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Ocular dominance and temporal dynamics in the venetian blind effect

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OCULAR DOMINANCE AND TEMPORAL DYNAMICS IN THE
VENETIAN BLIND EFFECT

BY

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DISSERTATION

Submitted to the University of New Hampshire
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the Requirements for the Degree of

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ABSTRACT

OCULAR DOMINANCE AND TEMPORAL DYNAMICS IN THE VENETIAN BLIND EFFECT

BY

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University of New Hampshire, May 2011

The visual system can use small disparities between the stimuli seen by each eye as a binocular cue for depth. Geometric disparities are the most commonly used cue for stereopsis, but disparities in contrast and luminance can also lead to the perception of depth and can both cancel perceived depth from a geometric disparity. Humans are able to perceive changes in depth from contrast disparities at frequencies up to approximately 1.4 Hz, whereas changes in depth from geometric disparities are visible at frequencies above 5 Hz (Dobias, 2008).

This dissertation is divided into two parts. The first part (experiments 1 & 2) explores the dynamics of canceling the perceived depth from a geometric disparity using a contrast or a luminance disparity. The second part (experiments 3-5) explores the role of individual differences in the dynamics of perceived depth from contrast, luminance, and geometric disparities. Dobias (2008) and results in experiments 3 & 4 show that the probability of reporting depth from contrast and luminance disparities diminish at frequencies much lower than from a geometric disparity (critical frequency). A generalized difference model (simple low-pass
filter), does not account for the data from experiment 1. However, a gated
generalized difference model, which applies low-pass filtering to the amplitude of
the modulation but not its rate of change, does account for the data. Results
from part two show that the frequency at which depth changes from contrast and
luminance disparities (experiment 3) differs from the frequency at which depth is
no longer visible for a geometric disparity (experiment 4), that the frequency can
differ depending on which eye views the changing stimulus (experiments 3 & 4),
and that either visual masking or eye movements are likely not causing the
decrease at lower frequencies for contrast and luminance disparities (experiment
5). The finding that results from part one follow the gated model, and the
differences depending on which eye views the dynamic stimulus found in part
two, suggest that the visual system processes depth from contrast and
luminance disparities much differently from what would be expected based on
our typical understanding of depth perception.
CHAPTER I

INTRODUCTION

**Stereopsis**

Each eye views the environment from a slightly different position in the head resulting in two slightly different visual images on each retina. The visual system can use the small differences between the stimuli from each eye as a binocular cue for depth. When both eyes are fixated on a point, large areas of the images falling on each eye overlap. Based on the overlap between images, a retinal point in one eye will receive the same information as a retinal point in the other eye, and these points are said to be corresponding (Ogle, 1962, p. 223). In the second century AD, Galen recognized that each eye sees a distinct part of an object and that two images are combined into one unified image. Later, in the ninth century AD, Alhazen showed that when an image falls on corresponding areas in the two eyes, the image appears single, but if the image falls on areas that do not correspond, the image would appear to be double (Howard & Rogers, 1995, p. 6-13).

Leonardo da Vinci described another aspect of binocular vision that is used to determine depth and the distance between two objects. When viewing an occluding object with both eyes, an area behind the occluding object is occluded from the left eye, and a separate area is occluded from the right eye, but the area occluded from the one eye remains visible to the other eye. Da Vinci noted that the object becomes “transparent” (figure 1) in that the area
Figure 1. Diagram adapted from A Treatise on Painting (da Vinci, 1796, pp. 178-179). Demonstrates that (for occluding images of a certain size) an occluded area exists for each individual eye but is not occluded for the other eye. da Vinci suggested that this caused the occluding image to be, in effect, transparent. Permission to use this figure is shown in Appendix B.
behind the object is not hidden (da Vinci, 1796, pp. 178-179). When the object becomes transparent, the observer can see at least some of the area behind an object and determine, based on how much area can be seen, how far the one object is behind the other. In terms of corresponding points, questions arise because there are points on one retina that are unable to be matched to points on the other retina (Nakayama & Shimojo, 1990).

The perception of depth does not require that the image actually contain depth. Like Galen earlier, in 1838 Charles Wheatstone determined that, along with the differences in the retinal image of an object and the background, each eye receives a different picture of the object itself. Wheatstone demonstrated that, stereograms (figure 2) with one two dimensional image shown to the left eye and a separate, slightly different, 2D image shown to the right eye, would create the perception of depth when properly fused (Wheatstone, 1838). The components of each image that are different, have a specific disparity that create the depth.

The stereograms developed by Wheatstone have slight differences in each image that are visible when using either one or both eyes. Although the perception of depth does not occur until the images are stereoscopically combined, monocularly visible differences still remain.¹

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¹ Julesz (1960) defines the terms monocular pattern recognition as: “performed on the visual field seen by one eye” and binocular pattern recognition as: being “performed on the fused field, which is a combination of the left and right monocular fields.”
Figure 2. Stereograms from Wheatstone (1838). Slight differences in the left and right images serve as binocular cues to depth. Permission to use this figure is shown in Appendix B.
To separate monocular from binocular depth cues, Julesz (1960) developed random-dot stereograms (figure 3), which monocularly appear to be a random field of dots, but when properly fused create the perception of depth. The images shown in figure 3, like other random-dot stereograms, contain a field of random dots, some of which are slightly distorted in the image shown to one eye, creating a collective pattern of dots that fall on points in each eye that do not correspond. It is the task of the visual system to determine which random point in one eye corresponds to another random point in the other eye and use the magnitude of the difference to determine depth.

Julesz determined that, in the absence of monocular cues, depth is perceived only after the images are stereoscopically combined and is not a result of searching for patterns before the images are combined. In cases when some monocular cues are available, however, depth perception is much quicker, suggesting that it may be a combination of both. Despite seeing depth more quickly in the presence of both monocular and binocular cues, it is most interesting that depth perception occurs when monocular cues are not available to help solve the correspondence problem (Julesz, 1960).

---

2 Julesz (1960) defines another set of definitions regarding pattern recognition. Micropattern recognition is "simple pattern organizations that take into account some geometrical, topological characteristics in a point's immediate neighborhood." Macropattern recognition is a higher order organization of several points.

3 The correspondence problem is the problem faced by the visual system when determining which points stimulated on one retina, do or do not, correspond to retinal points stimulated on the other retina.
Figure 3. Random-dot stereogram. When fused, a square appears in depth.
Venetian Blind Effect

Geometric retinal disparities are a leading contributor to stereopsis, but there are other cues that can create the perception of depth. Münster (1941) and Cibis & Haber (1951) independently found that a surface can appear to rotate in depth when one eye views a grating with lower luminance (luminance disparity). Later, Filley (1998; Filley, Khutoryansky, Dobias, & Stine, submitted) showed that the depth could also occur when one eye views a grating with lower Michelson contrast (contrast disparity).

Cibis & Haber (1951) describe the Venetian blind effect as resulting from "anisopia," or an unequal vision or imagery leading to a distortion of the visual space. The unequal vision can result from any alteration in the physical, receptive, or the neuro-physiological image of the stimulus that creates a larger image in one eye. If, for example, a cylindrical lens is placed in front of one eye, a surface will appear to rotate away from that eye (Figure 4). However, if a neutral density filter is placed in front of one eye to decrease the image

---

4 Stereopsis is defined as the impression of depth arising from binocular cues or from binocular disparity (Howard & Rogers, 1995, p. 2).

5 Michelson contrast is defined in terms of maximum and minimum luminance values (Michelson, 1927). It is the difference in the maximum and minimum luminance values divided by the sum of the maximum and minimum luminance values \( \frac{(L_{\text{max}} - L_{\text{min}})}{(L_{\text{max}} + L_{\text{min}})} \).

6 The physical image is a result of the illumination reaching the retina. The receptive image is determined by the photochemical processes in the retina. The neurophysiological image is determined by processes beyond the photoreceptors. (Cibis & Haber, 1951).
Figure 4. Apparent rotation of a fronto-parallel plane surface, resulting from a magnification of the image shown to one eye. The surface appears to rotate away from the eye with higher magnification. The effect will reverse when the eye receiving magnification is reversed (Cibis & Haber, 1951).
illuminance, a surface will appear to rotate towards that eye\(^7\) (Figure 5). It is the perceived rotation due to a disparity in retinal illuminance that Cibis & Haber call the Venetian blind effect.

Cibis & Haber (1951) measured the effect using two white squares against a black background (Figure 6) that could be physically rotated by the observer. Observers viewed a pair of white squares set against a black background with a neutral density filter placed in front of one eye and were asked to physically rotate the squares until they appeared to no longer rotate in depth. Observers rotated the squares farther as the density of the filter increased (Figure 7).

From their data, Cibis & Haber proposed a model suggesting that decreased illuminance in one eye physically decreases the size of the image in that eye. Due to the modulation transfer function of the eye (e.g., Williams, Brainard, McMahon, & Navarro, 1994), the original images falling on each retina (with a specific receptor threshold) would have a shape similar to the energy distributions shown in figure 8. The uncovered eye would have the solid-line distribution and the eye that is covered with a filter would the dotted line. As shown in figure 8, the energy required for perception of the square (above the receptor threshold) is subject to a "perceptual zone" that Cibis & Haber suggest would also have a threshold value. The remaining energy level that is above

\(^7\) Cibis & Haber (1951) also used pupillary diaphragms, spherical or cylindrical lenses, and bleaching of the retina to alter the perceptive image. All were found to alter the perception of the test images but will not be discussed further.
Figure 5. Apparent rotation of two fronto-parallel plane surfaces resulting from an overall decrease in the illuminance of the image to one eye. The surfaces appear to rotate towards the eye with lower illuminance. The effect will reverse when the eye receiving lower illuminance is reversed (Cibis & Haber, 1951).
Figure 6. Experimental setup used by Cibis & Haber (1951) to measure the perceived rotation caused by decreased overall illuminance in one eye. The two white squares could be physically rotated to cancel the perceived rotation. Permission to use this figure is shown in Appendix B.
Figure 7. Apparent rotation as a function of the density of the filter before the left eye and the right eye. Redrawn from Cibis & Haber (1951). Permission to use this figure is shown in Appendix B.
Figure 8. Cibis & Haber's interpretation of the retinal (top) vs. Perceptual (bottom) image when one eye receives an overall decrease in illuminance. Permission to use this figure is shown in Appendix B.
receptor and perceptual thresholds would have different sizes similar to that in figure 4. A geometric disparity would be created and would lead to a perception of a square rotating towards the eye receiving the darker image.

For a qualitative understanding of the perceived rotation from the Venetian blind effect, Gerathewohl & Cibis (1953) asked professional draftsmen, who were highly skilled in drawing, to draw what they perceived while viewing a white H-shaped stimulus with a filter over one eye. Figure 9 shows drawings made without a filter (left) and with a filter over the right eye (right).

Ogle (1952) argued that Cibis & Haber (1951) had not discovered anything new about visual perception, and that they had only measured one aspect of intensity gradients on the retina. Cibis & Haber had used what Ogle called a "special geometrical configuration" (p. 142), and that the Venetian blind effect is not special. Ogle (1962) continues to interpret Cibis & Haber's results in terms of geometric disparities and names the effect irradiation stereoscopy.

Cibis & Haber (1951) give the most commonly used explanation for the Venetian blind effect (Howard & Rogers, 1995 pp. 310-311), but more recent evidence suggests that it might not fully explain the effect. von Békésy (1970) showed that, when dark bars of a square wave grating were placed next to a white field while one eye was covered with a neutral density filter, the bars neighboring the white field would appear to rotate more (Figure 10). von Békésy concluded that the apparent rotation while looking through a neutral density filter is "a complicated combination of irradiation and lateral nervous interaction" and

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8 Figure 10 shows white bars next to a black field.
Figure 9. Drawings from Gerathewohl & Cibis (1953). Perception of the stimulus while not looking through a filter (left) and with a filter over the right eye (right). Below each image is the observers estimate of what the image would look like if viewed from above. Permission to use this figure is shown in Appendix B.
Figure 10. Dark field next to a series of white bars. von Békésy (1970) used a white field next to dark bars to show the role of lateral interactions in the Venetian blind effect. Permission to use this figure is shown in Appendix B.
that it may be from processes similar to those that lead to Mach bands\(^9\) (von Békesy, 1970). The influence of lateral interactions does not fit with the Cibis & Haber model of the Venetian blind effect and would indicate that the phenomenon is not entirely due to the optics of the eye. Alternatively, if perceived rotation in the Venetian blind effect is due to the optics of the eye, it is possible the increased rotation close to the white field may be due to a depth contrast effect (Howard & Rogers, 1995, Ch. 12).

The Cibis & Haber model predicts no perceived rotation when the dark part of the square wave is above threshold. Filley (1998; experiment 1 in Filley et al., submitted) used vertical square wave gratings (similar to those in figure 11) that were manipulated to increase or decrease the contrast or luminance in one eye while keeping the average illuminance and contrast constant in the other eyes. The standard grating had a contrast of 0.5 with an average luminance of 34.5 cd/m\(^2\). The variable grating was factorially varied with one of five contrast values (0.2, 0.35, 0.5, 0.65, or 0.8) and one of five average luminance values (12.0, 23.25, 34.5, 45.75, or 57.0 cd/m\(^2\)). Observers were asked to indicate which side of the light bars appeared rotated towards them. If the left eye was shown a grating with lower contrast or luminance, the light bars of the grating would usually appear to rotate towards the left eye. If the eye that received lower contrast or luminance was reversed, the direction of rotation would also reverse. Therefore, since the stimuli used by Filley et al. were entirely above threshold,

\(^9\) Mach bands are illusory bands of increased darkness or lightness induced by linear luminance gradients (Purves, 2004).
Figure 11. Two stereo pair, square wave gratings. Top: Left eye receiving higher contrast. Bottom: Right eye receiving higher contrast.
the apparent rotation of individual square wave bars is not explained by the Cibis & Haber model.

As described above, the model proposed by Cibis & Haber (1951) fails because it requires that the dark portion of the square wave grating be below the receptor threshold for the retina. A second irradiation model, however, does predict a perceived rotation when the entire stimulus is visible. von Helmholtz (1911/1924, pp. 186 - 193) suggested that, due to the eye’s optics, the intensity of an edge on the retina is reduced on the more intense side of the edge and enhanced on the less intense side (see von Helmholtz, 1911/1924, Fig 35). Further, Helmholtz, noted that the compressive non-linearity in the response of the visual system to retinal intensity causes the location of the edge to appear shifted toward the less intense side (von Helmholtz, 1911/1924, p. 189). “In a grating of dark bars with intervals exactly as wide as the bars themselves in front of a bright background, the intervals appear to be wider than the bars” (von Helmholtz, 1911/1924, p. 187). As a result, a square-wave grating viewed binocularly with an average luminance or a contrast disparity would appear to have rotated bright bars due to the increased apparent width of those bars in the higher-intensity image relative to that in the lower-intensity image (Filley et al., submitted). However, when the effect of the eye’s optics are modeled (using a point spread function) followed by a compressive non-linearity in neural response (using a Naka-Rushton equation), disparities are created in the correct direction but they do not quantitatively predict the observed data (Filley et al., submitted).
As described above, the edge within a grating can perceptually shift towards the darker region (von Helmholtz, 1911/1924). Further, and for similar reasons, the magnitude of the apparent shift will increase if the edge is blurred, with the amount of increase positively related to the width of the blur. As well, the magnitude of the shift increases with contrast (Bex & Edgar, 1996; Morgan, Mather, Moulden, & Watt, 1984; Mather & Morgan, 1986; Mather & Smith, 2000; Westheimer, 2007; Filley et al., submitted). Therefore, with the Venetian blind stimulus, the von Helmholtz model predicts that the shift in edge location would create wider light bars in the higher contrast grating and the light bar would appear to rotate towards the eye that is viewing the lower contrast grating. Also, if the edges of the bars are blurred, the perceived rotation should increase.

Khutoryansky, (2000; experiment 2 in Filley, et al., submitted) measured threshold for perceived rotation as a function of changes in the width (spatial frequency) of a sine wave blur at the edges within the grating. Results showed that width of blur did not influence contrast or luminance disparities to perceived rotation. The results of experiment two were replicated in experiment three of Filley et al. (submitted) and were generalized to supra-threshold levels of perceived depth and over a wider range of blurs widths.

The results described above from Filley, et al., (submitted) show that a disparity in interocular luminance or contrast can create the perception of rotated bars within a square wave grating. In addition to the perceived rotation, there is also a perceived luminance (brightness) or a perceived contrast of the grating. Hetley (2004; Hetley & Stine, accepted pending revision) attempted to separate
the perception of intensity (brightness or perceived contrast) from the perceived rotation caused by the disparities in luminance or contrast. In one part of the task, Hetley & Stine manipulated disparities in luminance and contrast while asking observers to report which of the two fused gratings had higher contrast or higher luminance. In the other part, geometric disparities were added to the gratings to create the perception of rotated bars. A contrast or luminance disparity was then introduced to cancel the perceived rotation from the geometric disparity. The perceived intensity (contrast or luminance) was found to be related to the sum of the interocular grating intensity, while perceived rotation was related to the difference in grating intensity. Since each perception (intensity or rotation) is tied to a separate relationship between each grating (sum or difference), results suggest that each perception relies on separate neural mechanisms.

Further, individuals with amblyopia who are unable to perceive depth from a geometric disparity and also, presumably, from a luminance or contrast disparity can respond to the perceived contrast or perceived luminance of a fused stimulus (Baker, Meese, Mansouri, & Hess, 2007). This ability to respond to perceived contrast or luminance again suggests that separate neural mechanisms control perceived rotation and perceived contrast/luminance.

Results also showed that observer’s response varied depending on which eye received the grating with higher contrast or luminance. Interestingly, two observers showed stronger input from one eye for perceived rotation and stronger input from the other eye for brightness and perceived contrast (opposite
eyes for each observer). A third observer showed dominance for perceived intensity and rotation in the same eye. As will be discussed in further detail below (Experiments 2 and 3), individual differences in response to specific stimuli can indicate that those processes are controlled by separate neural mechanisms. Experiments 2 and 3 below will use this individual-differences approach to explore perceived depth from contrast/luminance or geometric disparities.

As described above, the standard explanation for the Venetian blind effect is that it results from irradiation that leads to a geometric disparity in the retinal images of the stimulus. The results of Filley, et al. (submitted) and Hetley & Stine (accepted pending revision) suggest that there are problems with this traditional explanation. In my master’s thesis (Dobias, 2008; Dobias & Stine, in preparation), I compared the speed of processing by the visual system when a stimulus has a geometric disparity vs. processing with a disparity in interocular contrast. If the irradiation hypothesis correctly accounts for the Venetian blind effect, the visual system should process perceived depth in similar ways for both types of disparity because both would be due to different size images on each retina.

Stereopsis, like all types of visual processing, does not occur immediately. For local and global stereopsis, the amount of disparity necessary for stereopsis increases as stimulus exposure time decreases (White & Odom, 1985). One way to determine how quickly the visual system determines depth is to present a stimulus with a set of depth cues, reverse the cues, and then ask the observer to
report a change in depth. White & Odom (1985) used dynamic anaglyph\textsuperscript{10} stereograms with depth reversals occurring at intervals within a range between 0.11 to 15 Hz. The threshold to perceive depth reversals was highest at 15 Hz, reducing to its lowest point at about 1 Hz. When the frequency was below approximately 1.8 Hz, the threshold remained about the same but when above 1.8 Hz the threshold increased. Despite the higher thresholds, depth was still reported at frequencies up to 15 Hz.

Richards (1951) compared the ability to perceive a stimulus that moved in depth to the ability to perceive left-right movement. An apparatus showed three vertical bars to one eye and another set of vertical bars to the other eye. In the depth case, the center bar was moved in opposite directions in each eye to make the fused image appear to move towards and away from the observer.\textsuperscript{11} For movement in the frontal plane, one bar was moved in the same direction in each eye to make the bar appear to move to the left and right. In both cases the frequency of movement was increased up to 20 Hz. The probability of reporting lateral motion decreased very gradually and remained visible at 20 Hz. The probability of reporting depth, however, decreased much more quickly as the frequency of depth oscillations increased. Once the frequency of depth modulations reached approximately 3.2 Hz, depth was no longer visible.

\textsuperscript{10} Anaglyph images are created by superimposing two slightly different images one over the other. One image is colored red the other is colored green. The observer wears a red filter over one eye and a green filter over the other allowing each eye to see only one of the images (Howard & Rogers, 1995, p. 26).

\textsuperscript{11} Richards (1951) did not clearly define the type of motion that was created by his apparatus. It appears, however, that it moved in a triangle wave motion.
Tyler (1971) used a similar method to Richards (1951) except that Tyler’s stimuli were modulated in a sine wave motion. Observers set the amplitude of the sine wave movement at the point where movement was just noticeable. The sensitivity to motion-in-depth was found to be similar to the sensitivity to movement in the fronto-parallel plane, but that sensitivity to motion-in-depth was much lower than motion in the fronto-parallel plane. Both were most sensitive between 0.5 and 1 Hz, but sensitivity to motion-in-depth was consistently lower than fronto-parallel motion throughout the set of frequencies tested for the depth condition. Tyler did not specifically report the point where movement started to decline, or when depth was gone entirely, but the sensitivity began to decrease between 3 and 5 Hz. Frequencies above 5 Hz are not reported.

Richards (1972) compared the amount of perceivable depth as a function of the frequency of sine wave and square wave depth modulations. Observers viewed a bar that appeared to move back and forth through the fixation plane. The bar would either move smoothly in and out in a sine wave motion, or would jump back and forth at a specific frequency. While viewing the moving bar, observers would mark the most-forward position of the bar. The amount of visible depth began to decrease at frequencies between 1 and 2 Hz and was completely gone at about 4 Hz. Sine wave depth changes also began to decrease between 1 and 2 Hz, but did not completely disappear until approximately 6 Hz. The decrease of visible depth to the point of zero depth at 6 Hz was not dependent on the amplitude of sine wave modulation. Several different amplitudes were tested, showing a greater impression of depth at higher
amplitudes, but depth from all of the amplitudes decreased to zero at approximately 6 Hz.

Regan & Beverley (1973a) used a random-dot stereogram with two black bars positioned within the image. The apparatus adjusted the bars shown to one eye so that one bar oscillated back and forth in a sine wave motion. The other bar was controlled by the observer who adjusted the non-oscillating bar to the most-forward or most-behind point of the depth oscillations made by the other bar. As the frequency of the depth oscillations increased, the perceived depth decreased until it was completely gone at frequencies from 5-6 Hz. Regan & Beverley’s findings were replicated by Regan & Beverley (1973b) and by Beverley & Regan (1974a, b), who also found that, as frequencies were elevated to around 3-6 Hz, depth would be reduced and, eventually, both motion and depth would disappear.

The research discussed above shows that a geometric disparity can be modulated up to 5-6 Hz before the depth modulations are no longer visible. My Master’s thesis (Dobias, 2008; Dobias & Stine, in preparation) compared the speed of processing in the Venetian blind effect by altering contrast disparity cues to the speed of processing with a geometric disparity. As was stated previously, if the irradiation hypothesis correctly accounts for the Venetian blind effect, the visual system should process perceived depth in similar ways for both types of disparity and contrast disparity modulations should lead to perception of depth at frequencies up to 5-6 Hz. It is possible, however, that some process other than diminished sensitivity at high frequencies may cause subjects to be
unable to perceive depth changes at higher frequencies. A quick change in contrast may cause a saccade away from the stimulus location. If so, saccadic suppression may decrease the probability of reporting any change in perceived depth that occurred during the eye movement. The possible influence of eye movements will be discussed further below.

In all experiments, Dobias & Stine used stimuli that consisted of two square wave gratings placed side-by-side. Examples are shown in figure 20. Each standard grating consisted of four dark bars and three light bars, each of which was 1.6° in height and 0.4° in width. Each complete grating had a spatial frequency of 1.25 cycles per degree, and was 1.6° in height and 2.8° in width (top of figure 20). The contrast of each grating was manipulated to be higher in one eye while decreasing in the other (figure 20 middle).

Experiment one altered contrast of each grating in a sine wave modulation. Each grating started at an equal contrast. Grating contrast was then increased in one eye while being decreased in the other. Frequency of modulations was increased between 0.2 to 1.8 Hz. Results (figures 12-14) show that the perception of depth (top) and motion-in-depth (bottom) became more variable at approximately 1 Hz and that depth was rarely reported when at approximately 1.8 Hz. These results were replicated in experiment three (figures 15-18 gray lines), where the contrast of the gratings were increased and decreased in a square wave modulation. The perception of depth again decreased when above approximately 1 Hz, and was completely diminished before 1.8 Hz.
Figure 12. Probability of a depth response, upper panel, or motion-in-depth response, lower panel, to sine-wave contrast disparity modulations as a function of the contrast disparity modulation temporal frequency in Hertz. Subject JJD. Contrast disparity amplitudes of 0.6, 0.8, and 1.0 are presented. JJD did not report depth or motion in depth with a probability of 0.6 or greater when the contrast disparity amplitude was either 0.2 or 0.4.
Figure 13. Subject WWS. Contrast disparity amplitudes of 0.4, 0.6, 0.8, and 1.0 are presented. WWS did not report depth or motion in depth with a probability of 0.6 or greater when the contrast disparity amplitude was either 0.2.
Figure 14. Subject RSH. Contrast disparity amplitudes of 0.6, 0.8, and 1.0 are presented. RSH did not report depth or motion in depth with a probability of 0.6 or greater when the contrast disparity amplitude was either 0.2 or 0.4.
Figure 15. Probability of a depth response for JJD to square-wave contrast (gray lines) and geometric (black line) disparity modulations as a function of the geometric disparity modulation temporal frequency in Hertz. Psychometric functions are from the dynamic generalized-difference model reported in Dobias & Stine (in preparation). Standard errors are calculated using the score confidence interval (Agresti and Coull, 1998, Equation 2; Wilson, 1927) with $n = 12$ and $\alpha = 0.318$. 
Figure 16. Probability of a depth response for WWS to square-wave contrast (gray lines) and geometric (black line) disparity modulations as a function of the geometric disparity modulation temporal frequency in Hertz.
Figure 17. Probability of a depth response for RSH to square-wave contrast (gray lines) and geometric (black line) disparity modulations as a function of the geometric disparity modulation temporal frequency in Hertz.
Figure 18. Probability of a depth response for JRH to square-wave contrast (gray lines) and geometric (black line) disparity modulations as a function of the geometric disparity modulation temporal frequency in Hertz.
Experiment two presented disparity modulations with a geometric disparity. Stimuli were altered by dynamically increasing the width of the light bars by two pixels and decreasing the width of the dark bars in one eye while keeping the bars equal in the other eye (figure 20 bottom). Results (figures 15-18 black line) showed that, if the size of individual square wave grating bars were increased and then decreased in one eye, reports of depth became more variable above 1-2 Hz and was still reported at up to 5 Hz. These results were replicated with a naïve observer.

Figure 19 shows the critical frequency as a function of the contrast modulation amplitude averaged across subjects. There is no notable difference in critical frequency for sine wave and square wave contrast modulations. Frequencies for both modulations fall below 2 Hz, whereas, the frequency for the geometric disparity is near 5 Hz.

As suggested above, one might argue that the large difference in processing speed between contrast and geometric disparities is due to eye movements induced by contrast changes. If a contrast change causes a saccade, any motion occurring during the saccade would not be perceived due to saccadic suppression (e.g. Bridgeman, Hendry, & Stark, 1975) and, as the frequency of oscillations increases to a certain rate, each contrast change would occur before saccadic suppression ends and before depth from the Venetian blind effect could be perceived. However, the data do not support the influence of saccades because the frequency at which depth was no longer visible in all contrast disparity conditions was at frequencies between approximately 1.0 and
Figure 19. Critical frequencies as a function of disparity type and contrast disparity modulation amplitude with dynamic generalized-difference model predicted critical frequencies. Data points are critical frequencies averaged across JJD, WWS, and RSH for a geometric disparity modulation and contrast disparity modulations of amplitude 0.6, 0.8, and 1.0 with 95% ANOVA-based confidence intervals (Loftus and Mason, 1994).
1.5 Hz, which corresponds to 667-1000 ms per cycle. These frequencies are below those that would be influenced by saccadic suppression. However, it is useful to determine whether changes in interocular contrast can cause eye movements.

Locating object features in three dimensional space requires detection of both the depth and the visual direction of the feature (Mansfield & Legge, 1996). Typically the binocular visual direction of a feature is the average of each monocular image direction. To determine the influence of interocular contrast on the perceived visual direction of a stereoscopically viewed Gabor stimulus, Mansfield & Legge asked subjects to adjust horizontal alignment of a Gabor patch with equal contrast seen by each eye to the perceived location of an unequal contrast Gabor. Results showed that, as the difference in interocular contrast increased, the perceived binocular visual direction perceptually shifted towards the higher contrast monocular image.

Weiler, Maxwell, & Schor, (2007) replicated the results of Mansfield & Legge (1996) and, further explored how the perceived shift in binocular visual direction influences eye movements. Weiler et al. investigated whether the oculomotor system uses contrast differences to guide binocular saccades in a similar way to perceived binocular visual direction. Results for perceived visual direction replicated results from Mansfield & Legge, finding that stereoscopically viewed Gabor patches perceptually shifted towards the higher contrast monocular image rather than the average of the left and right monocular Gabor

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12 A patch of sine wave under a Gaussian window (Gabor, 1946; Daugman, 1980; Adelson & Bergen, 1985).
locations. To induce eye movements, a Gabor with equal 100% contrast was shown for 200 ms and then replaced with a Gabor offset to a position either 2.5° or 3.5° to the left or right from the equal contrast Gabor. The second Gabor contained either 100% contrast seen by each eye or were 40% contrast in one eye and 100% in the other. Amplitudes of binocular saccades were biased towards the higher contrast image. In both cases, Mansfield & Legge (1996) and Weiler et al. (2007) used Gabor stimuli that contained a crossed disparity. However, in a zero disparity control condition, Weiler et al. found no differences in binocular saccade amplitude for equal and unequal contrast stimuli. Therefore, when disparity is not present, the contrast induced bias in saccade amplitude does not occur.

Results from Weiler et al. show that if changes in object position cause a saccade, the amplitude of the saccade can be biased towards the higher contrast image. Unfortunately, eye movements were not recorded (or at least were not reported) with unequal contrast and zero horizontal offset. Therefore, their data are unable to show that the rapid change of interocular contrast alone can cause a binocular saccade towards the perceived direction the Gabor. However, since the perceived visual direction shifts, it is possible that an eye movement does occur.

Stimuli used in Experiments 1 and 2 of Dobias & Stine oscillated contrast disparity, which could shift the perceived location of the grating and could cause a binocular saccade. However, as described above, perceived depth from the Venetian blind effect diminishes at frequencies below those that would be
influenced by saccadic suppression. Saccades recored by Weiler et al. had onset and offset times of approximately 280 and 340 ms, whereas, for Dobias & Stine, perceived depth was no longer visible when contrast disparities changed every 667-1000 ms.

To determine whether eye movements and saccadic suppression are leading to lower depth thresholds for dynamic contrast modulations found by Dobias & Stine, an experiment could use both types of cues simultaneously or alone to determine the frequency at which depth is no longer perceived. If eye movements are causing lower thresholds, when contrast and luminance disparities are oscillated either alone or simultaneously with geometric disparities at low frequencies, depth should be perceived in all conditions. However, at higher frequencies, depth should only be perceived when geometric disparities are simultaneously present with contrast or luminance disparities. This will be discussed further in experiment five.

Summary

Typically the visual system uses small geometric differences between the image seen by each eye to determine depth. In addition to these geometric cues, the visual system can also use differences in interocular luminance or contrast to perceive rotation (Münster, 1941; Cibis & Haber, 1951; Filley et al., submitted; Hetley & Stine, accepted pending revision; Dobias & Stine, in preparation). Irradiation models would predict that the decreased illuminance or contrast for one eye’s image creates a geometric disparity, which leads to the
perception of rotation. Cibis & Haber (1951) proposed a model suggesting that decreasing illuminance by placing a neutral density filter over one eye decreases the energy distribution of the light reaching the retina. As a result, larger portions of the image will be above threshold in the eye receiving the bright image (geometric disparity) and will create the perception of rotation. von Helmholtz (1911/1924, pp. 186-193) noted that the retinal illuminance of an edge within an image is reduced due to the optics of the eye in such a way that the edge can perceptually appear shifted towards the less intense side of the edge. Also, this perceptual shift can increase as the edge becomes more blurred due to lack of accommodation (von Helmholtz, 1911/1924) or when the edges within the image are actually blurred (Bex & Edgar, 1996; Morgan, Mather, Moulden, & Watt, 1984; Mather & Morgan, 1986; Mather & Smith, 2000, Westheimer, 2007; Filley et al., submitted).

Filley et al. (submitted) presented stimuli that were completely above threshold, which should not lead to perceived rotation according to the Cibis & Haber model. After testing several models that would support the irradiation models of the Venetian blind effect, Filley et al. (submitted) concluded that an intensity difference model relating interocular difference in bright bars to the probability of perceiving rotation more accurately explains their data.

Dobias & Stine (in preparation) determined the frequency at which the visual system is no longer able to process changes in perceived depth from disparities in interocular contrast. Results showed that the visual system processes perceived depth from a geometric disparity much more quickly than
from a contrast disparity. Irradiation models would predict that perceived depth from both a contrast and geometric disparity should be processed at the same rate. Since perceived depth from a geometric disparity is visible at higher frequencies than depth from a contrast disparity, it is likely that both result from separate neural mechanisms at some level. Since a contrast (Hetley & Stine, Accepted Pending Revision) and a luminance (Cibis & Haber, 1951; Hetley & Stine, Accepted Pending Revision) disparity can be cancelled by a geometric disparity, perceived depth from each type of cue is likely a result of activity in the same neural tissue. This assumption relies on the psychophysical linking hypothesis (Brindley, 1960, p.144) that “…if two different stimuli (or their resulting sensations) are statistically indiscriminable, the corresponding neural signals must be rendered statistically indiscriminable somewhere within the sensory system, at or prior to the bridge locus” (Teller, 1984, p. 1237).  

Rationale for Current Research

The experiments conducted by Dobias & Stine (in preparation) tested contrast disparities and geometric disparities separately only measuring the dynamics of perceived rotation. As described above, the fact that disparities in average luminance (Cibis & Haber; Hetley & Stine) and contrast (Hetley & Stine) can cancel perceived depth from a geometric disparity suggests cues for each are fed into a common neural mechanism. Further, the results of Dobias & Stine suggest that the mechanisms feeding that information into the common

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13 The bridge locus is the collection of "...central neurons that form the most immediate substrate of conscious perceptual events" (Teller, 1984, p. 1237).
mechanism are separate. It might be better, however, to compare the rate at which the visual system processes depth from intensity (contrast or luminance) or geometric disparities by canceling an intensity disparity with geometric disparity. This method would provide a measure of the dynamics of cancellation rather than the dynamics of perceived rotation. If each disparity type is presented simultaneously to cancel perceived depth from the other, depth should be cancelled before either disparity can generate enough depth to detect. If, however, there is an offset between each disparity onset, a “jump” will be perceived when one disparity causes perceived rotation and then is cancelled by the other disparity. Based on the results from Dobias & Stine, it was predicted that, to perceive a “jump” when intensity disparities led the onset of geometric disparity, the offset would need to be different from when a geometric disparity led intensity. The Preliminary Experiment and Experiment 1 explore this prediction by manipulating the offset between the onset of a contrast disparity and a geometric disparity (Preliminary Experiment) and the offset between either a contrast or luminance disparity and a geometric disparity (Experiment 1).

Hetley & Stine separated perceived brightness and perceived contrast from perceived rotation within stimuli containing a difference in interocular luminance or contrast. Results showed that perceived contrast and luminance are related to the sum of interocular grating intensity but perceived rotation is related to the difference in interocular grating intensity suggesting that each type of perception relies on separate neural mechanisms. Further, they found that the responses of the visual system differed for each subject depending on which eye
received the higher intensity stimulus. As described previously, individual differences in response to specific stimuli can indicate that those processes are controlled by separate neural mechanisms. Experiments 3 and 4 will explore perceived depth from contrast/luminance or geometric disparities using an individual differences approach. This approach will determine whether some individuals show stronger input from one eye for perception of rotation from the Venetian blind effect and stronger input from the other eye for perceived depth from a geometric disparity.
CHAPTER II

PRELIMINARY EXPERIMENT:

DYNAMIC CANCELLATION OF PERCEIVED DEPTH FROM CONTRAST AND
GEOMETRIC DISPARITIES

Introduction

In this preliminary experiment, stimuli with geometric disparities and contrast disparities were presented simultaneously to allow one cue to cancel the perceived depth created by the other. The cues were presented dynamically with the onset of one cue being a few milliseconds before or after the other cue. Presenting each cue in this way allowed for a comparison between the rate at which the visual system processes depth from a geometric disparity vs a contrast disparity. As described above, if both cues are presented in close succession, each cue should cancel the other and no depth should be perceived. However, as the offset between cue onset increases, a “jump” should be perceived when one cue causes a perceived rotation and then the other cue quickly cancels it.

Participants

Subjects were JJD, WWS, and WJT. All subjects had normal or corrected vision and normal stereopsis. Approval for this study was obtained by the Institutional Review Board of the University of New Hampshire, and each subject provided written informed consent for participation. A copy of the document showing institutional review board approval is shown in Appendix A.
Apparatus

While sitting in a dark room, subject’s heads were stabilized by a bite bar individually molded for their teeth. To equalize the amount of light entering each eye, each subject viewed the stimuli through 3 mm apertures. Stimuli were presented on a LaCie electron19blue1V monitor with a refresh rate of 85 Hz and viewed from a distance of 1.58 m. At this distance, one pixel subtended 38 seconds of visual angle. A Power Mac G4 computer running Mathematica 4.2.1.0 controlled the display; Mathematica was used to generate the animated stimuli and record responses.

Luminance measures were taken with a Minolta LS-110 photometer. The maximum and minimum luminance values that could be generated by the monitor were approximately 86 and 2 cd/m² respectively, which set the minimum average luminance value at 44 cd/m², and the maximum contrast value to be approximately 0.95. The monitor was gamma corrected.

The range of luminance values was reduced to ensure that luminance values for experimental animations remained in a range that the monitor could generate. The standard average luminance value was set at 29 cd/m², and the maximum contrast value was set at approximately 0.65.

Each frame of the animation consisted of two square wave gratings placed side-by-side similar to those in the top of figure 20. A baffle was placed vertically between the two gratings to insure that the right side grating was visible only to the right eye and the left side grating to the left eye. Each grating consisted of four dark bars and three light bars, each of which was 1.6° in height and 0.4° in
Figure 20. Experimental stimulus with equal contrast in each eye (Top), with higher contrast on the right (middle), and larger light bars on the right side (bottom).
Each complete standard grating had a spatial frequency of 1.25 cycles per degree, and was 1.6° in height and 2.8° in width. The gratings had an overall luminance of 29 cd/m², which was equal to the luminance of the background, and an overall contrast of 0.325. Above and below each grating, 0.03° nonius lines were placed to aid in the fusion of the two images. The center of each nonius line contained a 0.1° by 0.5° vertical rectangle with the same luminance as each dark bar of the left grating.

To create experimental stimuli, gratings were first altered to allow light bars to widen in one eye while remaining the same in the other eye. The left and right sides of each “middle” dark bar and the one pixel of an “end” dark bar were replaced with a pixel that could be altered individually to be either lighter or darker. When the lighter bars were altered to be wider in one eye, each individual light bar was 1.6° in height and 0.4° in width (bottom of figure 20). The overall monocular image remained 1.6° in height and 2.8° in width. Second, a contrast disparity could be added to the stimuli to cancel depth created by the wider bars seen by one eye. If the left eye received wider bars, it would receive a grating with lower contrast.

**Procedure**

In preparation for each experiment, subjects sat in a chair facing the monitor while biting on a properly positioned bite bar to ensure a direct view of the monitor. An example stimulus was shown on the screen, and was viewed

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14 When fused, an identical line in each monocular image (nonius lines), fall on corresponding points in each retina and appear to be one single line. The lines help the visual system determine which horopter (Vieth-Müller circle) the image is on (Ames, Ogle, & Glidden, 1932), and thus helping to fuse the two images.
through an aperture that blocked all parts of the screen except for the stimulus. The apertures were closed to a minimal size and were roughly positioned to form a concentric circle around either the left or right grating. A sight constructed of two vertical wires was then aligned by the subject to create a direct line of sight from the eye to the center of the grating viewed by that eye. Once the sights were aligned for both eyes, an experimenter looked down the sight to create a direct line to the subject’s natural pupil. The experimenter then opened the aperture to a size that was just larger than the subject’s iris, and adjusted it to form a concentric circle around the iris. Both of the apertures were then reduced to 3 mm, the room was darkened, and the experimenter exited the room. The subject then initiated the start of the experiment by pressing a key on a keyboard.

Once the experiment began, the subject viewed a blank gray screen with a luminance of 29 cd/m² for five minutes to adjust to the darkened room. After five minutes, a stimulus containing only nonius lines was presented for 10 seconds and then was replaced with an animated experimental stimulus that was presented for 10 seconds. After 10 seconds, the experimental stimulus was replaced with a blank gray screen, the subject was prompted to make a response, a response was made, and then the process began again (the five minute adaptation occurred only before the first trial).

Experimental stimuli were animations constructed from 200 frames where average luminance remained constant while contrast was dynamically altered in a series of square wave modulations. Square wave modulations in one eye were π radians out of phase with the other eye so that, as one disparity was increased
in one eye, it was reduced in the other. Contrast and geometric disparities were used simultaneously to create rotations in opposite directions. The timing of contrast disparity modulations was varied with respect to the timing of geometric modulations. Each set of square wave modulations had the same frequency, and were calculated to create the same magnitude perceived rotation. The onset of contrast disparity modulation was determined for each trial by randomly choosing from a set of pre-determined offsets, or phase differences relative to the geometric disparity. Offsets were -150, -100, -50, 0, 50, 100, 150, and 200 ms.15

After each trial subjects indicated whether or not the perceived rotation changed rapidly, or “jumped,” during the trial. When the contrast and geometric disparity modulations were in phase, the perceived rotation caused by contrast cancelled rotation caused by the geometric and the individual bars appeared to either rotate only slightly or appear flat. However, if the phase of the two were not aligned, one disparity type would create rotation that would then be cancelled by the second disparity type, producing a rapid drop in perceived rotation, or a “jump.” The probability of a rapid change in rotation was measured as a function of phase, or timing offset.

For each session, a common frequency for both the contrast and geometric disparity modulations was randomly selected from the set 0.2, 0.4, 0.6, and 0.8 Hz. Two sessions were run for each frequency, giving eight sessions for each subject.

15 The actual offsets were within +/- .5 (1000/85) = 5.9 ms of these nominal values.
Subjects completed 10 individual trials for each offset during a session. Each trial was 10 seconds in duration followed by a 10 second inter-trial interval. With the five-minute adaption period, and 88 trials, each experimental session was about 35 to 40 minutes.

Results

Probability results for subject WWS can be seen in figures 21 and 22, for WJT in figures 23 and 24, and for JJD in figures 25 and 26. Temporal offsets are plotted on the x-axis and probability of reporting depth is plotted on the y-axis. Positive offsets indicate that geometric disparities occur before being cancelled by a contrast disparity and negative offsets indicate that contrast disparities occurred before geometric. Mathematica was used to find a best fitting line for each offset with a Laplace distribution by estimating the mean of the Laplace distribution (μ), the scale parameter β, and the maximum height of the distribution. The probability of reporting a jump did not reach fifty percent in all conditions, therefore, the threshold estimate is extrapolated for those conditions. However, for data visualization, distribution means and standard deviations are plotted if the probability of reporting a jump was significantly greater than reporting “no jump”. As a result, the mean and standard deviations for the positive offset in the 0.8 Hz condition are not included for subject WJT. Figure 27 shows a positive or negative offset on the x-axis and the absolute value of the mean, |μ|, (top) and standard deviation, β√2, (bottom) on the y-axis (separate lines for each subject). Individual frequency data can be seen for each subject in Appendix C. Figure 28 shows the means and standard deviations averaged
Figure 21. Probability of reporting a "jump" for WWS at a frequency of 0.2 Hz (top) and 0.4 Hz (bottom) as a function of offset in milliseconds between the onset of contrast and geometric disparities.
Figure 22. Probability of reporting a “jump” for WWS at a frequency of 0.6 Hz (top) and 0.8 Hz (bottom) as a function of offset in milliseconds between the onset of contrast and geometric disparities.
Figure 23. Probability of reporting a "jump" for WJT at a frequency of 0.2 Hz (top) and 0.4 Hz (bottom) as a function of offset in milliseconds between the onset of contrast and geometric disparities.
Figure 24. Probability of reporting a "jump" for WJT at a frequency of 0.6 Hz (top) and 0.8 Hz (bottom) as a function of offset in milliseconds between the onset of contrast and geometric disparities.
Figure 25. Probability of reporting a "jump" for JJD at a frequency of 0.2 Hz (top) and 0.4 Hz (bottom) as a function of offset in milliseconds between the onset of contrast and geometric disparities.
Figure 26. Probability of reporting a “jump” for JJD at a frequency of 0.6 Hz (top) and 0.8 Hz (bottom) as a function of offset in milliseconds between the onset of contrast and geometric disparities.
Figure 27. Means (top) and standard deviations (bottom) for Laplace distributions in Figures 21 to 26 for JJD (black dashed), WWS (gray), and WJT (black)
Figure 28. Means of the Laplace distributions for negative phase shifts (contrast) and positive phase shifts (geometric) (top) and the standard deviation of the Laplace distributions for negative phase shifts (contrast) and positive phase shifts (geometric) (bottom)
across subjects. Both the absolute value of the mean and the standard deviation of the Laplace distributions were lower when a contrast disparity was cancelled by a geometric disparity (Figure 28). However, there were individual differences between subjects (Figure 26). Individual means, standard deviations, and max values can be seen in Table 1.

Discussion

The results from the preliminary experiment are consistent with those from my master’s thesis (Dobias & Stine, in preparation). The visual system behaves differently when processing geometric and contrast disparities. The results from this experiment suggest that, to perceive a jump when one cue cancels the other, a larger offset is required to cancel when geometry leads contrast than when contrast leads geometry. The finding that the visual system does not process cues at the same rate, suggests that separate physiological pathways at some level are responsible for perceived depth from each type of disparity. Further, as described above, the fact that one type of disparity can cancel perceived depth from the other suggests that the separate pathways for contrast and geometric disparities are likely feeding into a common mechanism to assign a depth value to the stimulus.

The preliminary experiment and Experiments 1-3 reported below attempt to answer four questions about the relationship between perceived depth from the Venetian blind effect and depth from geometric disparities. As described above, Dobias & Stine (in preparation) only measured the dynamics of perceived rotation. First, are the dynamics of cancellation the same when one cue
Table 1. Means, standard deviations, and max values of Laplace distributions for the Preliminary Experiment

<table>
<thead>
<tr>
<th>Positive</th>
<th>Subject</th>
<th>JJD</th>
<th>WWS</th>
<th>WJT</th>
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<tr>
<td>0.2 Hz</td>
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<td>93.62</td>
<td>55.00</td>
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<td></td>
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<td>0.92</td>
<td>0.77</td>
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<tr>
<td>0.4 Hz</td>
<td>μ</td>
<td>74.69</td>
<td>93.91</td>
<td>170.00</td>
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<tr>
<td></td>
<td>σ</td>
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</tr>
<tr>
<td></td>
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<td>0.81</td>
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</tr>
<tr>
<td>0.6 Hz</td>
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</tr>
<tr>
<td></td>
<td>σ</td>
<td>122.62</td>
<td>14.14</td>
<td>84.85</td>
</tr>
<tr>
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<td>max</td>
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<td>0.64</td>
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<tr>
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<tr>
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<td>0.15</td>
<td>0.87</td>
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<table>
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<th>Negative</th>
<th>Subject</th>
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<th>WWS</th>
<th>WJT</th>
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<tr>
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<td>-43.69</td>
<td>-35.00</td>
</tr>
<tr>
<td></td>
<td>σ</td>
<td>42.19</td>
<td>7.07</td>
<td>11.31</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>1.00</td>
<td>0.89</td>
<td>1.00</td>
</tr>
<tr>
<td>0.4 Hz</td>
<td>μ</td>
<td>-33.05</td>
<td>-49.73</td>
<td>-62.00</td>
</tr>
<tr>
<td></td>
<td>σ</td>
<td>65.29</td>
<td>7.91</td>
<td>16.97</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>1.00</td>
<td>0.89</td>
<td>1.00</td>
</tr>
<tr>
<td>0.6 Hz</td>
<td>μ</td>
<td>-55.87</td>
<td>-58.67</td>
<td>-62.00</td>
</tr>
<tr>
<td></td>
<td>σ</td>
<td>152.48</td>
<td>7.07</td>
<td>11.31</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>1.00</td>
<td>0.93</td>
<td>1.00</td>
</tr>
<tr>
<td>0.8 Hz</td>
<td>μ</td>
<td>-50.50</td>
<td>-61.88</td>
<td>-62.00</td>
</tr>
<tr>
<td></td>
<td>σ</td>
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<td>max</td>
<td>0.18</td>
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<td>1.00</td>
</tr>
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</table>
(contrast or luminance) is used to cancel the other (geometric)? If yes, it was predicted that there should be no differences between the mean of psychometric functions for positive and negative offsets. The preliminary experiment tested this question and found that a larger offset is required to perceive cancellation ("jump") when geometry cues are presented and then quickly cancelled by contrast cues. Second, are the dynamics of canceling similar for contrast, luminance, and geometric disparity? If yes, and if the amount of depth created by each type of disparity is matched, the means of psychometric functions for positive and negative offsets should be the same for both contrast and luminance disparities. Experiment one replicates the results from the preliminary experiment and extends them to conditions with a luminance disparity. Third, are the dynamics of perceived rotation the same for contrast, luminance, and geometric disparities? If yes, perceived depth should diminish at the same frequency for all three disparity types. Experiment three replicates and extends the results of Dobias & Stine (in preparation) by testing the speed at which the visual system processes motion in depth with disparities in both contrast and luminance (luminance disparities were not used by Dobias & Stine (in preparation). Experiment four alters geometric disparity to replicate the results from Dobias & Stine (in preparation) that depth reversals can be perceived at frequencies up to 5 Hz and to compare results to contrast and luminance disparities in experiment two. Fourth, In light of the results of Hetley & Stine (accepted pending revision), will the dynamics be different for the left vs right eye for contrast, luminance, and geometric disparities? If yes, the pattern of critical
frequencies across contrast, luminance, and geometric disparities between the
two eyes may differ across subjects. Experiment three will alter contrast and
luminance in one eye while the other eye receives a constant stimulus and
experiment three will only alter the width of light bars in one eye while the width
remains constant in the other eye.
CHAPTER III
EXPERIMENT ONE

Introduction

Based on the results of the preliminary experiment it was interpreted that, as was found by Dobias & Stine, the visual system processes depth differently for contrast and geometric disparities. This experiment replicated the results from the preliminary experiment and extended them to conditions with a luminance disparity. It was expected that, as was found in the preliminary experiment, a longer offset would be necessary to detect a jump when geometric disparity is presented before a contrast disparity. Also, it was expected that the required offset would be similar to the offset when a luminance disparity was presented and then cancelled with a geometric disparity. If so, as described above, it was assumed that perceived depth from contrast, luminance, and geometric disparities is a result of activity in the same neural tissue but that separate mechanisms are likely feeding depth information into the stereo system for contrast/luminance and geometric disparities.

Participants

Participants were PCN, JJD, and WWS. WWS and JJD were experienced observers. PCN was naive to specific experimental details and expected results. All subjects had normal or corrected vision and normal stereopsis. Approval for this study was obtained by the Institutional Review Board of the University of New Hampshire, and each subject provided written informed consent for
participation. A copy of the document showing institutional review board approval is shown in Appendix A.

**Apparatus**

The apparatus was the same as in the preliminary experiment except for the computer that controlled the experiment and the monitor that presented stimuli. The computer was a Mac Book Pro laptop driving a Apple ColorSync display. Luminance calculations were adjusted so that range of luminance values did not differ from those presented on the monitor used in the preliminary experiment. Image size was the same and the monitor were at the same distance from the subject. Stimuli were created in the same manor as in the preliminary experiment. Each complete standard grating had a spatial frequency of 1.25 cycles per degree that is 1.6° in height and 2.8° in width. The gratings had an overall luminance of 29 cd/m², which was equal to the luminance of the background, and an overall contrast of 0.325. Above and below each grating, 0.03° nonius lines were placed to aid in the fusion of the two images.

**Procedure**

Procedures were similar to those in the preliminary experiment except for how stimuli were generated and which frequencies were presented within each trial. In the preliminary experiment, *Mathematica 4.2.1.0* calculated the values necessary to generate each frame of the animation separately for each trial. For this experiment, animations were generated and saved as *Quicktime* movie files. *Mathematica 7.0.0* then randomly chose one of the pre-made movie files, played the movie, prompted for a response, saved the response, and started the next
trial. Contrast and luminance disparities were altered in opposition to geometric disparity. Subjects were asked to respond in the same way as the preliminary experiment. Offsets were –200, -150, -100, -50, 0, 50, 100, 150, and 200 ms and frequencies were again 0.2, 0.4, 0.6 and 0.8 Hz. Combining each frequency and offset gave 36 possible combinations. The experimental program randomly chose from a combined set of 36 contrast combinations and 36 luminance combinations to create a total of 72 trials per experimental session. Each subject completed 20 sessions for a total of 20 choices at each frequency/offset combination.

**Results**

The Probability of reporting a jump for contrast disparities can be seen in figures 29-34 and for luminance disparities in figures 35-40. Temporal offsets are plotted on the x-axis and probability of reporting a jump is plotted on the y-axis. Mathematica was used to find a best fitting line for each offset with a Laplace distribution. The probability of reporting a jump did not reach one hundred percent in all conditions, therefore, when fitting each curve, the maximum height of the Laplace distribution was set to the value of highest probability of reporting jumps for that curve. The mean of the Laplace distribution μ and the the scale parameter β were then adjusted to fit a curve with the lowest total squared deviation from the probability values. Because there were several conditions where the probability of reporting a jump did not reach fifty percent, the threshold estimate is extrapolated for those conditions.
Figure 29. Probability of reporting a “jump” for contrast conditions for JJD at a frequency of 0.2 Hz (top) and 0.4 Hz (bottom) as a function of offset in milliseconds between the onset of contrast and geometric disparities.
Figure 30. Probability of reporting a “jump” for contrast conditions for JJD at a frequency of 0.6 Hz (top) and 0.8 Hz (bottom) as a function of offset in milliseconds between the onset of contrast and geometric disparities.
Figure 31. Probability of reporting a "jump" for contrast conditions for WWS at a frequency of 0.2 Hz (top) and 0.4 Hz (bottom) as a function of offset in milliseconds between the onset of contrast and geometric disparities.
Figure 32. Probability of reporting a "jump" for contrast conditions for WWS at a frequency of 0.6 Hz (top) and 0.8 Hz (bottom) as a function of offset in milliseconds between the onset of contrast and geometric disparities.
Figure 33. Probability of reporting a "jump" for contrast luminance for PCN at a frequency of 0.2 Hz (top) and 0.4 Hz (bottom) as a function of offset in milliseconds between the onset of contrast and geometric disparities.
Figure 34. Probability of reporting a “jump” for contrast luminance for PCN at a frequency of 0.6 Hz (top) and 0.8 Hz (bottom) as a function of offset in milliseconds between the onset of contrast and geometric disparities.
Figure 35. Probability of reporting a "jump" for luminance conditions for JJD at a frequency of 0.2 Hz (top) and 0.4 Hz (bottom), as a function of offset in milliseconds between the onset of luminance and geometric disparities.
Figure 36. Probability of reporting a “jump” for luminance conditions for JJD at a frequency of 0.6 Hz (top) and 0.8 Hz (bottom) as a function of offset in milliseconds between the onset of luminance and geometric disparities.
Figure 37. Probability of reporting a “jump” for luminance luminance for WWS at a frequency of 0.2 Hz (top) and 0.4 Hz (bottom) as a function of offset in milliseconds between the onset of luminance and geometric disparities.
Figure 38. Probability of reporting a “jump” for contrast conditions for WWS at a frequency of 0.6 Hz (top) and 0.8 Hz (bottom) as a function of offset in milliseconds between the onset of luminance and geometric disparities.
Figure 39. Probability of reporting a "jump" for luminance luminance for PCN at a frequency of 0.2 Hz (top) and 0.4 Hz (bottom) as a function of offset in milliseconds between the onset of luminance and geometric disparities.
Figure 40. Probability of reporting a “jump” for luminance luminance for PCN at a frequency of 0.6 Hz (top) and 0.8 Hz (bottom) as a function of offset in milliseconds between the onset of luminance and geometric disparities.
The absolute value of the mean, $|\mu|$, and the standard deviation, $\beta\sqrt{2}$, for each subject are plotted in figures 41 and 42. Figure 41 shows a negative or positive offset on the x-axis and the absolute value of the mean on the y-axis for each subject. As described in the preliminary experiment, offset refers to the difference in onset of each type of cue (contrast/luminance or geometric disparities). Negative offsets are when contrast/luminance modulations occur before geometric and positive offsets are when geometric modulations occur before contrast/luminance modulations. Figure 42 shows the negative or positive offset on the x-axis and the standard deviation on the y-axis for each subject. Individual frequency data can be viewed in Appendix D.

As described above, several conditions showed a low probability of reporting a “jump.” However, for data visualization, distribution means and standard deviations are plotted if the probability of reporting a jump was significantly greater than reporting “no jump.” As a result, the mean and standard deviations for the negative offset in the 0.2 Hz luminance condition are not included for subject PCN. Figure 43 shows the means and standard deviations averaged across subjects for contrast and luminance disparities. Figure 44 shows overall means and standard deviations.

As can be seen in Figures 29 to 34, results from the contrast disparity condition did replicate the preliminary experiment for subjects WWS and JJD. For WWS and JJD, when a contrast disparity was used to cancel a geometric disparity, the mean of the Laplace distribution (averaged across frequencies) was lower for negative offsets than positive offsets. For subject PCN, however, the
Figure 41. Means for contrast (top) and luminance (bottom) for Laplace distributions in Figures 29 to 34 for JJD (black dashed), WWS (gray), and PCN (black).
Figure 42. Standard deviations for contrast (top) and luminance (bottom) for Laplacian distributions in Figures 35 to 40 for JJD (black dashed), WWS (gray), and PCN (black)
Figure 43. Means (top) and standard deviations (bottom) for Laplace distributions in Figures 29 to 40 averaged across subjects for contrast (black) and luminance (gray).
Figure 44. Means (top) and standard deviations (bottom) averaged across subjects for Laplace distributions in Figures 29 to 40.
mean was higher for negative offsets than positive offsets. When a luminance disparity was used to cancel a geometric disparity, WWS and PCN showed lower means for positive offsets than negative offsets. Subject JJD did not show a difference between positive and negative offsets (Figure 41). For all subjects, in contrast disparity conditions, Laplace distributions had lower standard deviations for negative offsets than positive offsets. However, in luminance disparity conditions, WWS showed lower standard deviations for positive offsets. PCN and JJD had equal standard deviations for negative and positive offsets in luminance disparity conditions. Figure 43 shows a clear difference between contrast and luminance conditions for negative offsets while there is no difference for positive offsets. Finally, when contrast and luminance disparities are averaged, there are no differences between negative and positive offsets (Figure 44). Individual means, standard deviations, and max values can be seen in Tables 2 and 3.

Discussion

This experiment was designed to measure the dynamics of canceling perceived depth from a geometric disparity with perceived depth from a contrast or luminance disparity. It was predicted that luminance and contrast disparities would be processed at different rates from geometric disparities. This was predicted for two reasons. First, with a contrast disparity in the preliminary experiment, Laplace distributions fit to the data had lower means and lower standard deviations when stimuli were presented with negative offsets. Second, results from Dobias & Stine (in preparation) showed a large difference between
Table 2. Means, standard deviations, and max values of Laplace distributions for contrast conditions in Experiment One

<table>
<thead>
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<th>WWS</th>
<th>PCN</th>
</tr>
</thead>
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<td>$\mu$</td>
<td>119.00</td>
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<td></td>
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<tr>
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<tr>
<td>0.4 Hz</td>
<td>$\mu$</td>
<td>86.00</td>
<td>86.00</td>
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<td>$\sigma$</td>
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<td>0.90</td>
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<td>$\mu$</td>
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<td>0.95</td>
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<td>$\sigma$</td>
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<td>$\mu$</td>
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<td>$\sigma$</td>
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Table 3. Means, standard deviations, and max values of Laplace distributions for luminance conditions in Experiment One

<table>
<thead>
<tr>
<th>Subject</th>
<th>JJD</th>
<th>WWS</th>
<th>PCN</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Positive</strong></td>
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</tr>
<tr>
<td>0.2 Hz</td>
<td>μ</td>
<td>128.00</td>
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<td>max</td>
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<td>0.85</td>
</tr>
<tr>
<td>0.4 Hz</td>
<td>μ</td>
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<td>53.50</td>
</tr>
<tr>
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<td>σ</td>
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<td>μ</td>
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<td>0.95</td>
</tr>
<tr>
<td>0.8 Hz</td>
<td>μ</td>
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<td>70.50</td>
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<td>σ</td>
<td>44.97</td>
<td>26.02</td>
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<tr>
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<td></td>
</tr>
<tr>
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<td>μ</td>
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<td>-173.50</td>
</tr>
<tr>
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<td>σ</td>
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<td>0.30</td>
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<td>0.55</td>
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<tr>
<td>0.8 Hz</td>
<td>μ</td>
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<td>-144.50</td>
</tr>
<tr>
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<td>σ</td>
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<td>54.59</td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>0.90</td>
<td>0.65</td>
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processing speed for contrast vs geometric disparities. The observed difference in means and standard deviations for Laplace distributions in the preliminary experiment and in experiment one were thought to suggest a different processing speed for contrast, luminance, and geometric disparities. However, the large individual differences in this experiment makes it difficult to make overall comparisons. Subject PCN showed the same general results for both contrast and luminance disparity, but WWS and JJD showed opposite results for each cue. Further, as will be shown below, the prediction that results may show consistent differences between means for negative and positive offsets may have been inaccurate. For example, higher means and standard deviations for positive offsets in contrast conditions probably do not necessarily indicate a difference in dynamics.

To further explore the dynamics of cancellation for contrast, luminance, and geometric disparity cues, Appendix E shows two models that predict the probability of perceiving a "jump" when one cue cancels the other (Stine; personal communication)\textsuperscript{16}.

When one monitors square wave depth changes from a geometric, contrast, or luminance disparity, there are at least three changes that are likely to occur as the frequency of modulation approaches the frequency at which depth becomes no longer visible (critical frequency) for each type of disparity. (1) Because the next change occurs before the system can register the first change,

\footnote{The author of this dissertation developed some of the descriptions of the models in the appendix and all of the descriptions within the text but did not contribute to the development of either dynamic model.}
the sharp jumps in depth should begin to disappear and depth changes should appear similar to a sine wave modulation. In Fourier terms, as the frequency of the modulation approaches the critical frequency of the system, the harmonics will be above the critical frequency for the system and, so, a sharp depth change will not be visible. (2) With cues that have different dynamics (i.e. contrast/luminance vs geometric), when monitoring changes from the slower cue (contrast/luminance), the depth changes should begin to lag behind relative to changes that occur from the faster cue (geometric). (3) As described in # 1, because the next change occurs before the system can register the first change, the amplitude of perceived depth change should decrease and become zero as modulation frequencies reach the critical frequency for that disparity type.

The first model described in Appendix E (Generalized Difference Model) shows the probability of reporting depth by taking the difference in response to the contrast or luminance seen by each eye and by accounting for cases where the contrast/luminance is either equal to, much higher, or much lower than the contrast/luminance in the other eye. For example, if the contrast/luminance was equal, or if one eye received zero contrast or average luminance, no rotation would be perceived.

Using the probabilities for perceived rotation from the generalized difference model, figure 45 shows the probability of reporting a jump in experiment one as a function of delay between onset of contrast/luminance and geometric cues. The solid black line is the probability of perceiving a jump at a low frequency and the lines with progressively smaller dashes represent
Figure 45. Predicted probability of reporting a "jump" from the Generalized Difference Model for contrast and luminance conditions at a low frequency (solid black) and higher frequencies (progressively smaller dashes) as a function of offset in milliseconds between the onset of contrast/luminance and geometric disparities.
progressively higher frequencies. As can easily be seen, the probabilities do not resemble the observed data in either the preliminary experiment or in experiment one. Based on the simple model, one would expect that, because contrast/luminance modulations have lower critical frequencies, the perceived depth changes will lag behind perceived changes from geometric disparities (#2 above). As a result, longer delays will be necessary before contrast/luminance align with geometry to perfectly cancel, and the minimum probability of reporting a jump is expected to occur at delays above 200 ms when the critical frequency for geometric modulations is 5.5 Hz and for contrast or luminance modulations is 1.4 Hz.

The second model described in Appendix E (Gated Generalized Difference Model) was developed because predictions made by the generalized difference model fail to resemble observed data. The gated model again predicts the probability of reporting depth by taking the difference in response to the contrast or luminance seen by each eye and again accounts for cases where no depth is perceived but also multiplies the result by the perceived disparity at the edge of each bar. Multiplying by the perceived disparity at any given time avoids the loss of sharp depth changes described in #1 above, and allows for the perception of square wave depth changes. Using the probabilities for perceived rotation from the gated generalized difference model, figure 46 shows the probability of reporting a jump in experiment one as a function of delay between onset of contrast/luminance and geometric cues. As in figure 45, the solid
Figure 46. Predicted probability of reporting a “jump” from the Gated Generalized Difference Model for contrast and luminance conditions at a low frequency (solid black) and higher frequencies (progressively smaller dashes) as a function of offset in milliseconds between the onset of contrast/luminance and geometric disparities.
black line is the probability of perceiving a jump at a low frequency and the lines
with progressively smaller dashes represent progressively higher frequencies. At
the lowest frequency, the probability of reporting depth does resemble data from
the preliminary experiment and experiment one. Most importantly, as was shown
by the results of this experiment, the expected minimum probability of reporting a
jump was at zero delay. Also, as was found at some frequencies for some
subjects, the probability of reporting a jump decreases greatly at higher
frequencies.

It had been expected that, due to differences in dynamics, there would be
a difference between the means and standard deviations of Laplace distributions
for negative and positive offsets. This was expected to cause an asymmetry
between curves fit to probabilities of reporting a jump for negative and positive
offsets. Data for both the preliminary experiment and experiment one show this
asymmetry (opposite directions for contrast and luminance in experiment one for
JJD and WWS). Figure 46 also shows an asymmetry between positive and
negative offsets. However, as described in the gated model in Appendix E, when
one disparity is used to cancel another, an asymmetry may occur due to a
difference in the number of jumps that could be seen within a given trial for some
offsets. As a result, the observed asymmetries in the data (where large individual
differences are found) may be due to reasons other than a difference in
dynamics.

An interesting question is raised by the first model. The first model
suggests that, at frequencies close to the critical frequency, subjects should not
be able to discriminate a sine wave depth modulation from a square wave modulation. This inability to discriminate sine and square wave modulations would be due to prediction #1 above. At frequencies close to the critical frequency, square wave depth modulations should appear similar to a sine wave modulation. The second model, however, suggests that square wave depth modulations would retain the appearance of a sharp depth change. To measure this, Experiment Two described below asks subjects to report whether depth modulations appear to rotate slowly in a sine wave motion or pop back and forth in a square wave modulation.
CHAPTER IV

EXPERIMENT TWO:

DISCRIMINATING SINE VS SQUARE WAVE DEPTH MODULATIONS AT
FREQUENCIES NEAR THE CRITICAL FREQUENCY

Introduction

This experiment measured the ability of a subject to discriminate a sine wave depth modulation from a square wave depth modulation when those modulations were created using contrast or luminance disparities. Dobias & Stine tested both sine wave and square wave modulations of contrast disparity. Results and reports from subjects suggested that subjects were able to discriminate sine and square wave depth modulations at 1 Hz. Other experiments reported in this dissertation do not include a sine wave depth modulation, so this experiment will also attempt to replicate results from Dobias & Stine (in preparation) where results showed no difference between depth thresholds for sine wave and square wave depth modulations. The generalized difference model described above and in Appendix E would predict that subjects will not be able to discriminate sine and square wave depth modulations at frequencies close to the critical frequency. However, because the sharp depth changes remain visible, the gated generalized difference model would suggest that subjects will be able to discriminate sine vs square wave modulations. If so, results would support results from Dobias & Stine and the gated model.
Participants

Three subjects JJD, PCN (described above), and JRH completed this experiment. JRH was an experienced observer but was naive to specific experimental details and expected results. Subject JRH has myopia, which is corrected by glasses. Approval for this study was obtained by the Institutional Review Board of the University of New Hampshire, and each subject provided written informed consent for participation. A copy of the document showing that the institutional review board granted approval is shown in Appendix A.

Apparatus

Apparatus and basic stimuli were the same as in experiment 1. Each complete standard grating had a spatial frequency of 1.25 cycles per degree that was 1.6° in height and 2.8° in width. The gratings had an overall luminance of 29 cd/m², which is equal to the luminance of the background, and an overall contrast of 0.325. Above and below each grating, 0.03° nonius lines were placed to aid in the fusion of the two images.

Procedure

Procedures for experimental setup and individual experimental sessions were the same as in experiment 1. Each experimental session tested sine and square wave contrast modulations at six different frequencies and one amplitude value of 0.68 for both contrast only contrast disparities. Frequencies were 0.6, 0.8, 1.0, 1.2, 1.4, & 1.6 Hz. Subjects were asked to make one of three possible choices “motion-in-depth,” “depth with no motion,” or “no depth.” A choice of motion-in-depth indicates that subjects perceived smooth sine wave depth
modulations. However, a response of depth with no motion indicates the perception of square wave depth modulations. Experimental sessions consisted of 60 total trials. Each subject completed 4 sessions for a total of 20 choices at each frequency/type of modulation combination.

**Results**

The probability of reporting motion-in-depth and depth are shown in figure 47 for JRH, figure 48 for JJD, and figure 49 for PCN. Figures show the probability of reporting motion-in-depth with a sine wave (black, solid), motion-in-depth with a square wave (black, dashed), depth with a sine wave (gray, solid), and depth with a square wave (gray, dashed). For all three subjects, motion-in-depth was reported for sine wave modulations but not for square wave modulations. For JRH and JJD the probability of reporting depth fell below threshold at frequencies below 1.4 Hz. For PCN, however, the probability of reporting depth from square wave changes did not drop below 50% for the frequencies tested in this experiment. When compared, the results from experiments two and three show that, for PCN (figure 50), depth is visible at higher frequencies for square wave contrast modulations than it is for JJD and JRH. Individual means and standard deviations can be seen in table 5.

**Discussion**

As described above, the gated generalized difference model predicts that sine and square wave modulations would be discriminable at frequencies near the critical frequency for contrast modulations. Results showed that subjects reported smooth motion-in-depth with a sine wave modulation and sharp depth
Figure 47. Probability of reporting motion-in-depth with a sine wave (black, solid), motion-in-depth with a square wave (black, dashed), depth with a sine wave (gray, solid), and depth with a square wave (gray, dashed) for subject JRH.
Figure 48. Probability of reporting motion-in-depth with a sine wave (black, solid), motion-in-depth with a square wave (black, dashed), depth with a sine wave (gray, solid), and depth with a square wave (gray, dashed) for subject JJD.
Figure 49. Probability of reporting motion-in-depth with a sine wave (black, solid), motion-in-depth with a square wave (black, dashed), depth with a sine wave (gray, solid), and depth with a square wave (gray, dashed) for subject PCN.
Figure 50. Probability of reporting depth with a square wave contrast modulation in experiment two (gray) and experiment three follow-up G (black) for subject PCN.
Table 4. Means and standard deviations of Laplace distributions for responses of “motion-in-depth” and “depth” for sine and square wave modulations in experiment two

<table>
<thead>
<tr>
<th></th>
<th>JRH</th>
<th>JJD</th>
<th>PCN</th>
</tr>
</thead>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>μ</td>
<td>1.156</td>
<td>1.333</td>
<td>1.244</td>
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<td>σ</td>
<td>0.237</td>
<td>0.332</td>
<td>1.804</td>
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<tr>
<td><strong>Motion-in-Depth Square Wave</strong></td>
<td></td>
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<tr>
<td>μ</td>
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<tr>
<td><strong>Depth Sine Wave</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>μ</td>
<td>1.220</td>
<td>1.382</td>
<td>1.471</td>
</tr>
<tr>
<td>σ</td>
<td>0.285</td>
<td>0.333</td>
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<td><strong>Depth Square Wave</strong></td>
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<td>σ</td>
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<td>0.190</td>
<td>1.031</td>
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</table>
changes with square wave modulations. Further, results replicated experiments 1 and 3 from Dobias & Stine where the probability of reporting depth diminished for both sine and square wave modulations at frequencies below 1.4 Hz. It is clear that subjects are able to discriminate sine and square wave modulations close to the critical frequency as predicted by the gated model.
CHAPTER V
EXPERIMENT THREE:
OCULAR DIFFERENCES IN THE DYNAMICS OF PERCEIVED DEPTH FROM CONTRAST AND LUMINANCE DISPARITIES

Introduction

Dobias & Stine (in preparation) showed that there is a clear difference in processing time for perceived depth from a contrast and a geometric disparity. Hetley & Stine (accepted pending revision) showed that an observer’s response can vary depending on which eye received the grating with higher contrast or luminance. Two observers showed stronger input from one eye for perceived rotation and stronger input from the other eye for perceived brightness and contrast (opposite eyes for each observer). A third observer showed dominance for perceived intensity and rotation in the same eye. The results from Hetley & Stine suggest that, because individual differences reveal dominance of one eye for one type of perception (perceived contrast/brightness), and dominance of the other eye for the other perception (perceived rotation), each perception relies on separate neural mechanisms.

Individual differences can be used in this way to demonstrate the existence of separate mechanisms for specific perceptions (Underwood, 1975; Kosslyn, et al., 2002; Wilmer, 2008; Nefs, O’Hare, & Harris, 2010). As described by Nefs, et al. (2010), “if distinct mechanisms exist for processing stimuli along some dimension, they should be revealed by separable patterns of sensitivity
across a population of observers: some visual systems will display better sensitivity for one mechanism than another” (Nefs, et al., 2010, pp. 1-2). The perception of motion-in-depth is typically understood to result from monitoring changing geometric disparity over time and/or interocular velocity disparities. Monitoring changing geometric disparity consists of monitoring the rate at which a given binocular disparity changes over time. Monitoring interocular velocity disparities involves monitoring the the difference in motion between the two retinal images (Nefs, et al., 2010). In an attempt to show evidence for separate mechanisms underlying the perception of motion-in-depth from changing geometric disparities and velocity disparities, Nefs et al. measured thresholds for detection of motion-in-depth when subjects viewed stimuli containing both changing geometric disparities and velocity disparities, just changing geometric disparities, or just velocity disparities. Results showed that, even though changing geometric disparities is the primary cue used when detecting motion-in-depth, some subjects who had high thresholds for one type of stimulus (just changing geometric disparities or just velocity disparities) had low thresholds for the other type.

To determine how individual differences influence the probability of reporting depth when only one eye views a dynamic stimulus, Experiment 3 dynamically altered contrast and luminance disparities (Dobias & Stine did not present a luminance disparity) in one eye while the grating viewed by the other eye remained constant. The experiment attempted to determine the speed at which the visual system processes depth with contrast/luminance disparities and
the role played by ocular dominance that was found by Hetley & Stine (accepted pending revision), where results showed that perception of depth with a contrast or luminance disparity was influenced by which eye received the varying intensity grating. Dobias & Stine tested both sine wave and square wave modulations of contrast disparity. Results showed no difference between depth thresholds for sine wave and square wave modulations. Therefore, experiment three only tested square wave modulations.

The goal of experiment three and experiment four that follows, however, was not to answer questions about ocular dominance but was to possibly reveal the existence of different neural mechanisms (channels) that feed into a common mechanism for perceived depth from contrast, luminance, and geometric disparities.

**Participants**

Participants were PCN, JJD, and WWS. WWS and JJD were experienced observers. PCN was naive to specific experimental details and expected results. All subjects had normal or corrected vision and normal stereopsis. Approval for this study was obtained by the Institutional Review Board of the University of New Hampshire, and each subject provided written informed consent for participation. A copy of the document showing institutional review board approval is shown in Appendix A.

**Apparatus**

The apparatus was the same as in experiments one and two. Stimuli were constructed in the same way as stimuli in Dobias & Stine (in preparation).
Each complete standard grating had a spatial frequency of 1.25 cycles per degree that was 1.6° in height and 2.8° in width. The gratings had an overall luminance of 29 cd/m², which was equal to the luminance of the background, and an overall contrast of 0.325. Above and below each grating, 0.03° nonius lines were placed to aid in the fusion of the two images.

**Procedure**

Procedures for experimental setup and individual experimental sessions were the same as in experiments one and two. Each experimental session tested intensity modulations at six different frequencies and one amplitude value of 0.68 for both contrast and luminance changes that occur in only one eye while constant in the other (Figures 51 & 52). Frequencies were 0.8, 1.0, 1.2, 1.4, 1.6, & 1.8, and each were tested for contrast and luminance changes in both the left and right eye. Experimental sessions consisted of 72 total trials. Each subject completed 7 sessions for a total of 21 choices at each frequency/intensity/eye combination.

**Results**

It was expected that results for contrast and luminance modulation would replicate the results for contrast that was found in experiments 1 and 3 of Dobias & Stine (in preparation; figures 12-19) where the perception of depth decreased when above approximately 1 Hz, and was completely diminished before 1.8 Hz. Also, based on data from Hetley & Stine (accepted pending revision) it was expected that ocular dominance may cause perceived depth to diminish more quickly when contrast or luminance is varied in only one eye, but that individual
Figure 51. Examples of contrast disparity stimuli for experiment three. Gratings show higher contrast on the left while the grating on the right remains at the standard 32.5% contrast and 29 cd/m² average luminance (top) and lower contrast on the left while the grating on the right remains at the standard levels (bottom)
Figure 52. Examples of luminance disparity stimuli for experiment three. Gratings show higher average luminance on the left while the grating on the right remains at the standard 32.5% contrast and 29 cd/m² average luminance (top) and lower average luminance on the left while the grating on the right remains at the standard levels (bottom).
differences may lead the dominant eye to vary between subjects. The probability of reporting depth can be seen for each subject in figures 53 to 55. Frequency of modulation is plotted on the x-axis and probability of reporting a jump is plotted on the y-axis. Mathematica was used to find a best fitting line for each modulation type with a Laplace distribution. For all subjects the probability of reporting depth diminishes at frequencies below 1.5 Hz. For subject PCN (Figures 55 and 58), the probability of reporting depth was zero for both the left and right eye (explored further below). Figures 56 to 58 show the means and standard deviations of each Laplace distribution for each subject. For subject JJD, perceived depth from contrast and luminance disparity diminished at frequencies below 1.5 Hz but contrast and luminance disparity had different values in the left eye than in the right eye. For subject WWS there were no differences between the left and right eye for either contrast or luminance. However, contrast and luminance did have different standard deviation values in the right eye. For subject PCN, standard deviations were higher when contrast modulations were viewed by the right eye. Individual means and standard deviations can be seen in Table 5 on page 137.

**Discussion**

Dobias & Stine (in preparation) found that perceived depth from a contrast disparity diminished at frequencies below 1.5 Hz. Experiment three replicated those results and extended them to conditions with a luminance disparity. It was expected that perceived depth from contrast and luminance would diminish at roughly the same frequency but that individual differences in ocular dominance
Figure 53. Probability of reporting depth for contrast (dashed), luminance (solid), left (gray), and right (black) for subject JJD.
Figure 54. Probability of reporting depth for contrast (dashed), luminance (solid), left (gray), and right (black) for subject WWS.

Probability of Reporting Depth
Figure 55. Probability of reporting depth for contrast (dashed), luminance (solid), left (gray), and right (black) for subject PCN.
Figure 56. Means (top) and standard deviations (bottom) for contrast (solid) and luminance (dashed) conditions for subject JJD.
Figure 57. Means (top) and standard deviations (bottom) for contrast (solid) and luminance (dashed) conditions for subject WWS.
Figure 58. Means (top) and standard deviations (bottom) for contrast conditions for subject PCN (subject did not report depth in luminance conditions).
may influence the results. Results from JJD showed that perceived depth from contrast disparities was visible at higher frequencies in the left eye than in the right, and that depth from luminance disparities was visible at higher frequencies in the right eye than in the left. However, results from WWS did not show differences in critical frequency between contrast and luminance for the left or right eye. Finally, results from subject PCN, as described above, suggest that there are no differences between the left and right eye for contrast disparities but that depth is not visible for luminance disparities when changes only occur in only the left or right eye. To determine why PCN did not report depth in luminance conditions, follow-up experiments A-F explore luminance data for subject PCN and follow-up experiment G measures the frequency at which perceived depth from a luminance disparity is no longer visible when stimuli change in both eyes.

As described above, individual differences can indicate that a perception results from activity in separate neural mechanisms. Results from subject JJD suggest that contrast and luminance may rely on separate neural mechanisms. However, results from WWS do not show any differences. The results from experiment three will be compared to those in experiment four to compare the overall frequency at which depth is visible for each type of cue, and to determine any individual differences in response to contrast, luminance, and geometric disparity.
Experiment Three: Follow-Up A

Introduction

Since subject PCN did not report depth with a luminance disparity in experiment three, control experiments were conducted to determine a cause. In experiment one, PCN reported jumps in luminance conditions indicating that the subject is able to perceive depth from a luminance disparity. Stimuli from experiment one, however, had higher amplitude changes than in experiment three. For experiment one, luminance levels increased in one eye while decreasing in the other eye. However, for experiment three, the luminance only increased and decreased in one eye. This modulation in only one eye made the difference between the left and right images half of the amplitude in experiment one. To explore the influence of amplitude for PCN, a short experiment was conducted using both higher and lower amplitude values of 0.9 and 0.5.

Participants

One subject PCN (described above) completed this experiment. Approval for this study was obtained by the Institutional Review Board of the University of New Hampshire, and PCN provided written informed consent for participation. A copy of the document showing institutional review board approval is shown in Appendix A.

Apparatus

Apparatus and basic stimuli were the same as in experiment three.
Procedure

Basic procedures were the same as in experiment three. Stimuli were constructed with amplitude values of either 0.5 or 0.9 and were modulated in either the left or the right eye at frequencies of 0.8, 1.0, 1.2, 1.4, 1.6, and 1.8 Hz. PCN completed two sessions of 72 trials each. A total of 6 choices were made at each frequency/eye/amplitude combination.

Results

Figure 59 shows the probability of reporting depth as a function of amplitude and frequency for PCN when luminance was increased in only the left eye (Gray) or the right eye (Black) no cases were above chance.

Discussion

Again, PCN did not report depth from luminance disparities (Figure 55) suggesting that lack of depth with luminance is not due to amplitude. However, with an amplitude of 0.5 in the right eye, the probability at 1.2 and 1.4 Hz did increase above other conditions suggesting that if amplitude was lower, PCN might report depth. The increase in probability of reporting depth with lower amplitude suggests that higher amplitude stimuli may lead the high or low luminance image to suppress the standard image, causing PCN to not perceive depth. Follow-up experiment three B explored this further by decreasing the amplitude to determine whether the probability of reporting depth would increase.
Figure 59. Probability of reporting depth in follow-up experiment A for left (gray), and right (black) for subject PCN at amplitudes of 0.5 and 0.9.
Experiment Three: Follow-Up B

Introduction

Because the probability of reporting depth increased with lower amplitude (0.5) stimuli in follow-up experiment A, it is possible that, with high amplitude stimuli, one stimulus may suppress the other. This possibility seems unlikely, however, since PCN did report depth in experiment 1 where the difference between the left and right image was much greater. This follow up experiment used an amplitude value of 0.4 to determine whether or not a lower amplitude would increase the probability of reporting depth for PCN.

Participants

One subject PCN (described above) completed this experiment. Approval for this study was obtained by the Institutional Review Board of the University of New Hampshire, and PCN provided written informed consent for participation. A copy of the document showing institutional review board approval is shown in Appendix A.

Apparatus

Apparatus and basic stimuli were the same as in experiment three.

Procedure

Basic procedures were the same as in experiment three. Stimuli were constructed with only one amplitude value of 0.4 and were modulated in either the left or the right eye at frequencies of 0.8, 1.0, 1.2, 1.4, 1.6, and 1.8 Hz. PCN completed one session with a total of 72 trials. A total of 6 choices were made at each frequency/eye combination.
Results

Figure 60 shows the probability of reporting depth at each frequency for the left (gray) and right (black) eyes. PCN did not report depth in any condition.

Discussion

Follow-up experiment A found that PCN did not perceive depth at high (0.9) and low (0.5) amplitude stimuli but that the probability increased at two frequencies in the right eye for 0.5 amplitude stimuli. When the amplitude was decreased to 0.4, this experiment again found that PCN did not report depth when luminance was changed in only one eye. As described above, if lower amplitude had increased the probability of reporting depth, results would have contradicted those from experiment one. Because follow-up experiments A & B show that PCN’s results are not due to amplitude, follow-up experiment C decreased the frequency of luminance disparity changes.
Figure 60. Probability of reporting depth in follow-up experiment B for left (gray), and right (black) for subject PCN an amplitude of 0.4.
Experiment Three: Follow-Up C

Introduction

PCN is able to report the direction of rotation when a stimulus with luminance disparity does not dynamically change. Therefore, it is possible that, for PCN, the perception of depth from luminance disparities diminishes at much lower frequencies. This experiment decreases the frequencies at which luminance disparity cues are altered in either the left or right eye. If PCN only perceives luminance disparity changes at low frequencies, PCN should report depth.

Participants

One subject PCN (described above) completed this experiment. Approval for this study was obtained by the Institutional Review Board of the University of New Hampshire, and PCN provided written informed consent for participation. A copy of the document showing institutional review board approval is shown in Appendix A.

Apparatus

Apparatus and basic stimuli were the same as in experiment three.

Procedure

Basic procedures were the same as in experiment three. Stimuli were constructed with only one amplitude value of 0.68 and were modulated in either the left or the right eye at frequencies of 0.2, 0.4, 0.6, and 0.8 Hz. PCN completed one session with a total of 80 trials. A total of 10 choices were made at each frequency/eye combination.
Results

Figure 61 shows the probability of reporting depth for PCN. PCN did not report depth at any frequency.

Discussion

Follow-up experiments A & B found that increasing or decreasing amplitude does not increase the probability of reporting depth. Similarly, follow-up experiment C shows that decreasing the frequency of depth changes does not increase the probability of reporting depth. Follow-up experiment D explored the possibility that, for PCN, luminance changes must occur in both eyes. Remember, experiment three, and follow-up experiments A-C only changed luminance in the left or right eye while the other eye remained constant.
Figure 61. Probability of reporting depth in follow-up experiment C for left (gray), and right (black) for subject PCN an amplitude of 0.68 at lower frequencies than in experiment three.
Experiment Three: Follow-Up D

**Introduction**

In experiment one, PCN did report jumps with a luminance disparity. However, when luminance changes occur in only one eye in experiment three and the follow-up experiments described above, PCN did not report depth from a luminance disparity. This follow-up experiment and the two follow-up experiments after, explored the possibility that PCN does not register dynamic changes in average luminance disparities when the changes occur in only one eye. This experiment used both contrast and luminance disparities but stimuli either did not change or were modulated at a frequency of 0.4 Hz. Based on previous results, it was expected that PCN would report depth both when contrast did and did not dynamically change, but would only report depth when luminance disparities did not dynamically change.

**Participants**

One subject PCN (described above) completed this experiment. Approval for this study was obtained by the Institutional Review Board of the University of New Hampshire, and PCN provided written informed consent for participation. A copy of the document showing institutional review board approval is shown in Appendix A.

**Apparatus**

Apparatus and basic stimuli were the same as in experiment three.
Procedure

Basic procedures were the same as in experiment three. Stimuli were constructed with contrast and luminance disparities with amplitude values of 0.68. Again, stimuli changed in only one eye but changed at 0.4 Hz or were stationary. Two sessions of 80 trials were completed for a total of 20 choices at each eye/frequency/disparity combination.

Results

Figure 62 shows that when changed in only one eye, PCN reported depth from contrast disparities when stimuli were either stationary or were modulated at 0.4 Hz but only perceived depth from luminance disparities when stimuli did not dynamically change.

Discussion

As expected, PCN reported depth from contrast disparities when stimuli dynamically changed in only one eye but did not perceive depth when luminance dynamically changed. As described above, it is possible that PCN does not perceive depth from luminance disparities when dynamic changes only occur in one eye. To test this possibility, follow-up experiment E changed contrast and luminance in both eyes.
Figure 62. Probability of reporting depth in follow-up experiment D for contrast (gray) and luminance (black) at modulations that did not change or were modulated at and 0.4 Hz in the left (dashed) or right (solid) eye.
Experiment Three: Follow-Up E

Introduction

Results from experiment one showed that PCN did report jumps with a luminance disparity. However, in experiment three and all of the follow-up experiments described above, PCN did not report depth when luminance disparity changed in only one eye. In this experiment, contrast and luminance disparity were modulated at the same amplitude values and frequencies as follow-up experiment D except intensity changes occurred in both eyes. Based on results from experiment one, it was predicted that PCN will report depth in all conditions.

Participants

One subject PCN (described above) completed this experiment. Approval for this study was obtained by the Institutional Review Board of the University of New Hampshire, and PCN provided written informed consent for participation. A copy of the document showing institutional review board approval is shown in Appendix A.

Apparatus

Apparatus and basic stimuli were the same as in experiment three.

Procedure

Basic procedures were the same as in experiment three. Stimuli were constructed with contrast and luminance disparities with amplitude values of 0.68. Stimuli were modulated in both eyes in the same way as experiment one in which contrast or luminance increased in one eye while decreasing in the other.
Stimuli either did not change or changed at 0.4 Hz. PCN completed one session with a total of 80 trials. A total of 20 choices were made at each frequency/disparity combination.

**Results**

Figure 63 shows that when changed in both eyes, PCN reports depth from both contrast and luminance disparities when stimuli do not dynamically change and when stimuli are modulated at 0.4 Hz. However, the probability of reporting depth from a luminance disparity was slightly lower than from a contrast disparity.

**Discussion**

Results suggest that PCN does report depth from a luminance disparity when cues dynamically change, but only when the changes occur in both eyes. However, when stimuli changed in both eyes, the disparity between the image in the left and right eye was twice what it was when stimuli were only changed in one eye. As a result, perceived depth in this experiment may only be a result of the higher disparity stimuli. Follow-up experiment F presented stimuli in the same way as this experiment except luminance and contrast changes occurred at half the amplitude.
Figure 63. Probability of reporting depth in follow-up experiment E for contrast (gray) and luminance (black) at modulations that did not change or were modulated at and 0.4 Hz in both eyes at a modulation amplitude of 0.68.
Experiment Three: Follow-Up F

**Introduction**

Because the amplitudes were greater when changed in both eyes than when changed in one eye, it is possible that, results from follow-up experiment E are only a result of larger luminance disparities. If so, and if amplitude of luminance modulations are cut in half to match the disparity in experiment three, PCN should no longer perceive depth changes at 0.4 Hz. This would indicate that PCN’s failure to report depth is due to amplitude and not due to a lack of change in both eyes.

**Participants**

One subject PCN (described above) completed this experiment. Approval for this study was obtained by the Institutional Review Board of the University of New Hampshire, and PCN provided written informed consent for participation. A copy of the document showing institutional review board approval is shown in Appendix A.

**Apparatus**

Apparatus and basic stimuli were the same as in experiment three.

**Procedure**

Basic procedures were the same as in experiment three. Stimuli were constructed with contrast and luminance disparities with amplitude values of 0.34. Stimuli were modulated in both eyes in the same way as experiment one in which contrast or luminance increased in one eye while decreasing in the other. Stimuli either did not change or changed at 0.4 Hz. PCN completed one session
with a total of 80 trials. A total of 20 choices were made at each frequency/disparity combination.

**Results**

Figure 64 shows that, when luminance changes occurred in both eyes, PCN did not report depth at an amplitude of 0.4.

**Discussion**

Follow-up experiment A increased the amplitude to 0.9 in one condition but did not increase PCN's probability of reporting depth. However, the increase was restricted due to the luminance values that could be generated by the monitor. Therefore, the difference between the left and right eye in follow-up experiment A was smaller than when an amplitude of 0.68 changed in both eyes (follow-up experiment E). The results of this experiment suggest that, for PCN, a large luminance disparity is needed to perceive depth changes. Follow-up experiment G used stimuli that changed in both eyes to measure the dynamics of perceived depth from contrast and luminance for PCN.
Figure 64. Probability of reporting depth in follow-up experiment F for contrast (gray) and luminance (black) at modulations that did not change or were modulated at and 0.4 Hz in both eyes at a modulation amplitude of 0.34.
Experiment Three: Follow-Up G

**Introduction**

Based on the results of the follow-up experiments described above, PCN does report depth with a luminance disparity when changes occur at higher amplitudes and in both eyes. Therefore, to measure the actual frequency at which PCN is no longer able to perceive depth changes, this experiment will modulate contrast and luminance disparities in both eyes at the frequencies similar to those used in experiment three. Based on previous data for PCN, it was expected that perceived depth from contrast disparities would diminish at frequencies near 1.5 Hz. Based on results from WWS and JJD, it was expected that PCN would show similar critical frequencies for both contrast and luminance disparities.

**Participants**

One subject PCN (described above) completed this experiment. Approval for this study was obtained by the Institutional Review Board of the University of New Hampshire, and PCN provided written informed consent for participation. A copy of the document showing institutional review board approval is shown in Appendix A.

**Apparatus**

Apparatus and basic stimuli were the same as in experiment three.

**Procedure**

Basic procedures were the same as in experiment three. Stimuli were constructed with contrast and luminance disparities with amplitude values of
0.68. Stimuli were modulated in both eyes in the same way as experiment one in which contrast or luminance increased in one eye while decreasing in the other. Contrast and luminance disparities were modulated at frequencies of 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, and 2.0 Hz. PCN completed three sessions with a total of 84 trials per session. A total of 18 choices were made at each frequency/disparity combination.

**Results**

Results in figure 65 show that, for PCN, the probability of reporting depth diminishes at frequencies below 1.7 Hz for contrast disparities, and below 1.4 Hz for luminance disparities.

**Discussion**

The results for this follow-up experiment when contrast was changed in both eyes, are similar to those for PCN in experiment three when contrast was changed in only one eye. In experiment three, PCN did not report depth from luminance disparities. Follow-up experiments A-F suggest that, to perceive depth from a luminance disparity, PCN requires larger luminance differences between the images seen by the left and right eye. Therefore, when there is a larger difference between the image seen by each eye, the results of follow-up experiment E and this experiment show that PCN does report depth from luminance disparities. Further, as was found for JJD and WWS in experiments 3 and 4, the critical frequencies for perceived depth from contrast or luminance disparities for PCN are far below the critical frequencies for a geometric disparity. The difference that exists between contrast and luminance disparities, however,
Figure 65. Probability of reporting depth for contrast (gray) and luminance (black) for subject PCN when contrast and luminance change in both eyes.
does not necessarily reveal a difference in processing speed for contrast and luminance disparities. Rather, it may reflect a mismatch for PCN in the amount of depth caused by luminance and contrast, where a larger luminance may be necessary to perceive depth than for a similar amplitude contrast disparity.
CHAPTER VI

EXPERIMENT FOUR:

OCULAR DIFFERENCES IN THE DYNAMICS OF PERCEIVED DEPTH FROM A GEOMETRIC DISPARITY

Introduction

Experiment four attempted to replicate the results from Dobias & Stine that geometric disparities are visible up to 5 Hz but, as in experiment three, only changed the width of stimuli in one eye to determine whether ocular dominance also plays a role in geometric disparities and if the dominant eye is the same as for luminance or contrast disparities. Results are compared to ocular dominance results from experiment three.

Participants

Participants were PCN, JJD, and WWS. WWS and JJD were experienced observers. PCN was naive to specific experimental details and expected results. All subjects had normal or corrected vision and normal stereopsis. Approval for this study was obtained by the Institutional Review Board of the University of New Hampshire, and each subject provided written informed consent for participation. A copy of the document showing that the institutional review board granted approval is shown in Appendix A.

Apparatus

Apparatus was the same as in experiments 1-3. Stimuli were the same as in previous experiments. Each complete standard grating had a spatial
frequency of 1.25 cycles per degree that was 1.6° in height and 2.8° in width. The gratings had an overall luminance of 29 cd/m², which is equal to the luminance of the background, and an overall contrast of 0.325. Above and below each grating, 0.03° nonius lines were placed to aid in the fusion of the two images.

**Procedure**

Procedures for experimental setup and individual experimental sessions were the same as in experiments 1-3. The experiment attempted to determine the speed at which the visual system processes depth with contrast and luminance disparities and attempted to determine the role of ocular dominance when a geometric change occurs in only one eye. A sample stimulus can be seen at the bottom of figure 20. Stimuli dynamically widened/narrowed the light bars in the grating seen by one eye while the grating seen by the other eye remained constant.¹⁷ For two subjects, eighteen frequencies were used between 1.6 to 5.0 Hz in steps of 0.2 (1.6, 1.8, 2.0, etc.). Each experimental session consisted of two choices at each of the 18 frequencies when gratings change in the left eye and two choices when gratings change in the right eye for a total of 72 trials. PCN and JJD completed 10 sessions for a total of 20 choices at each frequency/eye combination. For WWS, only eight frequencies (2.0, 3.0, 4.0, 4.2, 4.4, 4.6, 4.8, 5.0) were used.

---

¹⁷ A comparable physical stimulus would be a surface rotated in depth towards or away from the observer. Further, as physical rotations occur, width would change to maintain the size of the image on one retina while making it smaller or larger on the other retina. The stimulus just described is unlikely to occur in everyday viewing conditions.
4.4, 4.6, 4.8, & 5.0) were used within 4 experimental sessions consisting of 80 trials each for a total of 20 choices at frequency/eye combination.

**Results**

It was expected that subjects would report depth at frequencies up to 5 Hz in replication of experiment three in Dobias & Stine (in preparation), however, it was unknown whether ocular dominance would cause depth to diminish at different rates when changes occur in the left vs right eye. Probability of reporting depth can be seen in Figure 66 for JJD, in Figure 67 for WWS, and Figure 68 for PCN. Frequency of modulation is plotted on the x-axis and probability of reporting a jump is plotted on the y-axis. *Mathematica* was used to find a best fitting line for each modulation type with a Laplace distribution. For all subjects the probability of reporting depth diminishes at frequencies above 4.5 Hz, which is much higher than the frequencies at which depth diminished for contrast and luminance disparities in experiment three. The means and standard deviations for the Laplace distributions for geometric disparities are plotted in figures 69 to 71 along with the means and standard deviations from experiment three. All subjects show no difference between the left and right eye for geometric disparity. For subject WWS the probability of reporting depth did not cross fifty percent so the means for the Laplace distribution are only estimates. To determine the exact frequency at which depth is no longer visible for WWS, a follow-up experiment was conducted where frequencies were between 5 and 6 Hz (5.0, 5.2, 5.4, 5.6, 5.8 and 6.0 Hz). Individual means and standard deviations can be seen in Table 5 on page 137.
Figure 66. Probability of reporting depth for geometric disparity conditions in left (gray), and right (black) for subject JJD.
Figure 67. Probability of reporting depth for geometric disparity conditions in left (gray), and right (black) for subject WWS.
Figure 68. Probability of reporting depth for geometric disparity conditions in left (gray), and right (black) for subject PCN.
Figure 69. Means (top) and standard deviations (bottom) for geometric disparity (gray dashed) conditions compared to contrast (black solid) and luminance (black dashed) conditions in experiment three for subject JJD.
Figure 70. Means (top) and standard deviations (bottom) for geometric disparity (gray dashed) conditions compared to contrast (black solid) and luminance (black dashed) conditions in experiment three for subject WWS.
Figure 71. Means (top) and standard deviations (bottom) for geometric disparity (gray dashed) conditions compared to contrast (black solid) in experiment three for subject PCN (subject did not report depth for luminance conditions in experiment three).
Table 5. Means and standard deviations of Laplace distributions in Experiments Three and Four

<table>
<thead>
<tr>
<th>Subject</th>
<th>JJD</th>
<th>WWS</th>
<th>PCN</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Contrast</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>μ</td>
<td>1.38</td>
<td>1.33</td>
</tr>
<tr>
<td></td>
<td>σ</td>
<td>0.16</td>
<td>0.27</td>
</tr>
<tr>
<td>Right</td>
<td>μ</td>
<td>1.26</td>
<td>1.39</td>
</tr>
<tr>
<td></td>
<td>σ</td>
<td>0.26</td>
<td>0.25</td>
</tr>
<tr>
<td><strong>Luminance</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>μ</td>
<td>1.02</td>
<td>1.38</td>
</tr>
<tr>
<td></td>
<td>σ</td>
<td>0.35</td>
<td>0.38</td>
</tr>
<tr>
<td>Right</td>
<td>μ</td>
<td>1.31</td>
<td>1.46</td>
</tr>
<tr>
<td></td>
<td>σ</td>
<td>0.24</td>
<td>0.55</td>
</tr>
<tr>
<td><strong>Geometric</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>μ</td>
<td>4.96</td>
<td>6.01**</td>
</tr>
<tr>
<td></td>
<td>σ</td>
<td>0.85</td>
<td>.01**</td>
</tr>
<tr>
<td>Right</td>
<td>μ</td>
<td>5.06</td>
<td>5.60**</td>
</tr>
<tr>
<td></td>
<td>σ</td>
<td>1.10</td>
<td>.44**</td>
</tr>
</tbody>
</table>

* From Experiment Three Follow-Up G
** From the Experiment Four Follow-Up Experiment
Discussion

Results from experiment four replicated the results from Dobias & Stine (in preparation) that depth from geometric disparities was visible at much higher frequencies than from contrast disparities. It had been predicted that ocular dominance may influence the frequency at which depth was visible when geometric disparities were only altered in one eye. Results, however, did not show a difference. Therefore, when compared to contrast and luminance results from JJD in experiment three where contrast and luminance were visible at higher frequencies in the opposite eye, results suggest that each perception may be controlled by separate neural mechanisms. This possibility will be discussed further in the follow-up experiment described below and in the Overall Discussion.
Experiment Four: Follow-Up

**Introduction**

For subject WWS the probability of reporting depth did not fall below fifty percent. To determine the exact frequency at which depth is no longer visible for WWS, a follow-up experiment was conducted where frequencies ranged between 5 and 6 Hz.

**Participants**

One subject WWS (described above) completed this experiment. Approval for this study was obtained by the Institutional Review Board of the University of New Hampshire, and WWS provided written informed consent for participation. A copy of the document showing institutional review board approval is shown in Appendix A.

**Apparatus**

Apparatus and basic stimuli were the same as in experiment four.

**Procedure**

Basic procedures were the same as in experiment four. Stimuli were constructed with geometric disparities modulated in the left and right eye in the same way as experiment four. Geometric disparities were modulated at frequencies of 5.0, 5.2, 5.4, 5.6, 5.8, & 6.0 Hz. WWS completed three sessions with a total of 84 trials per session. A total of 21 choices were made at each frequency/eye combination.
Results

Figure 72 shows a large difference between critical frequencies for the left and right eye. The mean of the Laplace distribution for the right eye is 5.61 but depth is still perceived at 6 Hz by the left eye.

Discussion

This follow-up experiment was conducted to determine the frequency at which depth changes from a geometric disparity are no longer visible for subject WWS and whether or not there is a difference in critical frequency between the two eyes. As described above, Hetley & Stine found that the amount of contrast or luminance disparity needed to cancel a geometric disparity differed depending on which eye viewed the higher intensity image. In experiment 4, subjects JJD and PCN showed no difference between the left and right eye. This follow-up experiment shows that WWS perceives geometric disparity changes at higher frequencies than JJD and PCN, and that depth decreases at lower frequencies when the changes occur in the right eye than when changes occur in the left eye. These findings will be discussed further in the Overall Discussion.
Figure 72. Probability of reporting depth for geometric disparities for the left (gray) and right (black) eyes for subject WWS.
CHAPTER VII

EXPERIMENT FIVE:

THE ROLE OF EYE MOVEMENTS AND MASKING DURING DYNAMIC MODULATION OF CONTRAST AND LUMINANCE DISPARITIES

Introduction

Previous work described above (Weiler et al., 2007) shows that perceived location of a binocularly viewed stimulus with a contrast disparity perceptually shifts towards the higher contrast image. Also, when an eye movement is induced by shifting image location, the amplitude of the saccade can be biased towards the higher contrast image. However, as described above, the results from Weiler et al. do not indicate whether a rapid shift in contrast disparity without an actual location shift will cause an eye movement.

Dobias & Stine (in preparation) and experiments 3 and 4 described above found that perceived depth from contrast and luminance disparity decreases at lower frequencies than perceived depth from a geometric disparity. Therefore, it is possible that, at higher frequencies, shifts in contrast or luminance may cause an eye movement which may cause subjects to not perceive depth changes due to saccadic suppression. However, as described previously, it seems unlikely that decreases in perceived depth are due to eye movements because the critical frequencies were between approximately 1.0 and 1.5 Hz (667-1000 ms per cycle). These frequencies are below those that would be influenced by saccadic suppression.
Alternatively, some form of masking may influence the perception of depth to cause lower critical frequencies for depth modulations from contrast and luminance disparities. Masking seems unlikely, however, for the same reasons as eye movements. Critical frequencies found by Dobias & Stine and experiments 2 & 3 were between approximately 1.0 and 1.5 Hz (667-1000 ms per cycle). Masking occurs at much lower offsets between the target and mask (<100 ms) (Breitmeyer, Ro, & Ogmen, 2004; Breitmeyer, 2007). Further, the fact that results in the preliminary experiment and experiment one show the perception of a jump from cancellation at very low offsets, suggests that lower critical frequencies found by Dobias & Stine and experiments 2 & 3 are not from masking caused by rapid shifts in contrast and luminance.

Despite the unlikely role of masking, eye movements, or some other factor, this experiment used both types of cues simultaneously or alone to determine the frequency at which depth was no longer perceived. If rapid shifts in contrast/luminance either visually mask the geometric change or cause an eye movement towards the higher contrast/luminance image, when contrast and luminance disparities are oscillated either alone or simultaneously with a geometric disparity, perceived depth should decrease in all conditions at higher frequencies. However, if shifts do not cause eye movements or masking at higher frequencies, depth should only be perceived when geometric disparities are simultaneously present with contrast or luminance disparities.
Participants

Participants were JJD, WWS, and PCN. Approval for this study was obtained by the Institutional Review Board of the University of New Hampshire, and each subject provided written informed consent for participation. A copy of the document showing that the institutional review board granted approval is shown in Appendix A.

Apparatus

Apparatus was the same as in experiments 1-3. Stimuli were the same as in previous experiments. Each complete standard grating had a spatial frequency of 1.25 cycles per degree that was 1.6° in height and 2.8° in width. The gratings had an overall luminance of 29 cd/m\(^2\), which is equal to the luminance of the background, and an overall contrast of 0.325. Above and below each grating, 0.03° nonius lines were placed to aid in the fusion of the two images.

Procedure

Procedures for experimental setup and individual experimental sessions were the same as in experiments described above. Each experimental session tested contrast and luminance modulations at three different frequencies (0.8, 1.6, and 2.4 Hz) and one amplitude value of 0.68. Stimuli contained either a contrast or luminance disparity alone or contained both contrast and geometric or luminance and geometric. For the combined conditions, both types of cues (contrast/luminance or geometric) caused a rotation the same direction. Subjects were asked to make one of two possible choices “depth” or “no depth.”
Experimental sessions consisted of 84 total trials. Each subject completed 3 sessions for a total of 21 choices at each frequency/type of modulation combination.

**Results**

The probability of reporting depth when contrast and luminance disparities were either modulated alone simultaneously with a geometric disparity is shown in figure 73 for JJD, figure 74 for WWS, and figure 75 for PCN. When contrast (gray solid) and luminance (black solid) were modulated with a geometric disparity, JJD and PCN reported depth at all frequencies but only reported depth at the lowest frequency when contrast (gray dashed) and luminance (black dashed) were modulated alone. WWS showed similar results for luminance modulations but showed a decrease in probability at higher frequencies for both types of contrast modulation. For WWS, the probability of reporting depth in the combined condition was slightly greater than the contrast alone condition but the probability was below threshold.

**Discussion**

To test the possibility that eye movements or masking causes the decrease in perceived depth at high frequency modulations of the Venetian blind effect, this experiment used stimuli that contained either a contrast or luminance disparity and a geometric disparity. When contrast and luminance are modulated alone, results from Dobias & Stine and experiments 3 and 4 above predict a decrease in perceived depth at frequencies above 1.4 Hz. Further, if eye movements or masking are not a factor, when contrast/luminance are modulated
Figure 73. Probability of reporting depth for contrast alone (dashed gray), luminance alone (dashed black), contrast & geometric (solid gray), and luminance & geometric (solid black) for subject JJD.
Figure 74. Probability of reporting depth for contrast alone (dashed gray), luminance alone (dashed black), contrast & geometric (solid gray), and luminance & geometric (solid black) for subject WWS.
Figure 75. Probability of reporting depth for contrast alone (dashed gray), luminance alone (dashed black), contrast & geometric (solid gray), and luminance & geometric (solid black) for subject PCN.
simultaneously with a geometric disparity, previous data predict that depth will remain visible at all frequencies below approximately 5 Hz. Results for subject JJD and PCN (figures 73 and 75) show that, when a geometric disparity is present, rapid shifts in contrast or luminance do not decrease the probability of reporting depth. PCN showed a lower probability of reporting depth for luminance disparity modulations, which is consistent with results for experiment three and is likely due to a mismatch between the amount of perceived depth from each type of cue. Subject WWS did not show a decrease in the probability of reporting depth when a geometric and luminance disparities are both present. WWS did, however, show a decrease when a geometric disparity is present with a contrast disparity.

As described above, if eye movements or masking does influence perceived depth, then perceived depth would diminish for all conditions at higher frequencies. The fact that WWS does not perceive depth at high frequencies for stimuli containing both contrast and geometric disparities does not necessarily indicate that eye movements or masking are the cause. For example, as the frequency of contrast modulations increases, WWS reports that the fused grating appears to move slightly to the left and right. It is possible that this apparent motion may act as a distractor when monitoring depth changes. Results do clearly show, however, that rapid changes in luminance (JJD, WWS, & PCN) and rapid changes in contrast (JJD & PCN) do not impair the ability to perceive a depth change from a geometric disparity.
Several studies have shown that changing geometric disparities over time can create the perception of motion-in-depth, and that, as the frequency of depth oscillations increases, the amount of depth that is perceived is reduced and eventually completely diminishes (Richards, 1951; Tyler 1971; Beverley & Regan, 1973a, 1973b; Regan & Beverley, 1973a, 1973b). Dobias & Stine (in preparation) found that perceived depth from contrast disparities diminishes at frequencies much lower than from a geometric disparity.

Experiment one further explores the timing difference between intensity and geometric disparities by dynamically reversing disparity cues to cancel perceived depth. Experiment one found that, when the contrast/luminance and geometric disparity modulations were in phase, the perceived rotation caused by contrast cancelled rotation caused by geometric and the individual bars appeared flat or appeared to rotate only slightly. However, if the phase of the two were not aligned, one disparity type would create rotation that would then be cancelled by the second disparity type, producing a rapid drop in perceived rotation, or a “jump.” Results showed that the ability to report a jump was greater when the offset between the onset of contrast/luminance and geometric disparities was larger but that there were large individual differences between subjects.

Two models were developed (Appendix E) to further explore the dynamics of cancellation with luminance, contrast, and geometric disparities. A model
based on a generalized difference between neural responses to contrast or luminance viewed by each eye made predictions that do not fit with observed data. However, a gated generalized difference model that can monitor the rate of rotation at higher frequencies did predict results that fit with data from experiment one.

The finding that perceived depth from contrast and luminance disparities follows the gated model is somewhat surprising because the un-gated model is what would be expected based on a physical system that is monitoring changes that increase in frequency. Because the probability of reporting motion-in-depth was zero for square wave depth modulations, results from Dobias & Stine (in preparation) support the gated model. Experiment two measured the ability to discriminate a sine wave depth change from a square wave depth change at frequencies close to the critical frequency. The un-gated generalized difference model would predict that subjects would be unable to discriminate each modulation type, whereas results from Dobias & Stine and the gated model would predict a clear ability to discriminate between each modulation type. Results of experiment two showed that subjects did successfully discriminate sine vs square wave depth modulations at frequencies close to the critical frequency supporting the gated model.

Hetley & Stine (accepted pending revision) found that if one eye views a grating that changes in luminance or contrast while the other eye receives a constant grating, the visual system can behave differently depending on which eye receives the varying grating. Experiment three replicates the results of
Dobias & Stine (in preparation) showing that perceived depth from a contrast disparity diminishes before a geometric disparity and extends them to luminance disparities. Experiment three with the results of JJD also replicates the results of Hetley & Stine (accepted pending revision) showing that perceived depth from luminance and contrast disparities may be influenced by which eye views the dynamic image.

Experiment four explored the influence of ocular dominance when cues for geometric disparity are dynamically altered in only one eye, allowing for a comparison between ocular dominance when the visual system processes intensity disparities vs processing geometric disparities. Results showed no differences between the eyes for geometric disparities in experiment four for JJD and PCN. However, because differences did occur in experiment three for JJD with contrast and luminance disparities as a result of which eye received the varying image, geometric, contrast, and luminance disparities may rely on separate underlying neural mechanisms. Also, interestingly, results for WWS in the experiment 4 follow-up experiment suggest that time constants for geometric disparities are eye-specific.

When there is a difference in contrast between the images seen by each eye, the perceived location of an image can appear to shift towards the higher contrast image (Weiler, et al., 2007). Also, when that grating is moved, the eye movement towards the new location can also be biased with a higher amplitude saccade. Therefore, the results from Weiler et al. would predict that the decrease in perceived depth as the frequency of contrast or luminance
modulations increases may be due to eye movements and saccadic suppression. Experiment five measured the probability of reporting depth when either a contrast or luminance disparity was viewed alone, or when contrast or luminance disparities were viewed simultaneously with a geometric disparity. Since depth changes from geometric disparities can be viewed at higher frequencies, if eye movements are not a factor, subjects should report depth in the combined condition but not in the alone condition. However, if eye movements do influence perceived depth at higher frequencies, depth changes should only be visible at low frequencies. Results showed that JJD was able to report depth at high frequencies in the combined condition but not in the alone condition for both contrast and luminance disparities. However, WWS only reported depth at high frequencies with the luminance/geometric combined condition. Overall, results suggest that eye movements do not cause the decrease in perceived depth at the frequencies used.

Stereopsis is processed in many areas throughout visual cortex (V1, V2, inferior temporal cortex, medial superior temporal area, medial temporal area, superior temporal polysensory area, and others). However, no site has been found to be dedicated to solely processing binocular disparity (Parker, 2007). When recording from neurons in the Macaque, signals from each eye have been found to first converge on neurons sensitive to absolute retinal disparity in visual area one (V1) and on neurons sensitive to both absolute and relative disparity.\textsuperscript{18} Absolute disparity can be defined as the difference in angle between the projections of a point on each retina with reference to the fovea, whereas, relative disparity is the difference between the absolute disparities. (Parker, 2007, p 381)
in visual area two (V2) (Cumming & Parker, 1999), possibly suggesting that our bridge locus is in V1 and/or V2. While the experiments described above cannot determine where cues for geometric and intensity (contrast/luminance) disparities are processed, results from Filley et al (submitted), Hetley & Stine (Accepted pending revision), and Dobias & Stine (in preparation) suggests that signals for geometric and contrast/luminance disparities converge on a common mechanism to signal depth and that separate mechanisms are likely sending each type of disparity.

The primate LGN is separated into six layers; four small-cell layers (parvocellular; layers 3-6) and two large-cell (magnocellular; layers 1-2) layers (Livingstone and Hubel, 1988). A third type of cells (koniocellular) can also be found between magnocellular and parvocellular layers in the LGN (Sincich & Horton, 2005). Based on a large amount of evidence reviewed by Livingstone and Hubel (1988) and Sincich & Horton (2005), it is likely that the mechanisms feeding depth information into V1 and then V2 pass through magnocellular cells in the lateral geniculate nucleus (LGN) and eventually into distinct areas of V1 & V2, into MT, and beyond. Unlike parvocellular and koniocellular cells, magnocellular cells do not show color sensitivity but are critical for luminance information. Further, isoluminant images do not elicit a depth response (Livingstone & Hubel, 1988; Sincich & Horton, 2005) suggesting that the magnocellular cells are important for depth perception. Magnocellular cells have larger receptive fields, are more sensitive to contrast, show faster and more transient responses than do parvocellular cells (Livingstone & Hubel, 1988). As
described by Livingstone & Hubel, the pathway for stereo and motion information through magnocellular cells goes from LGN → layers 4Cα → 4B in V1 → V2 → MT, whereas information from parvocellular cells goes from LGN → layers 4Cβ → 2 → 3 in V1 → V2. However, the connections described by Livingstone & Hubel do not necessarily show a clean isolated pathway for projections from magnocellular and parvocellular (and koniocellular) into V1, V2, and beyond (Sincich & Horton, 2005; Parker, 2007).

It is unclear where the difference in processing speed (gate) between contrast/luminance and geometric disparities occurs. One may suggest that, perhaps, the differences in processing speed for magnocellular and parvocellular cells shows that information for the Venetian blind effect may pass through parvocellular cells and then connect to the common mechanism in V1 or V2, as described above. However, information for luminance depends largely on the summation of long and medium wavelength sensitive cones that occurs in center-surround magnocellular cells (Livingstone & Hubel, 1988). Therefore, it seems unlikely that the Venetian blind effect relies on parvocellular cells. Further, the lack of overlap shown above in projections from LGN to V1 for magnocellular and parvocellular cells suggests that either Venetian blind information is fed through magnocellular cells and into V1, V2, MT and beyond, or that the common mechanism is in V2.

At least four statements can be made about the work described in this dissertation. First, as a group, all five experiments show strong evidence that the Venetian blind effect is not a result of irradiation. Second, ocular differences
were found for contrast/luminance (subject JJD) and geometric disparities (subject WWS) suggesting that separate monocular channels for contrast, luminance, and geometric disparities feed into the stereo system. Third, perceived depth changes from Venetian blind effect become no longer visible at frequencies that are much lower than those from a geometric disparity. Fourth, data support a gated model of the Venetian blind effect.
REFERENCES


Hetley, R. S., and Stine, W. W. Partitioning contrast or luminance disparity into perceived intensity and rotation. Under revision.


Wheatstone, C. (1838). Contributions to the physiology of vision. - Part the First. On some remarkable, and hitherto unobserved, phenomena of binocular
APPENDICES
APPENDIX A

APPROVAL FOR USE OF HUMAN SUBJECTS
Hi Bill --
You're all set for your IRB, "Dynamic aspects of the venetian blind illusion." For reference, the approval code is PS-110405A, and the approval is valid until April 5, 2011.
Best,
Andy

--

Andrew B. Leber, Ph.D.
Assistant Professor of Psychology
University of New Hampshire
APPENDIX B

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APPENDIX C

INDIVIDUAL FREQUENCY DATA FOR PRELIMINARY EXPERIMENT
Figure C.76. Means (top) and standard deviations (bottom) for individual frequencies 0.2 (solid), 0.4 (large dashed), 0.6 (medium dashed), and 0.8 (small dashed) Hz in the preliminary experiment for subject JJD.
Figure C.77. Means (top) and standard deviations (bottom) for individual frequencies 0.2 (solid), 0.4 (large dashed), 0.6 (medium dashed), and 0.8 (small dashed) Hz in the preliminary experiment for subject WWS.
Figure C.78. Means (top) and standard deviations (bottom) for individual frequencies 0.2 (solid), 0.4 (large dashed), and 0.6 (medium dashed) Hz in the preliminary experiment for subject WJT.
APPENDIX D

INDIVIDUAL FREQUENCY DATA FOR EXPERIMENT ONE
Figure D.79. Means for contrast (top) and luminance (bottom) for individual frequencies 0.2 (solid), 0.4 (large dashed), 0.6 (medium dashed), and 0.8 (small dashed) Hz in experiment one for subject JJD.
Figure D.80. Means for contrast (top) and luminance (bottom) for individual frequencies 0.2 (solid), 0.4 (large dashed), 0.6 (medium dashed), and 0.8 (small dashed) Hz in experiment one for subject WWS.
Figure D.81. Means for contrast (top) and luminance (bottom) for individual frequencies 0.2 (solid), 0.4 (large dashed), and 0.6 (medium dashed), and 0.8 (small dashed) Hz in experiment one for subject PCN.
Figure D.82. Standard deviations for contrast (top) and luminance (bottom) for individual frequencies 0.2 (solid), 0.4 (large dashed), 0.6 (medium dashed), and 0.8 (small dashed) Hz in experiment one for subject JJD.
Figure D.83. Standard deviations for contrast (top) and luminance (bottom) for individual frequencies 0.2 (solid), 0.4 (large dashed), 0.6 (medium dashed), and 0.8 (small dashed) Hz in experiment one for subject WWS.
Figure D.84. Standard deviations for contrast (top) and luminance (bottom) for individual frequencies 0.2 (solid), 0.4 (large dashed), 0.6 (medium dashed), and 0.8 (small dashed) Hz in experiment one for subject PCN.
APPENDIX E

DYNAMIC MODEL FOR EXPERIMENT ONE
Dynamic Model for Experiment One

This appendix contains a model developed by Stine (personal communication) to explore results from the preliminary experiment and experiment one\textsuperscript{19}.

For both models, a four second trial was described where, at zero ms phase, two superimposed gratings were presented with zero disparity. Disparity is then modulated for both gratings to induce rotations in opposite directions, with the net rotation, $r(t)$, being defined as the generalized difference in the rotation of the two superimposed gratings. The frequency of disparity modulation was varied over a range that would reduce perceived jumps to zero. The critical frequency for the geometric disparity was about four times that of the contrast disparity.

To model the probability of perceiving a jump, the net perceived rotation during the four s trial was passed through a discrete Fourier transformation, $F(r(t)) = F(\omega)$, for phases ranging from -200 ms to 200 ms in 50 ms steps. Power, $|F(\omega)|^2$, was then calculated for those temporal frequencies, $\omega$, exceeding twice the disparity modulation frequency but less than five Hz. A Laplace distribution was fit to the maxima of the power spectrum across phases for the case with a geometric disparity cancelled a geometric disparity with the

\textsuperscript{19} The author of this dissertation developed some of the descriptions of the model in this appendix and all of the descriptions within the text but did not contribute to the development of either dynamic model.
generalized difference model. That distribution was then used to calculate the probability of seeing a jump for all of the other simulations.

**Generalized difference model:**

The generalized difference model:

\[ r(t) = \int_{t - \frac{1000}{\omega_c}}^{t} (f_l(\tau) - f_r(\tau))(f_l(\tau) - M)(f_r(\tau) - M)d\tau \]

predicts the perceived rotation \( r(t) \) where \( f_i(\tau) \) is the neural response to the contrast of a rectangular-wave grating presented to the left eye, \( f_r(\tau) \) is the neural response to contrast in the right eye, \( M \) is a constant representing the contrast at which the other eye dominates perception, and \( \tau \) is time. The model takes the difference in response to the contrast or luminance seen by each eye and, using \( M \), accounts for cases where the contrast/luminance is either equal to, much higher, or much lower than the contrast/luminance in the other eye. Therefore, if the contrast/luminance is equal, or if one eye received zero contrast or average luminance, no rotation would be perceived.

When plotting the probability of reporting a jump, if a geometric disparity is used to cancel another geometric disparity, the probability is symmetric around the minimum probability of reporting a jump at zero ms delay. When a contrast disparity is used to cancel a geometric disparity at a low frequency, the lag between contrast and geometric grows and the minimum probability of reporting a jump occurs when contrast leads geometry by over 200 ms. However, when
the frequency is increased, the square wave depth modulations begin to resemble a sine wave modulation and no jump is perceived at any delay.

**Gated generalized difference model:**

The gated generalized difference model uses the same generalized difference used in the previous model

\[ r(t) = (f_l(t) - f_r(t))(f_l(t) - M)(f_r(t) - M)g(t) \]

but multiplies it by the perceived disparity at the edge of each bar \( g(t) \)

where:

\[ g(t) = \int_{t-\frac{1000}{\omega_c}}^{t} |(f_l(\tau) - f_r(\tau))(f_l(\tau) - M)(f_r(\tau) - M)| \, d\tau \]

When plotting the probability of reporting a jump, if a geometric disparity is used to cancel another geometric disparity, at positive delays, contrast is already non-zero when the trial starts. Therefore, the first jump lasts approximately one ms, giving only three jumps of any size during positive phase trials rather than four for the negative phase trials. The asymmetry in the number of jumps creates an asymmetry as a function of delay in the power spectra. When a contrast disparity is used to cancel a geometric disparity at a low frequency, with the gated model, the low frequencies essentially behave like a geometric cancellation since the contrast frequency is well below the critical frequency.

However, when the frequency is increased, as the contrast frequency approaches its critical frequency, the rate of rotation will remain constant but its
amplitude will drop. Further, given that the rate of rotation remains unchanged, the minimum probability of a jump remains at zero ms delay. Asymmetries between negative and positive delays are largely due to the same factors as those described above when one geometric disparity is used to cancel another.

It is important to note that, conceptually, the perceived rate of rotation is maintained in the gated model but not the un-gated model. Therefore, the gated model predicts that one could discriminate a sine-wave rotation from a square-wave rotation at modulation frequencies relatively close to the critical frequency while the un-gated model predicts that such a discrimination would not be possible when the disparity modulations are more that one third the critical frequency.