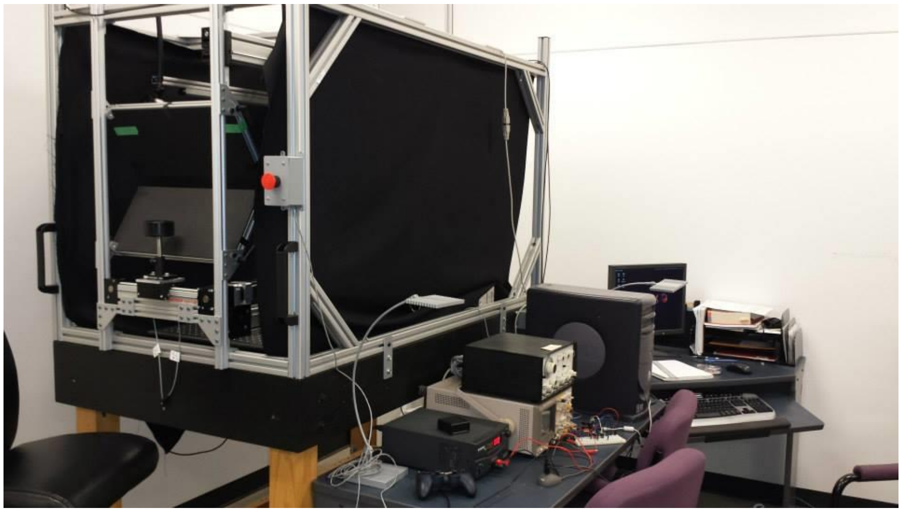

Figure 2.1. The Physical Stereo Robot (PSR) and supporting hardware.

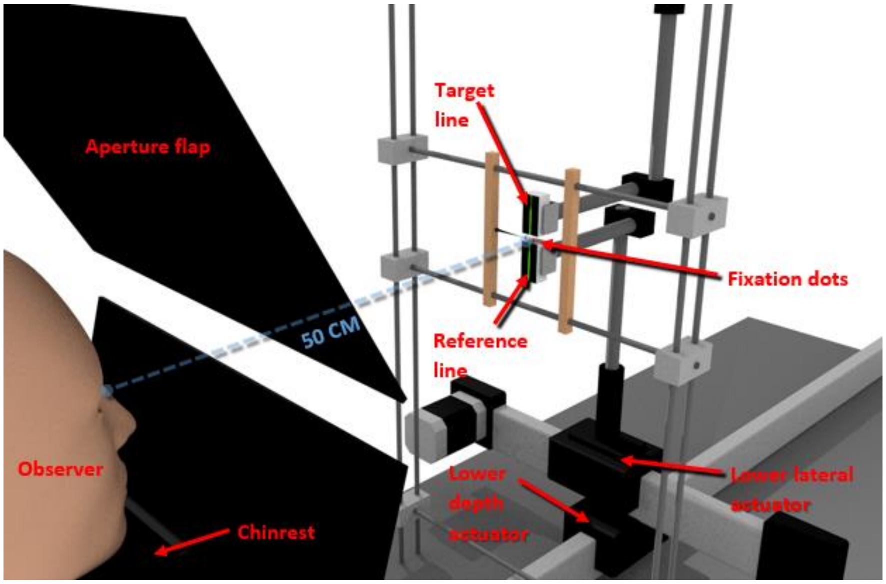

Figure 2.2. General configuration of the Physical Stereo Robot (PSR). *The above setup was used for all experiments conducted for this paper. The upper actuator is not shown. Note the dimensions of the lines and fixation dots in the figure are slightly exaggerated for better visibility.*

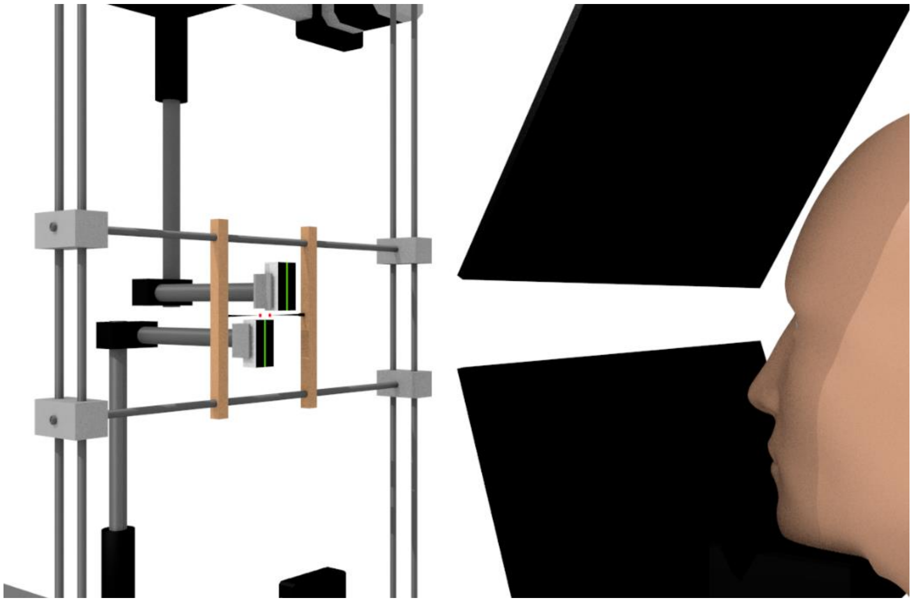

Figure 2.3. Setting relative depth between targets. *Disparity was set by changing the position of the target line relative to the bottom reference line, which stayed fixed in depth at 50 centimetres.*

$$\Delta = \frac{\boldsymbol{\delta z^2}}{\boldsymbol{i}}$$

Formula 2.1.

2.3. Fixation

Two small fixation points separated laterally by ½ a degree were positioned in the gap between the two target lines. Dots were created by terminating fibre optic wires to the end of rigid pins. The other end of each fibre optic wire was attached to the lens of a red LED. The visibility of the dots was toggled by switching the LED. The fixation dots remained at the same distance as the reference line (50 cm from the observer) at all times. When stationary, the line targets were centred on the fixation dots. When they moved laterally, the start and end point of the lines' trajectory centred on the fixation dots.

2.4. Measuring thresholds (general procedure)

All experiments described in this thesis follow the same general procedure to measure stereoacuity thresholds (see Figure 2.4). At the start of each trial a buzzer sounded and the fixation dots appeared. Observers were given an unlimited amount of time to fixate on the dots prior to initiating a trial by pressing a button on a game pad. Fixation would then be extinguished and followed immediately by the presentation of the targets. Target lines could either be stationary or laterally moving depending on the experimental conditions. The time between fixation dot extinction and line exposure was intentionally kept to a minimum to ensure vergence remained close to the plane where the reference line appeared.

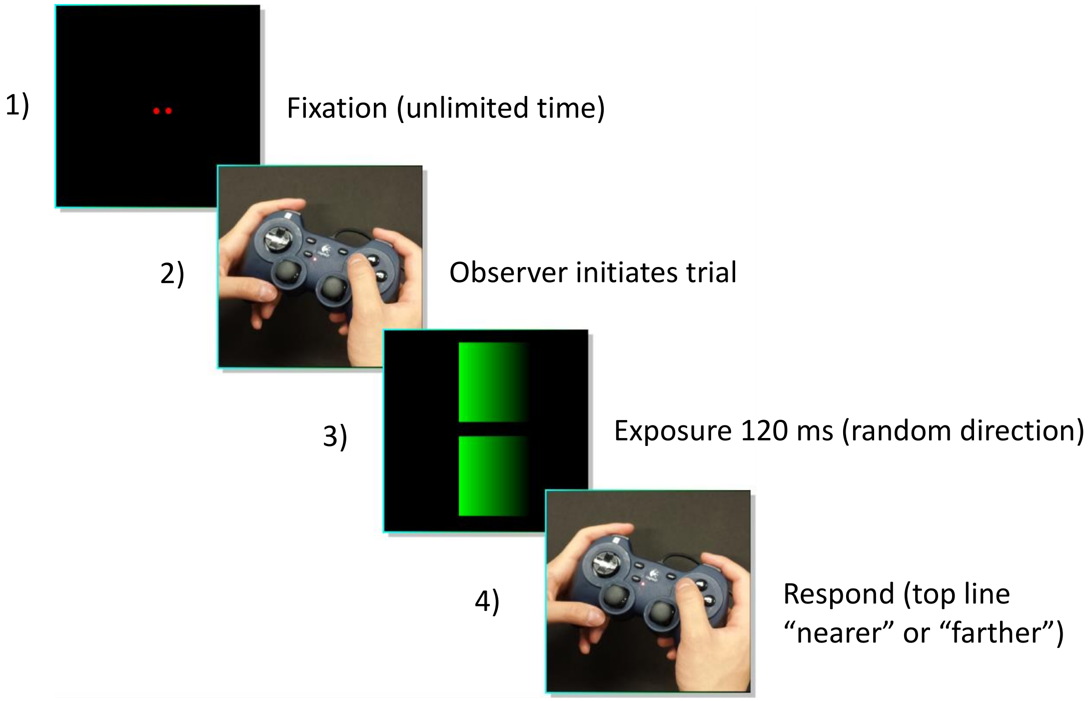

Figure 2.4. General procedure for each trial.

The observer indicated with the gamepad if the top target line appeared “nearer” to or “farther” from themselves, in comparison to the bottom reference line. A psychometric function based on the cumulative normal distribution was fit to the observer’s proportion “nearer” responses for each disparity (Wichmann & Hill, 2001). The threshold was computed by taking the difference between the 0.75 and 0.5 points on the psychometric function.

3. Experiment 1

3.1. Stereoacuity thresholds for laterally moving physical targets

As outlined in Section 1.1, factors such as motion blur and smear associated with lateral retinal motion should make it more difficult for the visual system to extract reliable relative depth information between objects in a scene. However, previous investigation of this phenomenon may have introduced artefacts by using graphics displays instead of physical stimuli. My hypothesis is that observers may sustain stable stereoacuity over a larger range of velocities given more precise depth discrimination has been reported when viewing physical stimuli over virtual analogues (Taylor & McKee, 2010).

3.2. Methods

3.2.1. Observers

Five observers participated in this experiment ranging in ages 18 to 53. All observers had normal or corrected-to-normal visual acuity. All had prior experience as participants in psychophysical studies of stereopsis and demonstrated on the Randot™ Stereoacuity Test a minimal stereoacuity threshold of 40 arc seconds.

3.2.2. Stimuli and Apparatus

For each lateral velocity condition, discrimination performance was assessed at seven crossed and uncrossed disparities bracketing zero using the method of constant stimuli paradigm. The range of disparity was determined for each subject in the practice sessions prior to running the main experiment. A total of seven disparity conditions were repeated ten times for a total of 70 trials per block (velocity); trials were presented in random order. Each block of trials used a single lateral velocity randomly selected without replacement at the beginning of each session. Five lateral velocities were used (0, 2, 4, 8, 16 °/s) and exposure time was 0.12 seconds.

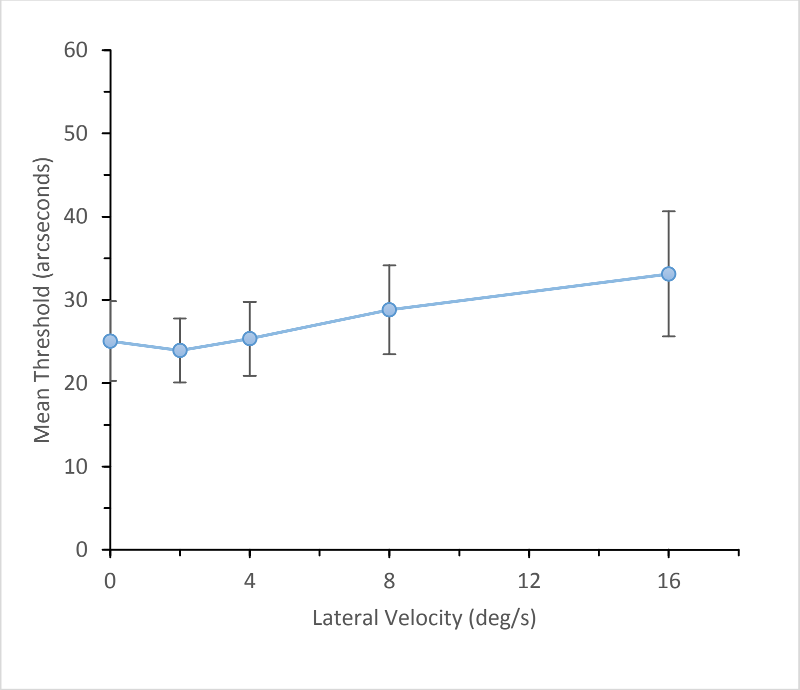

Figure 3.1. Lateral motion experiment results. *The above plot shows the averaged thresholds for all observers (n = 5) for each lateral velocity tested. The error bars represent one SEM.*

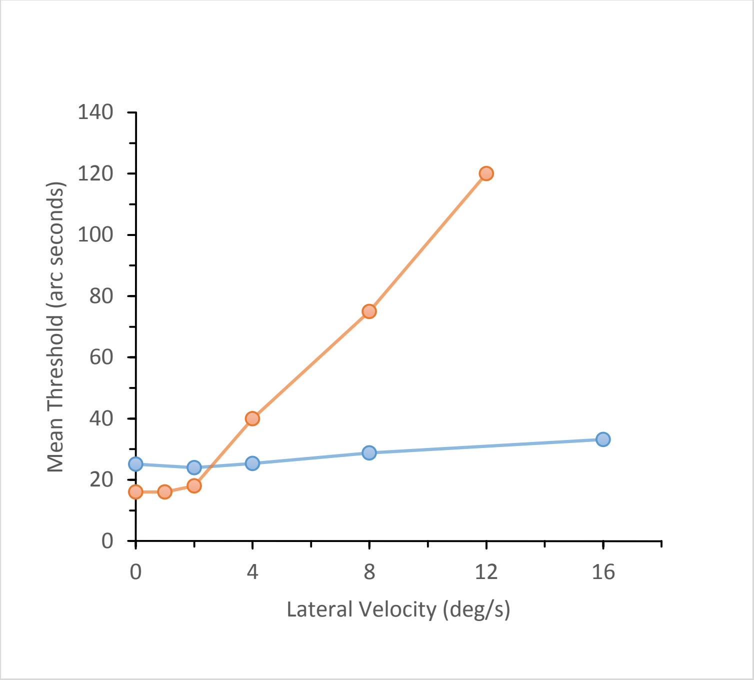

Figure 3.2. Comparison of lateral motion results. *The results of Experiment 1 (blue) superimposed on the data presented in Ramamurthy et al. (2005). Note Ramamurthy et al. (2005) assessed thresholds as the difference between 0.84 and 0.5 of proportion "farther" responses.*

3.3. Results and Discussion

Figure 3.1 shows the mean thresholds across observers (n = 5) for each velocity. A within-subjects ANOVA with Greenhouse-Geisser correction for sphericity ($F(1.24, 4.95) = 1.182$, $p = 0.34$, $\eta^2_G = 0.09$) revealed no significant effect of lateral retinal motion on stereoacuity over the entire test range. For velocities between 0-2 °/s, stereoacuity thresholds were observed to be stable. This is consistent with the results reported by Westheimer and McKee (1978) and Ramamurthy et al. (2005). However, I did not observe the dramatic rise in stereoacuity thresholds at higher velocities reported by Ramamurthy et al. (2005). Figure 3.2 shows the data from Experiment 1 plotted against that of Ramamurthy et al. (2005), showing a substantial divergence of thresholds at the higher end of the velocity test range. This resilience of stereoacuity to lateral retinal motion is surprising given that the range of velocities I tested was approximately 1.33 times larger than Ramamurthy et al. (2005). As a result, I must consider other factors that could be enhancing acuity in order to account for this difference.

4. Experiment 2

4.1. The effect of exposure duration on stereoacuity using physical stimuli

How can we account for the observed stability in thresholds over such a wide range of speeds? As mentioned in Section 1.2, Westheimer and McKee (1978) suggested that several discrete samples of depth signals are averaged over the entire presentation interval. However, there is not much evidence in the literature that the visual system performs such an operation. I propose an alternative explanation; that observers rapidly acquire a depth signal at stimulus onset, ignoring subsequent blur and smear due to motion. This proposal is consistent with the fact that stereopsis has a short integration time (Dove, 1841; Ogle & Wiel, 1956; Foley & Tyler, 1981; Uttal, Davis & Welke, 1994).

To evaluate this hypothesis, I measured stereoacuity thresholds with the same stimuli used in Experiment 1. Instead, observers viewed static lines at various exposure durations. If observers were capable of rapidly acquiring relative disparity in the stimulus used in Experiment 1; thresholds should be comparable those seen in Experiment 1 even at extremely brief exposure durations.

4.2. Methods

4.2.1. Observers

A total of five observers participated in this experiment. Four of them previously participated in Experiment 1. All observers had normal or corrected-to-normal visual acuity and demonstrated the ability to perceive depth through binocular disparity using the Randot™ Stereoacuity Test with a rejection criteria of 40 arc seconds.

4.2.2. Stimuli and Apparatus

Luminous lines were the same as used in Experiment 1, however they remained stationary during presentation and only exposure duration was varied. Exposure durations were verified prior to testing using an oscilloscope to ensure the LED driving pulse width corresponded to the specified exposure time. Six exposure durations were selected (10, 20, 40, 80, 120, 190 milliseconds) for this experiment. The disparity values used were the same as Experiment 1.

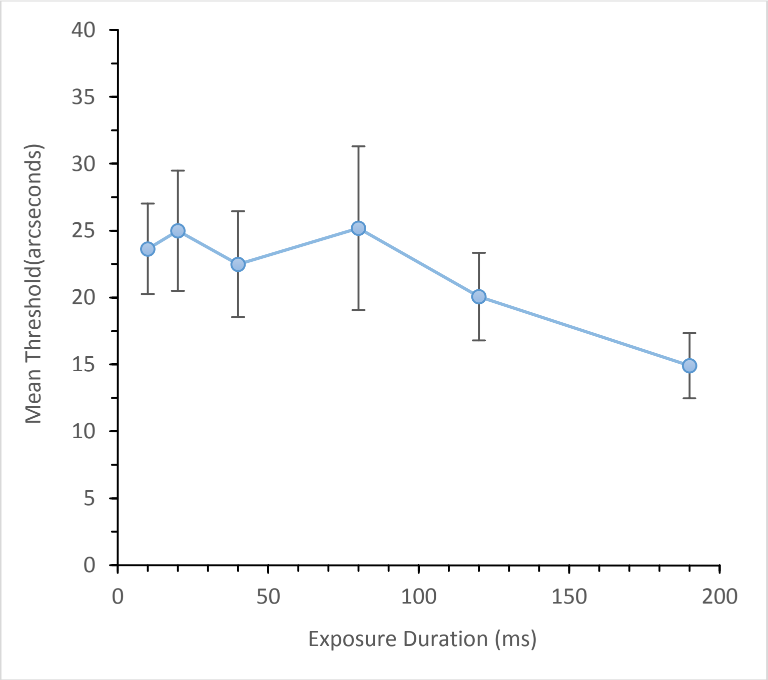

Figure 4.1. Exposure duration and thresholds. *Mean thresholds across all observers (n = 5) at each exposure duration. Error bars indicate one SEM.*

4.2.4. Results and Discussion

Figure 4.1 shows a plot of mean thresholds for each exposure duration ($n = 5$). As expected, thresholds lowered somewhat with increasing exposure across the full range of test durations. However, a dependent-samples ANOVA shows there was no significant change in thresholds from 10 to 190 milliseconds ($F(4, 20) = 2.69$, $p = 0.051$, $\eta^2_G = 0.158$). However, the effect size is quite substantial indicating that exposure duration is likely driving the subtle downward trend in mean thresholds observed with increasing exposure duration.

These results show that the visual system is able to reliably interpret depth from binocular disparity at exposure durations as low as 10 milliseconds. The data confirmed my hypothesis that observers are able to rapidly extract depth from disparity for these stimuli, thus avoiding the disruptive effect of motion smear. While this proposal explains the stable thresholds reported in Experiment 1, it does not account for the elevation in thresholds reported by Ramamurthy et al. (2005). In Experiment 3, I evaluated whether extraneous monocular depth cues in the physical stimuli are used here were responsible for facilitating performance in Experiment 1.

5. Experiment 3

5.1. Controlling for extraneous cues: monocular estimates of depth

A potentially important difference between the apparatus used here and the virtual stimuli used by Ramamurthy et al. (2005) is that the PSR apparatus may have introduced extraneous monocular depth cues that could have assisted observers in making depth judgments across all velocity conditions. While the stimuli and apparatus were specifically designed to eliminate most monocular cues, some cues such as motion parallax, optical accommodation and perspective cannot be easily controlled in a physical environment. To evaluate the role that these monocular cues played in Experiment 1 and Experiment 2, we measured depth discrimination thresholds for the stimuli of Experiment 1 under monocular viewing. If monocular cues enhanced thresholds in the preceding experiments, observers should be able to perform the depth discrimination task under these conditions with comparable thresholds to Experiment 1.

5.2. Methods

5.2.1. Observers

The same five observers that participated in Experiment 2 (Section 4.2.1) participated in this experiment.

5.2.2. Stimuli and Apparatus

The overall configuration of the apparatus and stimuli were identical to that of Experiment 1. The exception is that observers wore an eye-patch over their non-dominant eye to ensure only monocular depth cues were used when making relative depth estimates.

5.2.3. Procedure

The procedure followed that described in Section 2.4 (General Methods), except that in this study only three lateral velocities were tested (0, 8, 16 °/s) in separate blocks, in random sequence.

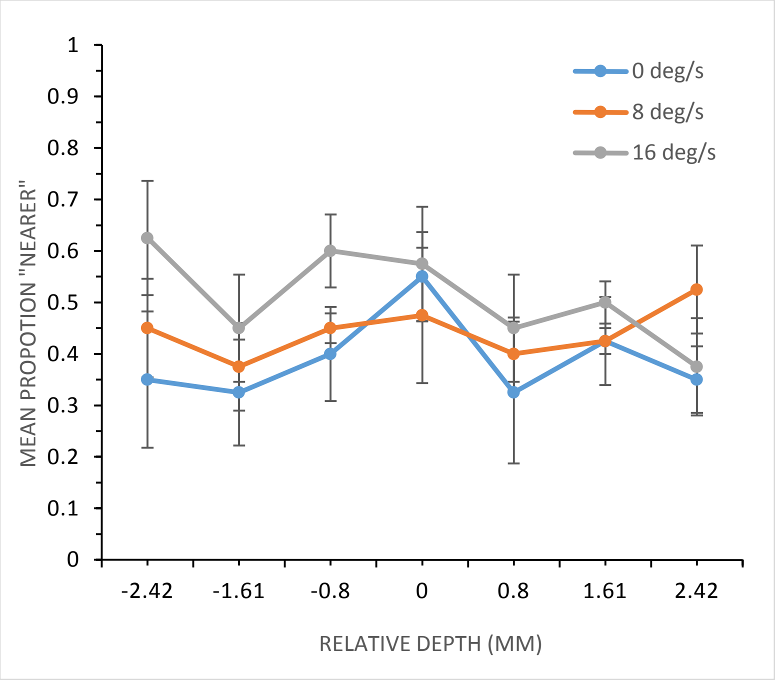

Figure 5.1. Proportion "nearer" data for monocular cues only. *Each curve represents the averaged proportion "nearer" responses for all observers in Experiment 3 at three velocities. Errors bars represent one SEM.*

5.3. Results and Discussion

Figure 5.1 shows the averaged proportion "nearer" response data for each test disparity across all observers (*n* = 5). It was not possible to fit a reasonable psychometric function to any of the observer's data because they were near chance for all test disparities. The data suggest that there were no additional cues that could be exploited by observers in Experiment 1 and that binocular disparity is the only determinant of depth perception. This experiment supports our argument that the visual system is able to extract the binocular disparity signal rapidly and that artefacts induced by motion do not impact performance.

6. Experiment 4

6.1. Subjective measurements of stimulus smear size

I found in Experiment 1 that stereopsis is unaffected by motion in the range of velocities tested. Ramamurthy et al. (2005) attributed the dramatic rise in thresholds the measured resulted from the increasing prevalence of blur and smearing due to lateral motion; attenuating high spatial frequencies from the stimuli and shifting the processing of depth information to less precise, low-frequency channels. It is possible the physical stimuli used in Experiment 1 do not produce a perceptible smear over a wide range of lateral velocities, reducing the negative effects of spatial frequency attenuation that would cause thresholds to rise. This is a possibility given Ramamurthy at al. (2005) used line targets with a luminance of 30 $cd{\cdot}m^{-2}$ opposed to 4.2 $cd{\cdot}m^{-2}$ used here.

Experiment 4 was conducted to verify that motion smear was present in the stimuli used here, and to evaluate its dependence on motion speed. To do so I measured the width of the perceived motion smear for the stimuli used in the preceding experiments. If the difference in the pattern of results reported here and by Ramamurthy et al. (2005) is due to reduced smear, or the lack thereof, estimates of smear should be small and should not vary with velocity.

6.2. Methods

6.2.1. Observers

The five observers who participated in Experiment 2 (Section 4.2.1) also participated in this study.

6.2.2. Stimuli and Apparatus

The line stimuli described in Section 2.4 (General Methods) were used here, but were presented binocularly with zero relative disparity, at a viewing distance of 50 cm throughout the entire course of the experiment. Observers indicated the perceived width of a smear using an onscreen ruler displayed on a laptop screen, located 80 cm to the right of the observer, outside of the PSR enclosure. The ruler consisted of a thin white line on a black background whose length was adjusted using a computer mouse. The observer clicked a button on the mouse to submit a response, which was then converted from length in pixels to degrees of visual arc.

6.2.3 Procedure

Following fixation, observers indicated verbally when they were ready to start the trial. I then triggered exposure of the lines after the fixation dots disappeared. Following exposure, the observer adjusted the width of a line on the laptop screen to match the perceived size of the smear. The observer was instructed to maintain their distance from the screen when submitting a response by matching the position of their head to a point on the side of the PSR enclosure. Five lateral velocities were tested (0, 2, 4, 8 and 16 °/s) in separate blocks consisting of 10 trials each, for a total of 50 trials. Perceived smear sizes in degrees were averaged across all observers for each velocity.

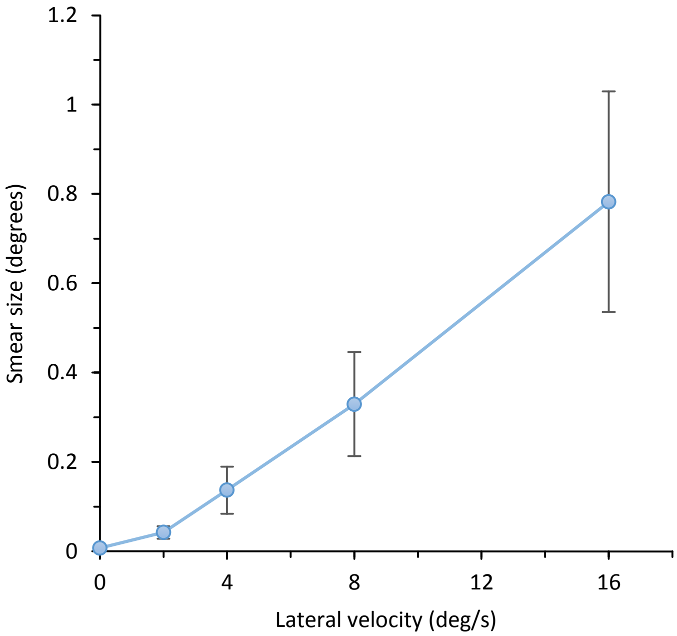

Figure 6.1. Perceived smear length and velocity. *Averaged apparent smear lengths in degrees of visual angle averaged across five observers. The error bars represent one SEM.*

6.3. Results and Discussion

Figure 6.1 shows the averaged smear length in degrees reported by all observers (n = 5). The results of this experiment show that smear is perceived by observers and on average increased with increasing velocity. This is consistent with previous research on motion smear (Burr & Morgan, 1997; Morgan & Benton, 1987). Note that variability also increased as velocity increased, indicating individual difference in the amount of smear perceived between observers at the higher end of the velocity range. A dependent-samples repeated measures ANOVA revealed a significant and large effect of velocity on perceived smear size ($F(4, 12) = 7.271$, $p < 0.01$, $\mu^2_G = 0.591$). Post hoc one-tailed Welch t-tests with FDR p-value correction revealed significant differences in blur length across all velocities ($p < 0.01$).

It is clear that observers in Experiment 1 perceived smear when they judged relative depth of lines. However, I did not find a significant increase in thresholds that Ramamurthy et al. (2005) attributed to smearing. In light of my findings, one must re-consider the role smearing has on stereoacuity thresholds and consider other possible explanations for the elevated stereoacuity thresholds reported by Ramamurthy et al. (2005).

7. Experiment 5

7.1. Effect of inter-stimulus delay on stereoacuity thresholds

In the experiments reported in this thesis the stimuli appeared immediately following extinction of the fixation points. However, in Ramamurthy et al.’s (2005) study there was a 246 ms delay between fixation extinction and target lines onset. During this period, eye movements could have resulted in fixation moving away from the stimulus plane. It is known that stereoacuity thresholds are finest when targets fall on the plane of fixation (Blakemore, 1970). However, changing vergence moves the fixation plane away from the reference target line. This results in the reference falling on a non-zero ‘pedestal’ disparity. It is known that stereoacuity thresholds degrade when depth discrimination is between targets displaced in depth relative to a fixation plane (Krekling, 1974; McKee, Levi & Bowne, 1990). Furthermore, mechanically induced vergence instability has been shown to raise thresholds (Ukwade, Bedell & Harwerth, 2003). Given Ramamurthy et al. (2005) preceded the presentation of their line targets with a 246 ms dark period, it is possible that vergence shifted contributing to the elevation of stereoacuity thresholds they measured. They were aware of the possibility of pursuit eye movements. In response, they measured observers’ horizontal eye movements using an eye tracker to determine if significant motions were being made during the exposure period. They found that observers’ had negligible pursuit eye movement during the presentation interval. However, they seem to indicate that only a single eye’s horizontal position was measured. These data do not necessarily mean that vergence was stable across the entire blank interval because the eye traces may not reflect disjunctive, binocular eye movements.

To assess if stereoacuity thresholds are adversely affected by a delay between fixation and stimulus onset, I replicated Experiment 1 but added a 246 milliseconds delay between fixation extinction and stimulus onset. If this delay contributes to the elevation in thresholds reported by Ramamurthy et al. (2005) stereoacuity thresholds should increase substantially as a function of speed.

7.2. Methods

7.2.1. Observers

Seven observers took part in this experiment. Four participants have already participated in Experiment 1. The other three had little experience with psychophysical tests of stereopsis and had not participated in any other experiment previously described in this thesis. All observers had normal and corrected-to-normal visual acuity and achieved a 40 arc seconds or better on the Randot™ Stereoacuity Test.

7.2.2. Stimuli and apparatus

The stimuli and apparatus were identical to that described in Experiment 1, with the exception of the insertion of a 246 millisecond period of complete darkness between fixation offset and target appearance.

7.2.3. Procedure

Prior to testing, naïve observers ran through a practice session which determined their appropriate disparity range. As in previous experiments, the procedure followed that described in Section 2.4 (General Methods). However, after the observer initiated a trial, instead of immediately presenting the moving stimulus, a blank period of 246 milliseconds was inserted, followed by presentation of the moving line targets for 120 milliseconds. Three lateral velocities were assessed (0, 8 and 16 °/s). For comparison, observers who did not participate in Experiment 1 were also assessed at these velocities with no delay between fixation offset and target onset.

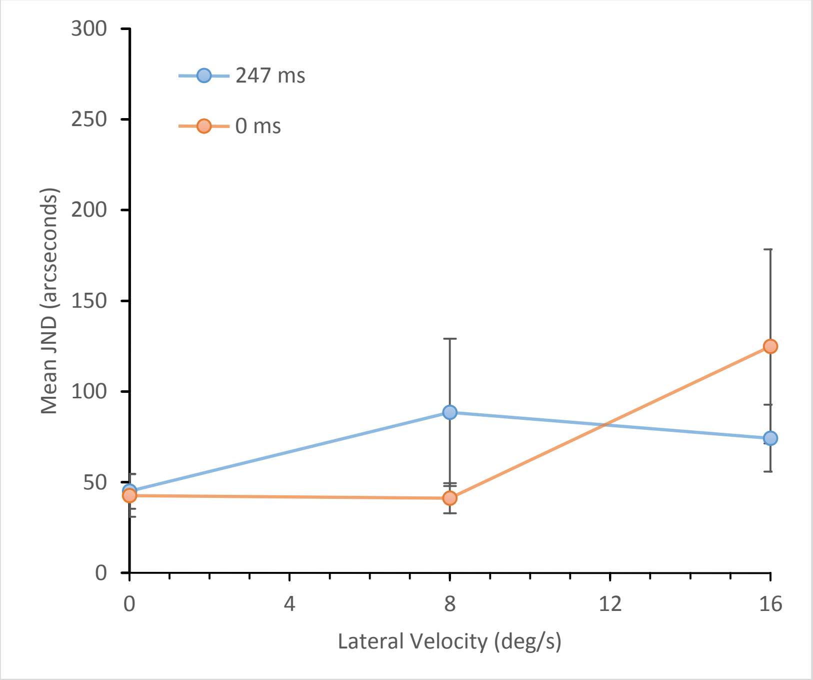

Figure 7.1. Thresholds comparisons with and without onset delay. *The above plot shows the averaged thresholds values for seven observers as a function of velocity. Data with and without a delay are plotted separately. The error bars represent one SEM.*

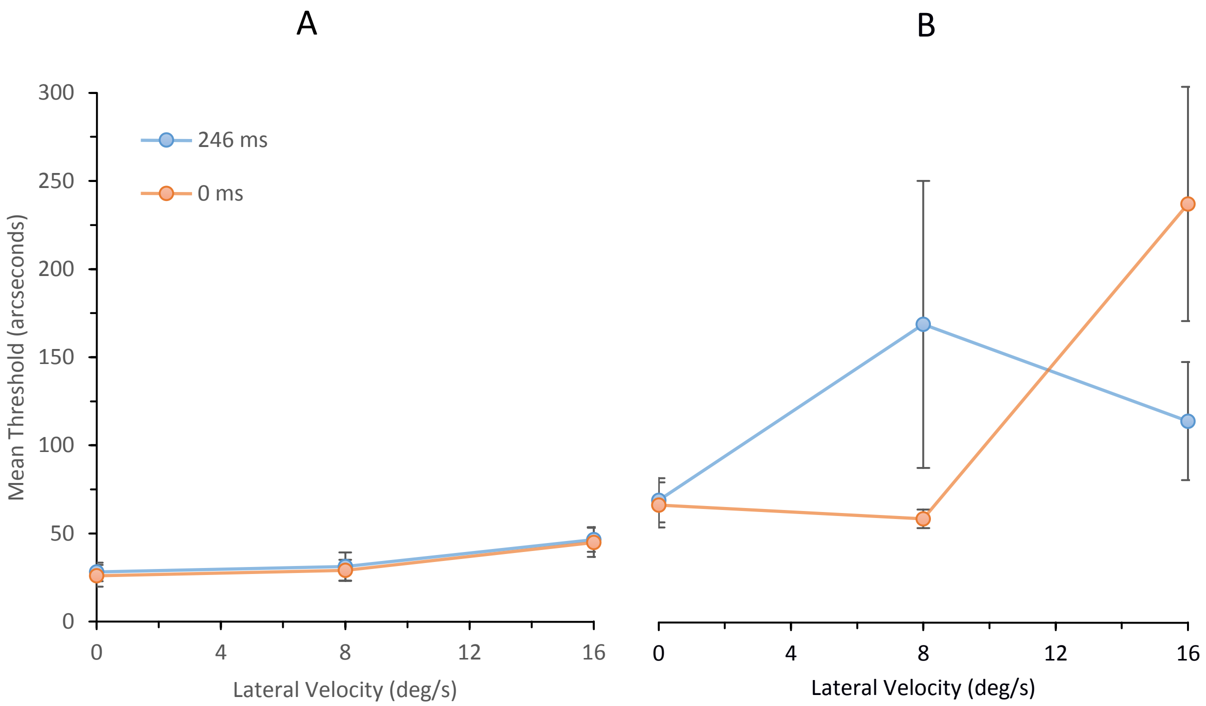

Figure 7.2. Comparison between naïve and experienced observers. *The above plots show the difference between experienced (n = 4) and naïve (n = 3) observers. The plot on the left (A) shows mean threshold values as a function of velocity for only experienced observers. The right (B) plot shows only the data from naïve observers. Error bars show one SEM.*

7.3. Results and Discussion

Figure 7.1 shows the means thresholds for all observers participating in this experiment for the “delay” and “no delay” conditions. A two-way, dependent-samples ANOVA with Greenhouse-Giesler corrected degrees of freedom revealed no significant interaction between lateral velocity and delay ($F(1.198, 7.186) = 2.627$, $p = 0.14$ n.s., $\eta^2_G = 0.0857$). It was also shown there was no significant main effect of delay ($F(1, 6) = 0.0005$, $p = 0.98$ n.s., $\eta^2_G > 0.0001$). It is clear that the lack of a dark interval in Experiment 1 did not create a significant difference in thresholds and was unlikely to have been responsible for the difference in results between Experiment 1 and Ramamurthy et al. (2005).

Qualitative examination of the data shown in Figure 7.1 revealed a substantial difference between the experienced and naïve observers tested here. This difference in pattern of results is reflected in the large error bars in Figure 7.1. Given this, I performed a post-hoc comparison of the naïve and experienced observers. These data are shown in Figure 7.2. A comparison of plots in Figure 7.2 shows that the thresholds for experienced observers were virtually the same when viewing lines with and without a delay (see Appendix A for plots of individual data). In contrast, naïve observers performed at about the same level when viewing stationary stimuli, with and without delay, but variability increased as velocity increased. The differences in the results of these two groups of observers could be due to vergence instability. It is possible that the practiced observers were able to maintain convergence. However, the observers used in Ramamurthy et al. (2005) were practiced and it is unlikely that vergence stability played a role in degrading stereoacuity.

8. General Discussion

In Experiment 1 (Section 3) I reported that stereoscopic discrimination thresholds were stable when observers viewed physical lines moving laterally across the retina up to 16 °/s. This resilience to lateral motion was also reported by Westheimer and McKee (1978) and Ramamurthy et al. (2005), at velocities of 0 to 2.5 °/s. However, the pattern of results is not consistent with a subset of results shown by Ramamurthy et al. (2005) that indicated a large increase in thresholds at lateral velocities greater than 3 °/s.

In Experiment 2 (Section 4) I found that thresholds did not vary significantly with exposure durations over a range from 10 to 190 ms. These results show that depth is still as apparent and precise at short exposures, even with the reduction in perceived contrast that occurs with decreasing exposure time. I maintain that the stability in stereoacuity thresholds observed in Experiment 1 is most likely attributed to observers obtaining depth rapidly at stimulus onset when stimuli are still broadband.

In subsequent experiments, I evaluated a number of potential explanations for the difference between my results and those of Ramamurthy et al. (2005). In Experiment 3 (Section 5) I evaluated if the physical stimuli used here provided additional depth cues that helped facilitate stereopsis. This role of monocular cues can be discounted as none of the observers could perform the task at any velocity under monocular viewing. Further, Experiment 4 (Section 6) showed there was a clear increase in perceived stimulus width due to smearing with increasing velocity. According to Ramamurthy et al. (2005), one should expect this increase in smear to raise thresholds. However, in my experiments stereoscopic thresholds did not rise precipitously with lateral velocity even though the apparent width of the stimulus did change markedly. In Experiment 5 (Section 7), I assessed if the dark interval between fixation offset and target onset used by Ramamurthy et al. (2005) was responsible for increased thresholds at higher lateral speeds. I found that this was not the case for our expert observers and likely not responsible for the difference of results. However, I did measure greater variability in the thresholds of inexperienced observers.

8.1. Rapid depth acquisition

I have proposed that stereoacuity is resilient to lateral retinal motion because binocular disparity is very rapidly processed. As discussed in Section 1.2.1, smears are drawn out on the retina over time from retinal motion. The characteristics of smear, such as salience and size, depend heavily on the retinal velocity and the properties of the stimuli image that created it. Ramamurthy et al. (2005) proposed that larger smears degrade stereoacuity because they attenuate high spatial frequency content. However, at their onset the retinal images of the smears are broadband, therefore observers are possibly able to extract depth from disparity before the images are degraded by smear to the point that stereoacuity is disrupted.

I assessed the feasibility of this hypothesis in Experiment 2 by having observers view static targets at a range of exposure durations. Line luminance remained the same as set in Experiment 1, therefore observers received the exact same amount of energy as they would from an interval some fraction of the exposure duration in Experiment 1 (120 ms). The results of Experiment 2 suggested that the critical integration period for binocular disparity is less than 10 ms. It is likely that at even shorter exposures, or more rapid stimulus speed, that thresholds would increase due to decreased visibility (either due to effective contrast or backward masking). However, I did not find evidence of such threshold increases for the range of conditions tested here.

8.2. Stimulus differences

Arguably, the observers of Ramamurthy et al. (2005) should have also have been able to acquire depth rapidly from disparity at stimulus onset. However, other factors may have made it difficult for their observers to do so at higher velocities. The following section discusses the issues surrounding the stimuli they used and the potential artefacts introduced by their virtual display.

8.2.1. Stimulus luminance

Ramamurthy et al. (2005) used bright line targets (30 cd·m^{-2}) compared to the lines using in this thesis (4.2 cd·m^{-2}). The lower luminance of our lines could have resulted in diminished smearing, which may have caused the perceived moving targets to remain reasonably broadband. I evaluated this in Experiment 3 by measuring the perceived width of my moving stimulus. The result of that experiment showed observers did perceive smearing and its size increased with velocity, which according to Ramamurthy et al. (2005) should have caused thresholds to elevate. Since I have not measured a significant, monotonic increase in stereoacuity thresholds even in the presence of smearing, I can rule out smearing as the source of threshold elevation.

8.2.2. Properties of virtual displays

Can graphics display properties explain the difference in thresholds seen between the experiments presented here and those of Ramamurthy et al. (2005)? As mentioned before display artefacts are present and are intrinsic to the operation of CRT displays. These artefacts were not present in the physical stimuli used here as they were constantly illuminated LEDs with negligible persistence.

Images on a CRT display are produced by exciting photo-luminescent phosphor with an electron beam. The position of the beam is controlled by deflection via electromagnets. In raster-scan mode, a pixelated image is divided into ‘scanlines’ or rows of pixels on the image. The electron beam sweeps horizontally across a row of pixels on the screen to transcribe the scanline, modulating its intensity to correspond to the intensity of each pixel being displayed; as increasing the beam intensity causes the phosphor to re-emit more brightly. After the beam completes traversing the row, it moves down to the next row and this process continues until the image is completely rendered. Since the phosphor is quickly decaying, the beam must return to the top of the screen and repeat the process to maintain the image. The frequency this redrawing operation occurs corresponds to the ‘refresh rate’ of the display. This is the highest frequency that a particular CRT display can redraw individual frames onscreen. Given CRTs operate in this manner; presentation of images is always stroboscopic. Humans are able to perceive stroboscopic or ‘flicker’ up to a frequency of 500 Hz if the stimulus contains sharp spatial edges (Davis, 2015). Frame rate corresponds to the number of times a single image or frame is draw on screen. A single frame can be drawn numerous times onscreen to some fraction of the refresh rate.

Ramamurthy et al. (2005) reported the CRT oscilloscope displays used in their haploscope apparatus to have a refresh rate of 240 Hz. Since no additional details were given, one may assume that their frame rate matched their refresh rate. Only a single frame was being draw repeatedly between the two displays. Binocular eye images were drawn simultaneously, a display protocol known to cause the fewest perceptible motion artefacts (Hoffman, Karasev, & Banks, 2011). In addition, motion was induced through the use of motorized mirrors, which prevents the appearance of phosphor aftertraces due to motion across the screen. However, this method does not resolve problems of stroboscopic presentation and phosphor persistence extending the duration of the stimulus after presentation ended.

A consequence of stroboscopic motion is perceptible artefacts such as discontinuity in motion (juddering) at higher velocities. Juddering would not be present at any velocity with the continuously illuminated targets used in the experiments presented in this paper. Ramamurthy et al. (2005) displayed lines using a motorized mirror haploscope and CRT display with a framerate of 240 Hz, corresponding to five milliseconds per refresh of the line targets. While this framerate is quite high compared to television (about 30 Hz according to the NTSC standard), any discontinuous motion may still be an issue for precise depth perception considering the high-resolution of stereopsis. A line travelling across the retina 12 °/s would ‘jump’ horizontally two arcminutes every five milliseconds as the image is refreshed. Furthermore, individual photoreceptors at the fovea subtend about 0.5 arcminutes of an image (Geisler, 1984; Deering, 1998). As a result, a line travelling across a stationary retina at 12 °/s will skip over several photoreceptors, resulting in discontinuous stimulation that could degrade stereoacuity.

Watson (2013) describes the influence frame rates has on the visibility of laterally moving targets. Much like the contrast sensitivity function, the ‘Window of Visibility’ described by Watson (2013) delineated a range of temporal and spatial frequencies that lines are visible to observers. The boundaries of this window represent critical temporal and spatial limits, outside of which moving targets become invisible. It is possible that the targets used by Ramamurthy et al. (2005) fell within the observer’s window of visibility and appeared to be free of motion artefacts, but in fact disrupted stereoacuity. However, there is insufficient detail within the literature to be confident that stroboscopic presentation at 240 Hz led to the rise in stereoacuity threshold at higher velocities measured by Ramamurthy et al. (2005). Whether or not the refresh rate of the display they used was adequate to capture the true capabilities of the visual system is an unknown and should be considered a topic of future investigations.

9. Conclusion

I found that the visual system's ability to process stereopsis was resilient to lateral retinal motion between 0-16 °/s using physical stimuli. At low velocities (0-2.5 °/s) our findings are consistent with the past work of Westheimer and McKee (1978). However, there was a considerable difference in results from Ramamurthy et al. (2005) at higher velocities. I ruled out the effects of monocular cues, smearing visibility and stimulus delay relative to fixation offset as possibilities for the difference. Since spatial frequency attenuation is known to affect stereoacuity thresholds (Stigmar, 1971; Westheimer & McKee, 1980) with static stimuli, I proposed that observers maintained stable thresholds in Experiment 1 by sampling depth early at stimulus onset; before the target's retinal image is smeared by motion. I asserted that Ramamurthy et al.'s (2005) results do not reflect some limitation of disparity processing, but are rather due to insufficient temporal-spatial properties of their display leading to degraded fine acuity. Future studies conducted using periodically flickering targets at a range of frequencies would provide insight on the relationship between refresh rate and retinal velocity on stereoacuity. In sum, the experiments reported here highlight the both impressive resilience of stereopsis to lateral retinal motion, and the importance of considering display properties when assessing the limits of visual processing.

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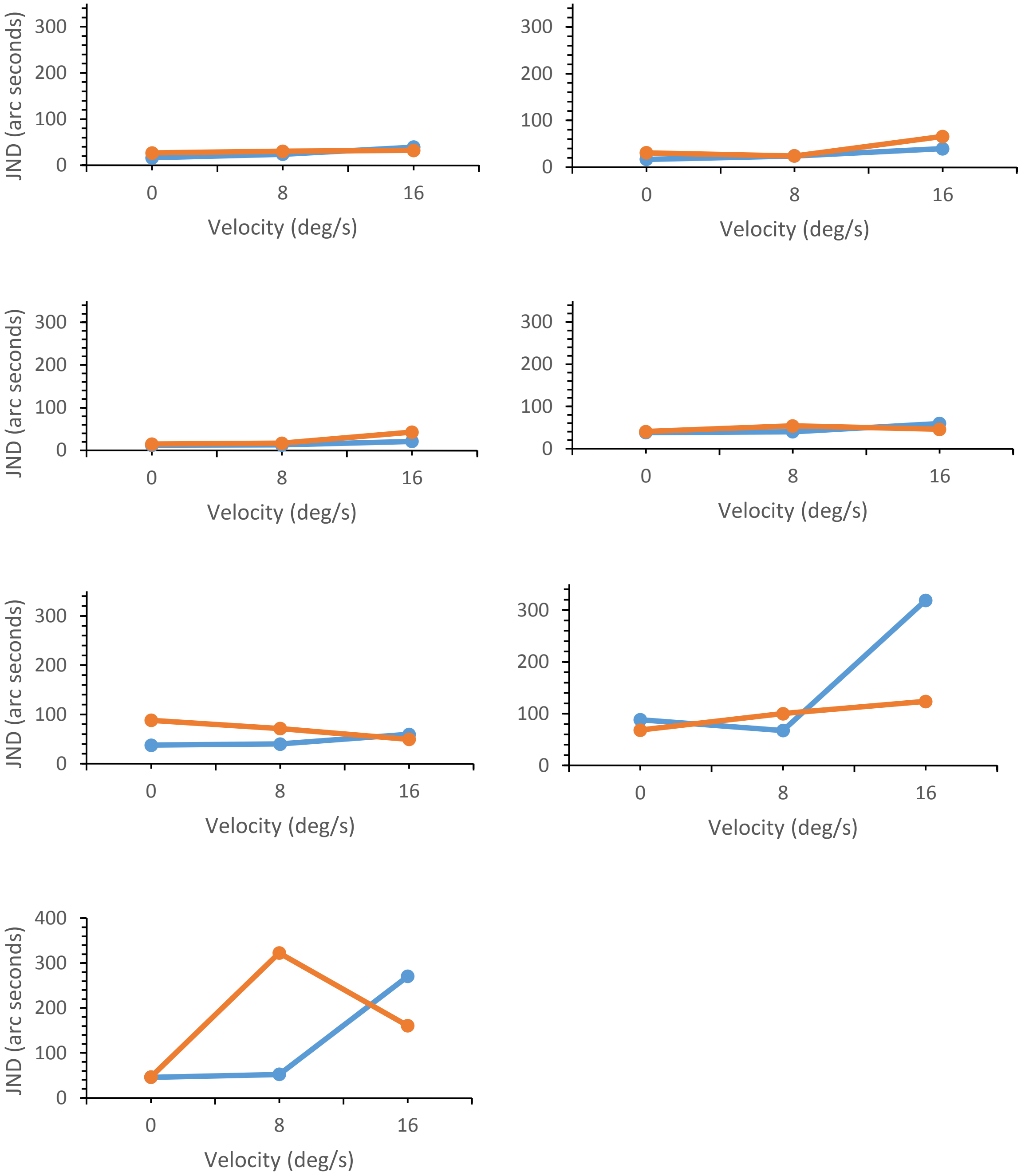
11. Appendices

Appendix A: Individual observer threshold plots



Appendix A. *Each plot shows the results of an individual observer for Experiment 5 (Section 7). The top two rows of plots are 'expert' observers where the remainder are 'naïve'.*