Temporal dynamics of the venetian blind effect

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TEMPORAL DYNAMICS OF THE VENETIAN BLIND EFFECT

BY

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B.S., Northern Michigan University, 2006

THESIS

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ABSTRACT

TEMPORAL DYNAMICS OF THE VENETIAN BLIND EFFECT

By

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University of New Hampshire, May, 2008

When square wave gratings are viewed binocularly with lower luminance or contrast in one eye, the individual bars of the grating appear to rotate around a vertical axis. Studies of motion-and-depth using geometric disparities have shown that perceived depth vanishes at frequencies near 5 Hz. By changing contrast disparity over time, this study measured the frequency at which both the perception of motion-and-depth and the perception of depth are no longer visible. For experienced observers, the perception of motion-and-depth decreased at 1 Hz (Experiment 1) and the perception of depth decreased at 1.4 Hz (Experiments 1 and 3); both of which are lower than the frequency where depth from a geometric disparity diminishes (above 5 Hz in experiment 2). These results were replicated with a naïve observer (experiments 4 and 5). The differences between the dynamics of depth from geometric and contrast disparities suggest that the perception arises from separate neural mechanisms.
CHAPTER I

DEPTH PERCEPTION

Humans possess two laterally separated frontward facing eyes, each of which receives a slightly different view of the world. A majority of the information obtained through the visual system does not require simultaneous use of both eyes, such as cues for size, shape, color, distance, and some cues to depth (monocular depth cues). Other cues, however, such as some movement cues (interocular velocity differences) and depth cues such as retinal disparity (a binocular depth cue) cannot be determined using only one eye. To perceive depth, individuals with binocular vision use slight geometrical differences in images shown to each eye as cues for distance, depth, etc. (Figures 1 & 2).

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 noncorresponding areas, the image would appear to be double (Howard & Rogers, 1995, p. 6-13).
Figure 1. Figure demonstrating retinal disparity. In A, points P1 (fixation point) and P2 fall on the same isodisparity circle (Vieth-Müller circle); each point has the same binocular subtense. In B, points P1 (fixation point) and P2 fall on different isodisparity circles; when focusing on point P1, point P2 is disparate. Figure adapted from Howard & Rogers (1995). Permission to use this figure is shown in Appendix B.
Figure 2. Illustration of a hypothetical table with two bars standing upright one behind the other. Top left: image falling on the left retina when viewing the table. Top right: image falling on the right retina. Bottom: combination of the two images falling on each retina. The gap between the two upright bars represents the retinal disparity. Note that there would also be slight differences in the retinal images of the lines on the table that are not shown in the figure.
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 (Figure 3), but the area that is occluded from the one eye remains visible to the other eye. Da Vinci noted that the object becomes “transparent” in that the area 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 asked what would be seen if each eye were separately shown an illustration of what a physical stimulus would look like if seen by each eye individually? He demonstrated that, by using stereograms (see Figure 4) with one two-dimensional image shown to the left eye and a separate, and slightly different, 2D image shown to the right eye, would create the perception of depth when properly fused (Wheatstone, 1838). The slight components of each image, which
Figure 3. 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.
Figure 4. 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.
were different, would have a specific disparity that would create the depth. Using stereograms, small controlled changes can be made to the image shown to each eye that can help to determine exactly what cues are being used for depth and how changes to those cues alter what is perceived.

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. The question according to Julesz (1960) is whether we recognize the patterns before we combine them (monocular pattern recognition), after we combine them (binocular pattern recognition), or a combination of both (Figure 5).

To separate monocular from binocular depth cues, Julesz (1960) developed random-dot stereograms (Figure 6), which monocularly appear to be a random field of dots, but when properly fused create the perception of depth. The images shown in figure 6, 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 uncorresponding points in each eye. 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.

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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 5. Three possible methods of pattern recognition adapted from Julesz (1960). Top Left: Micropattern recognition. Top Right: Macropattern recognition. Bottom: combination of Micropattern and Macropattern recognition. Permission to use this figure is shown in Appendix B.
Figure 6. Random-dot stereogram. When fused, a square appears in 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 for solving the correspondence problem (Julesz, 1960).

So far, this description has discussed depth perception in terms of images falling on corresponding or noncorresponding retinal points. The information received by retinal receptors, however, must travel to the brain for further processing. Hubel & Wiesel extensively studied response rates of cortical neurons in cats (Hubel & Wiesel, 1962) and in monkeys (Hubel & Wiesel, 1968) as bars of light and edges stimulated them. Several neurons responded in specific ways depending on the bar or the edge that was used. “Simple cells” preferentially responded to stationary bars or edges at a specific angle. “Complex cells” preferentially responded to bars or edges that were moving across their receptive field. “Hypercomplex cells” preferentially responded to the

---

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.
same properties as a simple or complex cell but were restricted to bars or edges at a specific length.

In addition to finding simple, complex, and hypercomplex cells, Hubel and Wiesel also found cells that were driven by both eyes. The binocularly driven cortical cells have receptive fields that exist in corresponding retinal areas (Hubel & Wiesel, 1959, 1962, 1965, 1968). The existence of binocular cells helps to demonstrate how images that fall on noncorresponding points can give cues to depth. Images that fall on points with perfect or nearly perfect correspondence would lead to a certain level of response, and as the amount of correspondence changes, so would the level of responding from that binocularly driven cell.

Barlow, Blakemore, & Pettigrew (1967) also found cortical cells driven by both eyes. Binocularly located stimuli caused more responding than monocularly located stimuli and when the binocular stimulus fell only on one of the corresponding points, the response from the one eye was cancelled by the response of the other. If the eyes were fixated on a single point, the response of a given binocular cell was activated most effectively in cases when an object was placed at a specific distance from the fixation point (retinal disparity).

Along with cells that respond to specific distances and disparities, Blakemore, Fiorentini, & Maffei (1972) found cells tuned to objects tilted around a horizontal axis towards or away from the animal. Cells responded maximally when retinal images fell on corresponding points and had a “correct orientation” for both receptive fields. Blakemore et al. (1972) suggest that preferred disparities and orientations are probably not the only cues that may be used to
determine depth. "The nervous system may not use a single geometric convention to analyze three-dimensional space: it might utilize any complex cue available to it (Blakemore et al., 1972, p. 727)." They mention, in passing, a few other disparities that could be used for depth perception. Both rotation about a vertical axis, instead of a horizontal axis, and movement towards or away from the viewer through the visual field would create different types of movement in one eye from that in the other eye.

Julesz (1960) showed that, when using a random-dot stereogram, monocular cues were not necessary to determine depth. Slight disparities created by shifting a portion of the dots in the image shown to one eye created a disparity that was detectable only while using both eyes. Geometric retinal disparities have been shown to be a leading contributor to stereopsis, but what other types of disparity create the perception of depth? Münster (1941) and Cibis & Haber (1951) independently found that, when viewing a vertical square wave grating (Figure 7) with a decreased level of illuminance in one eye, individual bars of the grating can appear to rotate around a vertical axis. Filley (1998) later showed that the effect could also occur under conditions when the grating had a disparity in Michelson contrast between the eyes. Thus, it may be possible

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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. It is the difference in the maximum and minimum luminance values divided by the sum of the maximum and minimum luminance values $(L_{\text{max}} - L_{\text{min}})/(L_{\text{max}} + L_{\text{min}})$.
Figure 7. Example of a vertical square wave grating.
for the visual system to perceive depth in cases where there are no geometric disparities.

Like any perceptual experience, vision and stereopsis require at least some amount of time between the instant that the stimulus is transduced by the receptors and the moment of perception. In the 1860's, Dove found that depth could be seen when stereoscopically viewed stereograms were illuminated for very short durations by an electric spark (Ogle, 1962). Regan & Beverley (1973a) found that disparity changes over time lead to the perception of movement-in-depth of a stereoscopically viewed stimulus. They also found that, if those movement-in-depth oscillations were at a frequency between 5 and 6 Hz, the ability to determine depth from disparity cues was disrupted. Thus, it took between 165 and 200 milliseconds to process the movement-in-depth from geometric disparity changes over time.

Animals that use stereopsis have a great advantage. Indeed, it is not difficult to determine which mammals are predators and which are prey. Predators tend to have frontward facing eyes with a large amount of binocular overlap that enables the predator to determine distance to the prey. Prey, on the other hand, tend to have eyes on the side of the head and are able to see far more of the visual space allowing them to better escape an attack. In 1738 Robert Smith noted that “it is no wonder” (implying that two eyes are useful) that individuals who had lost the use of one eye were “subject to mistakes in small distances, as in pouring out liquors from vessel to another, or in snuffing a candle, or in the like actions” (Smith, 1738, p. 41).
As noted above, geometric disparity cues are not alone in their ability to create the perception of depth. Altering the luminance or the contrast of a square wave grating shown to one eye can also create the impression of depth; the next section will elaborate on these findings.
CHAPTER II

VENTIAN BLIND EFFECT

Cibis & Haber (1951) introduce the Venetian blind effect as being a result of what they call "anisopia," or the unequal vision or imagery leading to a distortion of the visual space. Cibis & Haber suggest that unequal vision can result from any alteration in either the physical, receptive, or the neuro-physiological image of the stimulus.\(^6\) When the image in one eye is a different size from the image in the other, the spatial distortions lead to alteration of the perceived object. For example, increasing the image size in one eye with a magnifying lens creates a rotation away from that eye (Figure 8). Decreasing the image illuminance in one eye with a neutral density filter creates a rotation towards that eye\(^7\) (Figure 9). It is the perceived rotation as a result of decreased illuminance that Cibis & Haber call the Venetian blind effect.

To measure the effect, Cibis & Haber used two white squares set against a black background (Figure 10); the observer could physically rotate the squares. Each observer viewed the squares with neutral density filters that had varying densities (darkness) over one eye. The task was to rotate each square

\(^6\) 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 neuro-physiological image is determined by processes beyond the photoreceptors. (Cibis & Haber, 1951).

\(^7\) 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 8. Apparent rotation of a fronto-parallel plane surface, resulting from an overall 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)
Figure 9. 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 10. 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.
until rotation of the squares was no longer visible. The degree of rotation to cancel the apparent rotation was measured and can be seen in figure 11. More rotation of the squares was necessary as the density of the filter increased and the effect was found to be symmetrical in each eye.

To explain the effect, Cibis & Haber gave a model suggesting that decreases in illuminance to an eye decreases the image size to that eye. It is assumed that, due to the modulation transfer function of the eye (e.g., Williams, Brainard, McMahon, & Navarro, 1994), the image falling on the retina would have an energy distribution shown in figure 12. With a filter over one eye, the illuminance of the image falling on the retina (which has a specific threshold) would be different for each eye. Also, beyond the retina, they assume that the “perceptual zone” would also have its own threshold value. According to Cibis & Haber, with a contrast of 1.0, and dark areas that are below threshold, the two images would cross the threshold at different points. If the image crosses the threshold at different points, two different size images would exist, and would lead to a perception where the surface appears to rotate toward the eye with the smaller image (figure 8).

For a qualitative understanding of the Venetian blind effect, Gerathewohl & Cibis (1953) asked professional draftsmen, who were highly skilled in drawing, to make observations with a filter over one eye and draw what was perceived. Each observer viewed a white H-shaped stimulus (figure 13) with a neutral density filter over one eye and then completed sketches of how the stimulus
Figure 11. 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 12. 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.
Figure 13. Drawings from Gerathewohl & Cibis (1953). Perception of the stimulus while not looking through a filter (left) and with a filter over the left eye (right). Below each image is the observer's estimate of what the image would look like if viewed from above. Permission to use this figure is shown in Appendix B.
appeared. Figure 13 shows drawings made by one of the observers with one eye covered by a filter (right), and another without a filter (left).

Ogle (1952) rejected the use of the term anisopia by arguing that nothing new about visual space perception had been found, and that Cibis & Haber had only measured one aspect of light intensity gradients on the retina. Ogle calls the Venetian blind effect a “special geometrical configuration” that is not a special type of spatial perception or a new anomaly in perception. Ogle (1962) continues to interpret Cibis & Haber’s results as geometrically based and names the effect “irradiation stereoscopy.”

The Cibis & Haber model has been the most commonly used explanation for the effect (Hetley, 2005), but other (in some cases more recent) evidence has suggested that it may not be the full explanation. von Békésy (1970) suggested that if irradiation was the only explanation for the effect, then lateral interactions would not play a part in the apparent rotation. By placing dark bars next to a white field he found that the closer the bars were to the neighboring edge the greater the perceived rotation was. Figure 14 shows a square wave grating bounded on one end by black and on the other end by white. When viewed with a filter over one eye, the bars appear to rotate more when they are closer in proximity to the black edge. von Békésy suggests that the apparent rotation of a surface while looking through a neutral density filter is likely a “complicated combination of irradiation and lateral nervous interaction” and that they may be
Figure 14. 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.
from processes similar to processes that lead to Mach bands⁸ (von Békésy, 1970). Evidence of lateral interactions is a large blow to the Cibis & Haber model that doesn’t include the possibility that such lateral interactions could play a role in producing the Venetian blind effect.

The Cibis & Haber model is also unable to account for cases when the dark part of the square wave is above threshold. Filley (1998) used vertical square wave gratings (similar to those in figure 15) that were manipulated to increase or decrease the contrast in one eye while keeping the average illuminance constant in both eyes. If the left eye were shown a grating with lower contrast, the light bars of the grating would usually appear to rotate towards the left eye. If the eye receiving lower contrast were reversed, the direction of rotation would also reverse.

The stimuli used by Filley (1998) and Cibis & Haber (1951) are different in at least one way. Cibis & Haber used two white squares against a dark background with what they report as a contrast of 1.0. Cibis & Haber’s model relies on the assumption that the dark background behind the squares was below the threshold for the receptors in the eye. The stimuli used by Filley are completely above threshold. Therefore, the apparent rotation of individual square wave bars is not explained by the Cibis & Haber model (Filley, 1998).

In summary, several studies have established that the Venetian blind effect occurs when illuminance or contrast is reduced in the image reaching one

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⁸ Purves (2004) has defined Mach bands as illusory bands of increased darkness or lightness induced by linear luminance gradients.
Figure 15. Two stereo pair, square wave gratings. Top: Left eye receiving higher contrast. Bottom: Right eye receiving higher contrast.
eye. Despite the agreement that the effect can occur, disagreement still remains as to what causes the effect. Regardless of the model used to explain the effect, it is of interest to study its other characteristics. How much processing time is required to perceive rotation? Can disparity changes over time create the perception of motion-and-depth? These questions have yet to be answered.

Cibis & Haber (1951) concluded that the Venetian Blind effect resulted from a decrease in illuminance to one eye that decreased the image size on the retina, and created a geometric disparity. Therefore, the time course to perceive depth should be the same for both. If, however, the time course to perceive depth from the Venetian blind effect were found to differ from that to see depth from a geometric disparity, it would suggest that the two are not controlled by the same mechanism. A separate set of mechanisms would support the results of Filley (1998) that were not accounted for by the Cibis & Haber model and would lead to a deeper understanding of how the visual system analyzes disparities in luminance and contrast.
CHAPTER III

MOTION PERCEPTION

Motion perception evolved very early in the visual system and is sometimes regarded as the most ancient and primitive aspect of vision (Anstis, 1970). The perception of motion provides perceptual knowledge about an object in the environment and can be derived in "at least" two ways: either from the analysis of retinal motion, or from changes in the retinal position of objects over time (Derrington, Allen, & Delicato, 2004). The utility of motion perception can be understood when observing cases of motion blindness; everyday activities such as crossing the street or judging when a teacup is full, can become nearly impossible (Zihl, von Cramon & Mai, 1983). Motion blindness can be a result of brain damage such as a stroke (Zihl et al., 1983), or can be artificially created by temporarily deactivating areas V1 or V5 in the visual cortex through transcranial magnetic stimulation (Beckers & Zeki, 1995).

As discussed in the section on depth perception, Hubel & Wiesel distinguished between what they called simple and complex cells in the striate cortex of cats and monkeys that responded to different types of stimuli. Simple cells responded to stationary bars, slits, or edges that were at a specific angle. Complex cells responded to the same types of stimuli, but only when they would move across the receptive field (Hubel & Wiesel, 1962, 1968).
Hubel & Wiesel used unchanging stimuli moving across a stationary retina, which, in most cases, are perceived as a moving object. As these, or other environmental stimuli move across the retina, there is a link between the pattern seen at one time \( t_1 \) and a pattern seen at a later time \( t_2 \). Unchanging movement across the retina is separate from motion seen when viewing animated stimuli on a television or movie screen, where the stationary patterns shown at \( t_1 \) and \( t_2 \) have no linkage between each other; there is a complete change of scene between \( t_1 \) and \( t_2 \) (Anstis, 1970), which is an example of the \( \varphi \) phenomenon (top of Figure 16) and was described by Max Wertheimer in 1912. Stimuli separated by spatial location changes in an alternating sequence over time, appear to move from one position to another (Harston, 1937). Classic examples of the \( \varphi \) phenomenon (simple spots or lines separated by time, intensity, and distance) use stimuli that do not have total link at \( t_1 \) and \( t_2 \) but that are similar (Anstis, 1970).

Anstis (1970) asked how much and what type of similarity is required to see \( \varphi \) movement. To measure the necessary amount of similarity, Anstis used two stimuli that were photographic negatives of each other, such as black and white stimuli (bottom of Figure 16). The stimuli would appear to move in the opposite direction than when similar images were used. Anstis called the effect “reversed \( \varphi \) movement” and suggested that it resulted from the same visual process as forward \( \varphi \) movement; both relying on corresponding

\[ ^9 \text{As a result of the voluntary, involuntary, or non-movement of the eyes, in comparison to the movement of the retinal image, movement may be perceived differently.} \]
Figure 16. Forward (top) vs. Reversed (bottom) $\varphi$ movement. Two stimuli are alternately presented in two different locations $L_1$ and $L_2$. The dot appears to move to the right in forward $\varphi$ and to the left in reversed $\varphi$. 
brightness points in successive frames. Anstis suggested that the visual system searches for corresponding brightness points that are not present when using photographic negatives, which would cause the only direction for movement to go to be in the opposite direction. The results show that similarity of the images is not required to see movement, but that it is required to see forward movement.

To test what type of similarity was necessary for movement, Anstis used random-dot images that reduced monocular form cues without removing monocular "micro-texture" cues. Two random-dot images were built similarly to those shown in figure 6. One image had a random field of dots. The other had the same random field of dots but with a central square of dots shifted in one direction. The stimuli were presented to one eye and were alternated back and forth from one random-dot image to another creating movement of the entire center square, but sometimes required an extended amount of time to perceive movement. Anstis' claim was supported, the visual system makes a point-by-point search for corresponding brightness points and that brightness, not form, determines movement.

Anstis compared motion perception to depth perception by suggesting that motion and depth perception are both dependent on the correlation of similar brightness points, but are not dependent on monocular form cues. They are different, however, in that motion does not need compact areas of similar

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10 If the two images shown in figure 6 are alternated back and forth, a central square will appear to move to the right.
disparity, it does not rely on small horizontal disparities, and it can result from one image being a photographic negative of the other.

When using random dot images to cue apparent motion, at least two problems arise. With random dot images, dots in one image are paired with dots in another image, and are shifted in a specific direction. First, why does the visual system not use any one of the dots that are neighbors of the correct "partner dot" to determine movement? Since coherent motion perception of a random-dot square is possible, the visual system is able to pair the dots correctly, which raises two more questions. Is the process of pairing the dots similar to the process used in stereopsis? Is there a global process that uses information over a spatially extended area to determine which dots are and are not shifted to one side (Braddick, 1974)?

Braddick (1974) used stimuli similar to those of Anstis (1970) with a central rectangle shifted in one direction. The dots of the images were varied in the size of each individual element and the distance over which the elements were displaced. If a global process is not involved when determining motion in a random dot image, then incoherent motion should be visible and no unified square should be perceived as moving. If, however, a global process is used

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11 Horizontal and Vertical disparities of a point are measured by: First, determining how far away a given point is from a point with zero horizontal disparity or zero vertical disparity; the horizontal difference is the azimuth (\(\mu\)) and the vertical difference is the elevation (\(\lambda\)). Second, by subtracting the azimuth in the left eye from the azimuth in the right eye (\(\alpha_{R}-\alpha_{L}\)) and the elevation in the left eye from the elevation in the right eye (\(\beta_{R} - \beta_{L}\)), which gives the point's disparity from zero. The relative disparity between two points is found by taking the difference in azimuth (\(\alpha_{R} - \alpha_{2L}\)) and the difference in elevation for each eye (\(\beta_{1R} - \beta_{2L}\)). (Howard & Rogers, 1995, pp. 246-250)
then it should be possible to shift dots over a wide range of displacements and
over a large spatial separation.

Braddick found that movement and clarity of the moving square depended
on the size of the spatial displacement of the dots and not on the number of dots
between the new and old positions. Perception of a unified moving square
began to deteriorate after a separation of 5 minutes of visual arc and was
completely gone at displacements of 20 minutes of arc. The drop-off was not a
result of a small interstimulus interval (ISI), because when ISI was varied with
spatial displacement, movement perception did not occur above 20 minutes of
arc, even at increased durations of the interstimulus interval. Also, when each
image was shown to a separate eye, movement was not seen in the same way
as when shown to both eyes.

Braddick suggested that there might be a fundamental difference between
classic examples of apparent motion and examples using random-dot images.
There may be a low-level motion detecting process that has a limited spatial
range. Also, since unified movement is not seen with dichoptic viewing, the
process occurs early in the visual pathway that, along with the low upper limit for
spatial separation and the presence of incoherent motion (incoherent stereopsis
is not possible), further distinguishes motion perception from stereoscopic vision
(Braddick, 1974).

Anstis (1970) had also described differences between motion and depth
perception, but not when those differences were restricted to random dot images.
Braddick's finding that motion perception drops off as the spatial separation of
displacement increases, suggests that depth perception and motion perception might not be as similar as Anstis had suggested.

Motion detectors such as the ones found by Hubel & Wiesel signal when motion occurs, but in many cases the true direction of motion is not determined (Adelson & Movshon, 1982). The cases are illustrated by the aperture problem resulting from motion detectors with small spatially defined receptive fields. The receptors signal motion but only have a limited view of the stimulus similar to looking through an aperture (Hildreth & Koch, 1987). The result is illustrated in the top of figure 17. A grating that moves behind an aperture can move in a variety of directions but movement will only be seen in a direction orthogonal to the grating (Adelson & Movshon, 1982). The bars of the grating are only seen in the context of the aperture, so the only cues available are the bars moving across the field. Since the end of each bar is not visible the true direction of movement is hidden.

A second aspect of movement viewed through an aperture is shown in the lower two panels of figure 17. In most cases, when the two gratings are superimposed they appear to move together in the same direction rather than on their own path (Adelson & Movshon, 1982). Adelson & Movshon call the effect motion coherence, and suggest that it may represent processing at a level beyond normal one-dimensional motion detectors where, responses of several one-dimensional detectors may combine to create cohesive motion.

Feature-matching and global matching models of apparent motion have been widely used but are generally not well defined. Feature-matching models
Figure 17. Example of the type of gratings used by Adelson & Movshon (1982). Top: movement could be in any direction indicated by the arrows, but movement is seen in the direction orthogonal to the grating. Middle: movement in one grating up and to the right, when combined with movement down and to the right, creates movement to the right. Bottom: movement down and to the right, when combined with movement down and to the right in a slightly different direction creates movement up and to the right. Permission to use this figure is shown in Appendix B.
have problems determining what a "feature" is, and what features are to be matched. Global matching models are unable to predict motion in complex patterns with many features moving in several different directions (Adelson & Bergen, 1985). Adelson & Bergen suggest that an early stage containing a temporal filter would process the stimulus in a continuous way, whereas matching makes use of distinct images at two distinct times. Also, if the temporal filter could extract motion information by itself, then there is no need for matching (Adelson & Bergen, 1985).

Figure 18 shows a spatiotemporal representation of stimulus movement. A bar that moves to the right over time (top left) can be represented in a three-dimensional $x, y, t$ space, where $x$ and $y$ are the spatial dimensions and $t$ is the temporal dimension. The top right and the bottom images in figure 18 represent spatiotemporal movement in $x, y, t$ space as the bar is continuously sampled, such as in physical movement (top right) or when sampled in separate frames such as a movie (bottom). The top of figure 19 shows spatiotemporal representations after removing the $y$ dimension that, in the present example, does not change. Higher or lower velocity movement will produce more or less slant as the bar is sampled in the temporal dimension.

Adelson & Bergen (1985) note that continuous and sampled movement similar to that shown in the top of figure 19 will appear the same. Also, that motion will be seen regardless of direction or velocity, as long as the spatiotemporal orientation is appropriate. How then is spatiotemporal motion extracted? Adelson & Bergen suggest that, like simple cells that have spatially
Figure 18. Spatiotemporal representation of bar moving to the right. Top Left: movement of the bar represented in the x and y spatial dimensions. Top Right: continuous sampling of the bar in spatial (x and y) and temporal (t) dimensions. Bottom: movement sampled in separate frames over time. Adapted from Adelson & Bergen (1985). Permission to use this figure is shown in Appendix B.
Figure 19. Spatiotemporal representation after removal of the y dimension. Top: spatiotemporal representations from figure 18. Bottom: hypothetical spatiotemporally oriented receptive fields to detect movement. Adapted from Adelson & Bergen (1985). Permission to use this figure is shown in Appendix B.
oriented receptive fields producing a spatial response, there may be cells with receptive fields oriented in spatiotemporal space (bottom of figure 19) that would produce a spatiotemporal response. As shown in the bottom of figure 19, the cells would respond equally well to both continuous and sampled motion.

Problems arise with the spatiotemporally oriented motion detectors described above because they are phase dependent (Adelson & Bergen, 1985). At some points during stimulation, depending on how the stimulus lines up with the receptive field, the response will not be uniform. To "build" a phase independent motion detector and to measure local energy, Adelson & Bergen used two linear filters whose responses are 90° out of phase from each other (Figure 20). The outputs of each are squared and added together to produce the measure of local energy that will create a uniform energy response as a sine-wave grating is moved across the field. Energy detectors that are tuned for leftward or rightward movement can be combined to create opponent energy detectors. For example, a right vs. left opponent detector would have a positive response for right and a negative response for leftward movement.

Adelson & Bergen concluded that spatiotemporal energy models have many advantages. The models sidestep the correspondence problem, they explain motion either continuous or sampled, and individual features need not be analyzed. They do have trouble, however, when explaining long-range global mechanisms, such as those described by in Braddick (1974), or the motion coherence described by Adelson & Movshon (1982). Despite the failures,
Figure 20. Two linear filters that are 90 degrees out of phase from each other. When their output is squared and summed, a phase-independent measure of local motion energy is given. Adapted from Adelson & Bergen (1985). Permission to use this figure is shown in Appendix B.
spatiotemporal energy models can be useful when trying to answer a variety of questions about low-level motion perception (Adelson & Bergen, 1985).

As has already been suggested, stimuli that undergo displacement in space and time, require a mechanism to detect spatiotemporal continuity of the displacement by matching what is seen at \( t_1 \) and what is seen at \( t_2 \) (Albright & Stoner, 1995). The medial temporal area of visual cortex (MT) in the macaque has been found to be highly sensitive to visual motion (Krekelberg & Albright, 2005) with approximately 95% of MT neurons responding in direction specific ways, and has lead some to call MT the primary neural component of motion processing (Rust, Mante, Simoncelli, & Movshon, 2006).

In support of the spatiotemporal energy models proposed by Adelson & Bergen, Krekelberg & Albright (2005) found that apparent motion in the reversed \( \psi \) phenomenon is driven by motion energy rather than feature tracking, and also that responses of MT neurons elicited by two separate components can be entirely separate from responses when the two components are combined. The result is consistent with the opponent energy detectors proposed by Adelson & Bergen that would have a positive response for one direction while giving a negative response for the other direction (Krekelberg & Albright, 2005). Rust et al. (2006) found that some MT cells respond specifically to the direction of motion of a single pattern, while other cells respond to motion of single stimulus components.

The goal of this section has not been to determine the exact process that enables motion perception because it is not clear that a specific process exists.
It may be that there are several processes, working alone or together, to interpret motion. The small subset of the literature reviewed here suggests that no clear explanation has been obtained for all motion phenomena.
Hubel & Wiesel conducted several studies that explored, among other things, the response of cells in cats and monkeys driven by both eyes. Hubel & Wiesel (1959) found cells in the striate cortex of cats that were activated independently by either eye. Some cells had equal activation by each eye, whereas other cells were driven more dominantly by one eye. The binocularly driven cells fell on corresponding points on each retina and were activated by the same type of stimuli. The responses of some excitatory areas were additive, in that, simultaneous stimulation of both areas elicited a greater response than when only one area had been stimulated. The responses of other cells, however, could be cancelled by simultaneous stimulation.

Independent stimulation of one area would give an “on” response, and stimulation of another area would give an “off” response, but would give no response when stimulated together. Responses to moving stimuli could also be increased when a stimulus was moved from an inhibitory area in one eye to the excitatory area of the other eye. A square moving down and to the left produced more responding than when it moved up and to the right (Hubel & Wiesel, 1962). Later the findings were replicated for cells in the striate cortex of the macaque and the spider monkey (Hubel & Wiesel, 1968).
Barlow, Blakemore, & Pettigrew (1967) suggest that some of the cells studied by Hubel & Wiesel, which were thought to have corresponding receptive fields in both eyes, may have actually been tuned to stimuli that had non-zero disparities, but some movements of the eyes may have caused this to go unnoticed. If so, the neurons could determine which object features seen by one eye belong with features seen by the other eye, and to measure the differences to determine depth.

Barlow et al. (1967) tested neurons in the visual cortex of anesthetized cats as the cats were shown stimuli varying in the amount of horizontal or vertical disparity\textsuperscript{12} between the stimulus and the point of fixation. Correctly placed disparate stimuli would evoke the most vigorous responding, while stimuli at other disparities would evoke a smaller response. These neurons, tuned to binocular disparity, provide a basis for stereopsis (Barlow et al., 1967).

Along with the retinal disparity projected onto each retina, the two eyes are able to determine other qualities that give cues to depth, including: different velocities of a moving object in each eye, differences in the size of the retinal image in each eye from rotation around a vertical axis, and different orientations in each eye from tilt around a horizontal axis (Blakemore, Fiorentini, & Maffei, 1972).

Using cats, Blakemore et al. (1972) attempted to find neurons tuned to stimuli tilted around a horizontal axis either towards or away from the two eyes.

\textsuperscript{12} In part B of figure 1, point P2 does not lie on the same Vieth-Müller circle as Point P1. The point is said to have uncrossed disparity because it is beyond the circle defined by point P1. A point which would fall closer than point P1 would have crossed disparity.
Some cells were found to respond to a stimulus at a preferred orientation. For some cells, however, the preferred orientation was different for each eye. Blakemore et al. found several cells that had a range of up to 15° of difference in the preferred orientation between each eye. However, to obtain the largest response when the stimulus was simultaneously shown to both eyes, it had to be in the correct place on the retina and to have the correct orientation in space. Blakemore et al. suggest that there is no reason to assume that geometric disparities are the only cue the visual system uses to determine depth. They have shown that rotation around a horizontal axis is a good cue, and have suggested two other possible cues (rotation around a vertical axis and interocular velocity differences). Also, other studies on the Venetian blind effect (Cibis & Haber, 1951; Filley, 1998; Hetley, 2004) have shown that a luminance or contrast disparity can create perceived rotation of individual bars in a vertical square wave grating. An interesting question would be whether or not there are cells specifically tuned to rotation around a vertical axis, and if so, are the same cells responding when vertical bars appear to rotate during the Venetian blind effect. If not, what cells are?
CHAPTER V

MOTION-AND-DEPTH

The research cited in the section on motion perception (e.g. Anstis, 1970; Braddick, 1974; Adelson & Bergen 1985, etc.) describes left vs. right motion over time but does not discuss motion-and-depth. Everyone who is alive and has functional eyes experiences motion that moves either towards or away from himself or herself in 3D space. When one drives a car or catches a ball, position and speed/direction of movement-in-depth must be judged precisely (Regan, Beverley, Cynader, & Lennie, 1979).

With regards to motion-and-depth, the visual system could respond individually to a series of stimulus attributes such as position in depth or size, or it could respond directly to changes in stimuli, such as movement in depth or changes in size. The proposed second method would be far more rapid and precise, and would indicate that two systems may exist; one for depth and another for motion-and-depth (Regan et al., 1979).

Depending on the direction and speed of movement, objects that move in depth have movements and velocities that are different in the two eyes. Thus, motion-and-depth could, at least in part, result from changing retinal disparities over time or from differences in object velocity in the two eyes (Cumming & Parker, 1994). Beverley & Regan (1973a, 1973b) define separate movements in the left and right eyes by the ratio of the motion in the left vs. the right eye. When the eyes are fixated on a target, two lines are directed towards each eye.
(Figure 21). As shown in figure 21, when the target oscillates in a sine wave motion in the direction of the left or the right eye, the sine wave motion is in phase in both eyes, when oscillating in a direction towards the area between the eyes, the oscillation is in anti-phase, and if in a direction directly towards one eye there is no motion in that eye (the image would get larger or smaller on the retina of that eye though). Figure 21 does not, however, show how the amplitude of sine wave oscillation is changed as a result of direction changes. Figure 22 gives a range of possible movement ratios starting and ending at (1:1) with examples of changes in sine wave amplitude from changes in direction.

Beverley & Regan (1973a, 1973b) showed identical images to each eye while moving both images to create movements similar to those shown in figure 21, at an amplitude ratio falling within the range shown in figure 22. Baseline thresholds were obtained for the entire range of L:R ratios. Later, observers viewed an image oscillating in depth defined by one L:R ratio for a ten minute adaptation period. At the start of the adaptation period motion-and-depth was clearly seen but by the end depth was no longer visible.

Results showed that, after adaptation, the threshold to perceive depth had increased greatly over baseline, although only for the direction of movement-in-depth observed during adaptation. If the L:R ratio was switched to a cue for a different direction, movement-in-depth was seen immediately. Thirteen separate L:R ratios were tested and all 13 showing similar increases in threshold that could be described by five different curves. Beverley & Regan summarized the five curves into four sensitivity curves for four hypothetical neural mechanisms.
in phase motion  anti-phase motion

Figure 21. Differences in phase between the eyes depending on the direction of movement towards or away from the eyes/head. Beverley & Regan (1973a).
<table>
<thead>
<tr>
<th>Direction of movement from eyes</th>
<th>L/R Ratio (L:R)</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>↔</td>
<td>(1:1)</td>
<td>in-phase</td>
</tr>
<tr>
<td>↔</td>
<td>(1:2)</td>
<td>in-phase</td>
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<tr>
<td>↑</td>
<td>(0:1)</td>
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<tr>
<td>↑</td>
<td>-(1:2)</td>
<td>anti-phase</td>
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<td>↑</td>
<td>-(1:1)</td>
<td>anti-phase</td>
</tr>
<tr>
<td>↑</td>
<td>-(2:1)</td>
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<td>↓</td>
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<td>↔</td>
<td>(2:1)</td>
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<tr>
<td>↔</td>
<td>(1:1)</td>
<td>in-phase</td>
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</table>

Figure 22. Differences in phase between the eyes depending on the direction of movement towards or away from the eyes/head in terms of the ratio of differences in movement in the left vs. the right eye (L:R). Beverley & Regan (1973a).
underlying motion-and-depth tuned to the L:R ratio of movement. They suggest that the hypothetical mechanisms could provide a basis for determining the direction of movement-in-depth.

Detection of movement-in-depth and detecting the direction of movement-in-depth are not necessarily the same. Beverley & Regan (1975) found that determining the direction was far better when a target was moving toward a spot near the nose and was much worse when a target was moving away from that spot. Despite the high sensitivity to the direction of movement toward the nose, detecting that a target was moving in depth was far better when it was moving away from the head. Beverley & Regan suggest that a neural system compares outputs from a set of directionally tuned motion detectors and increases the sensitivity to directional movements of an object that is likely to hit the head.

Recording from neurons in area 18 of the cat's visual cortex, Cynader & Regan (1978) and, later, Regan & Cynader (1982) found neurons that responded to stimuli giving cues for motion-and-depth. The cat viewed similar bars in each eye that varied in the value of relative velocity and relative direction of movement in each eye.

Cynader & Regan (1978) found three types of cells that required simultaneous stimulation of both eyes, while targets moved at different velocities and directions in each eye. The first type of cell was completely inhibited when both eyes received cues for movement parallel to the fronto-parallel plane (objects giving the same cues for phase, velocity, etc., in both eyes) but gave strong responses to stimuli with cues for movement towards the head (cues with
large differences in phase, direction, velocity, etc. between the two eyes). The first type of cells were highly sensitive to the direction of movement; they responded to a very small range of changes in direction of movement-in-depth corresponding to an object that was likely to hit the head, which supports the finding by Beverley & Regan (1975) that some hypothetical units would be more sensitive to this type of movement-in-depth. The second type of cell produced the greatest response when both eyes were given cues for an object moving in a direction in depth away from the head. Finally, the third type of cell was only sensitive to cues that had inhibited the first cell type; for movement parallel to the fronto-parallel plane from cues that moved at the same speed, phase, direction etc. in both eyes.

The responses of some cells, however, are not a result of summing the responses (monocular firing characteristics) of the two eyes (Regan & Cynader, 1982). When stimulated monocularly, some cells were sensitive to the same direction of movement, but were sensitive to opposite movements during simultaneous stimulation of the eyes. Also, cells that were sensitive to movements directly toward the head, responded very little when one of the eyes was stimulated monocularly, but would give strong responses to binocular stimulation.

The most important finding by Cynader & Regan (1978) and Regan & Cynader (1982) is that determining the direction of motion-and-depth is not predicted by monocular stimulation. Cynader & Regan (1978) found that the discrimination of direction of movement-in-depth only occurred when both eyes
were stimulated. Regan & Cynader (1982) found that some cells made either an opposite response, or no response, when stimulated monocularly as opposed to binocularly.

The results above show that velocity differences can be used to determine motion-and-depth, but are velocity differences able to create motion-and-depth in the absence of other cues? Shioiri, Saisho, & Yaguchi (2000) used random-dot images that removed binocular disparity cues by presenting two sets of random dot images in a sequence (two frames for each eye). The dots in the upper and lower halves of each monocular image were displaced in opposite directions for frame two of the monocular image sequence, and were displaced in the opposite direction in each eye (Figure 23). The displacement of the dots created relative motion between each half in the monocular image and motion signals in the opposite direction for the binocularly fused image. The observers reliably determined which half of the image was moving towards or away in depth, suggesting that motion-and-depth from interocular velocity differences can be perceived with binocularly uncorrelated random dots. Motion-and-depth, however, was not due to the visual system randomly pairing dots, because when Shioiri et al. controlled for binocular overlap of random dots, motion-and-depth was reliably perceived.

Fernandez & Farell (2005) did not attempt to determine if inter-ocular velocity differences alone could create motion-and-depth, but tried to determine what contribution inter-ocular velocity differences had on motion-and-depth, and if the visual system uses a specific mechanism to respond to these differences.
Figure 23. Example of stimuli used by Shioiri et al. (2000). The dots shown in frame one are identical to the dots shown in frame two, but each eye received a different set of dots for frame one. Thus, the only correlation between dots was monocular. The upper half and the lower half were displaced in opposite directions between frames one and two and were in opposite directions in each eye. The lines that separate the two halves, and the arrows that indicate direction of movement, are only present to demonstrate one possible displacement. They were not present for the experiment.
They suggested that, since fronto-parallel speed discrimination improves after adaptation and determining inter-ocular velocity differences is a task of fronto-parallel speed discrimination, adaptation to fronto-parallel motion would improve the discrimination of motion-and-depth. Observers adapted to fronto-parallel motion that, if motion-and-depth were only from disparity changes over time, would have no effect on seeing motion-and-depth. After adaptation, observers improved at discriminating the direction of movement in depth, suggesting that inter-ocular velocity differences do contribute, in at least some way, to the perception of motion-and-depth.

In summary, when studying motion perception, left/right motion from detectors for left/right motion does not show the whole picture. Everyone who has two functional eyes, see objects that move towards or away from those eyes. If one eye is impaired, other monocular cues could be used to determine that an object was moving towards the eye but would be far less effective than when using two eyes together. Object movements that are in opposite directions, velocities, phases, etc., in each eye are extremely powerful cues to motion-and-depth and help greatly when moving throughout the environment.
CHAPTER VI

TEMPORAL ASPECTS OF STEREOPSIS

In the 1860's Dove found that depth was visible when stereoscopically viewed stereograms were illuminated for very short durations by an electric spark (Ogle, 1962). When Julesz removed monocular cues with random-dot stereograms he found that the perception of depth took longer to achieve, but that the perception was stable once depth was seen. What then is the time course for perceiving depth? Also, do some methods of creating depth perception take longer to create depth than other methods?

For local and global stereopsis, the amount of disparity necessary for stereopsis increases as a function of the reduction in stimulus exposure time (White & Odom, 1985). If the disparity cues for crossed or uncrossed disparity are reversed at specific intervals, the perception of depth flips back and forth. If however, the cues are reversed over time in a sine wave motion, the stimulus will appear to move in depth in a sine wave motion; this was discussed in the previous section and will be discussed further in the next section.

White & Odom (1985) used dynamic anaglyph\textsuperscript{13} stereograms with depth reversals occurring at intervals within a range between 0.11 to 15 Hz. The threshold to see depth reversals was highest at 15 Hz and gradually reduced to

\textsuperscript{13} 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).
its lowest point at about 1 Hz. When the frequency was below approximately 1.8 Hz, the threshold remained about the same. However, when the frequency was above 1.8 Hz the threshold began to increase greatly. Despite the higher thresholds, depth was still seen up to frequencies of 15 Hz.

When looking at a roughly textured 3D surface, each eye sees a different part of the background and foreground elements of that surface. Also, when scanning across the roughly textured surface, one of the eyes sees elements of the background and foreground at different times (Ross, 1974). Using random-dot stereograms with two areas of dots shown to each eye at different times, Ross (1974) found that if the delay was below 50 ms depth was not seen; the background appeared to be in the same plane as the foreground. When the delay was between 50 and 70 ms, depth was ambiguous with perception of depth occurring randomly from trial to trial. However, when the delay was above 70 ms, the background appeared to be in a plane behind the foreground, suggesting that depth perception can occur when there are differences in binocular delay, with no retinal disparity, but that timing is important.

When looking at surfaces in a three dimensional environment, many surfaces exist that do not lie in the fronto-parallel plane. Many surfaces are slanted in various ways around different axes. Looking at a table extended in space or at a door that is partially open will give a different image of that surface on the retina of each eye. Despite a greater number of slanted surfaces in the environment, typical studies of stereoscopic vision use stimuli standing in depth in the fronto-parallel plane (Gillam, Chambers, & Russo, 1988). Does the greater
number of slanted surfaces in the environment influence the speed at which we can perceive slanted surfaces in depth? Is stereopsis faster or slower when viewing a complex scene?

The measurement of the time needed to see depth when viewing a stereogram can be divided into two parts: the time needed to properly fuse the stimulus and the time needed to make use of depth cues to perceive depth. Gillam, et al., (1988) measured both of the times, for stimuli containing cues for surfaces slanted in depth. Six random-dot stereograms were used, showing three types of rotation around either a vertical or horizontal axis. The horizontal and vertical slant images appeared to rotate as an entire field around their respective axis. The "twisted" images had sharp borders of disparity (disparity discontinuities) between the two parts of each image that created two surfaces; one in the fronto-parallel plane and the other slanted around an axis. The "hinged" images did not have a disparity discontinuity but had a discontinuity in the disparity gradient that would create two connected surfaces; one of which slanted in depth. Representations of what the six slanted surfaces would look like are shown in figure 24.

As mentioned above, two measurements were made: the time to properly fuse and the time to stereoscopically resolve the images correctly. Once the images had been properly fused, the time to perceive slant around a vertical axis was much slower than for slant around a horizontal axis. Mean viewing time for rotation around a vertical axis was 35.2 and 37.7 seconds respectively for slants of the entire field and for hinge images but were 15.2 and 13.8 seconds
Figure 24. Types of slant used by Gillam, Chambers, & Russo (1988). Actual stimuli were random-dot stereograms with disparity cues creating slant in the directions shown. Permission to use this figure is shown in Appendix B.
respectively when slant was around a horizontal axis. However, in the case of “twisted” images, the average viewing time for slant around vertical and horizontal axes was similar at 7.4 and 7.2 seconds.

The speed to discriminate slant was similar for whole-field slant and hinged conditions suggesting that contrast created by disparity gradients in the hinged stimuli did not help to resolve depth. The twisted stimuli, however, did seem to help to resolve depth; sharp depth discontinuities between parts of an image that makes one surface appear to rotate away from the other, is a powerful cue to slant perception.

Van Ee & Erkelens (1996) used anaglyph stimuli shown for limited periods of time to test how much time was needed to perceive slant and to determine the amount of slant that can be seen. From trial to trial, a visual reference (may be used to aid in slant perception) was either added or removed. In support of Gillam et al. (1988), van Ee & Erkelens found that slant perception occurred more quickly if a visual reference was present. Also, at short presentation times, without a reference, only a small amount of slant was seen that, along with the findings of Gillam et al. (1988), suggest that an area that has two sets of dissimilar cues for comparison is useful when determining how one area is different from another area.
CHAPTER VII

TEMPORAL DYNAMICS OF MOTION-AND-DEPTH

In the previous section it was shown that, in certain cases, depth could take up to several seconds to become visible. It seems likely, then, that an object moving in depth may also take some length of time to process.

To determine how the system might process depth, Richards (1951) compared the ability to perceive a stimulus that moved in depth to the ability to perceive left-right movement. Richards was not necessarily looking to discover information about how we process movement-in-depth, but used a method for movement-in-depth to learn about the differences in stereo and Vernier acuities. 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 viewer.\(^{14}\) 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 thresholds to see depth or lateral movement diverged rapidly as the frequency of movement increased. Thresholds for lateral movement increased very gradually and lateral movement remained visible at 20 Hz. Thresholds for

\(^{14}\) Richards (1951) did not clearly define the type of motion that was created by his apparatus. It appears, however, that it moved in a non-sinusoidal, triangle wave motion.
depth, however, increased greatly as the frequency of depth oscillations increased. Once the frequency of depth modulations reached approximately 3.2 Hz, depth was no longer visible. Richards suggests that the processes for stereoscopically viewed lateral movement and movement-in-depth may rely on different mechanisms, with the one for movement-in-depth possibly requiring higher processing.

It is important to note that, since Richards was not specifically looking for motion-and-depth, he did not note when the perception of movement stopped, just the perception of depth. However, as the threshold increased, the observers would, on occasion, report a combination of stereo and lateral motion. When a combination of motions was reported, the bar “appeared to execute various elliptical movements as the views alternated” (Richards, 1951), which suggests that there is some range where the stimulus is not just moving in depth or just sitting in the frontal plane, but is doing something else.

To compare the influence of monocular cues on movement and binocular cues on movement-in-depth, Tyler (1971) used a similar method to Richards (1951). The apparatus, stimuli, and type of movement were different from Richards (1951) but the movements were similar, in that, one part of the image would either have left-right movement or would move in depth. The type of movement was different from Richards because Tyler altered the images to move 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-and-depth was
found to be similar to the sensitivity to movement in the fronto-parallel plane, but that sensitivity to movement-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-and-depth was consistently lower than fronto-parallel motion throughout the set of frequencies tested for the depth condition. Tyler concluded that the visual system is less sensitive to movement that requires both eyes. Tyler did not specifically report the point where movement started to decline or when depth was gone entirely, but the sensitivity begins to decrease between 3 and 5 Hz, and frequencies above 5 Hz are not reported.

The results described above are slightly different from Richards (1951) who reported depth to be completely removed at approximately 3.2 Hz, which may be due to the differences in apparatus and the stimuli used by Richards and Tyler (1971) or it could be due to Tyler's use of sine wave movement that may have helped in perceiving motion. Tyler (1971) did not discuss the results of Richards (1951).

The notion that sine wave modulation could have helped to perceive motion has been supported by Richards (1972), who 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 depth that could be seen decreased as the frequency of the depth changes increased. 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.

When asking why sine wave modulation may allow for better depth judgments, it may be that there are more chances to make a guess as to what the most-forward point is with a sine wave motion. If the movement is in a continuous motion, there are several nearby locations where the bar had just been; this allows one to compare where the bar appears to be now to where the bar appeared to be at \( t_1, t_2, t_3 \), etc. However, if the bar jumps back and forth, its most-forward point is at \( t_1 \) and its most-behind point is at \( t_2 \), so there are fewer example points to be used as a comparison. Fewer points for comparison might lead to increased processing time necessary to perceive changes in depth. The explanation described above, however, does not account for the results of Richards (1951), who used stimuli that had similar nearby points but found that depth was no longer visible above 3.2 Hz. It is likely that there is a lot more to the way in which the visual system interprets depth than is suggested by this explanation.
Regan & Beverley (1973a) used a random-dot stereogram that had two black bars positioned within the image. The apparatus could adjust 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, while using a controller, 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, motion and depth would both disappear.

Regan & Beverley (1973a) made note of a point within the range of frequencies that they called the breakaway point. When the frequency of modulation was below the breakaway point, the bar would appear to move in depth. When the frequency was above the breakaway point, however, the bar would not appear to move but would appear to be two bars, one at a different depth than the other. One would expect that if the frequency were so high that depth could not be processed, the two bars would appear to be oscillating left-to-right in the frontal plane. However, Regan & Beverley report that the bars appear to stand still with one standing in depth in front of the other. So, the perception of movement-in-depth and the perception of depth decrease in two steps at high frequencies: first, the change from movement-in-depth to stationary depth, and
second, from stationary depth to no depth. It may be that, at frequencies above 6 Hz, depth would be completely diminished and the appearance of double bars would look more like two bars oscillating in the frontal plane.

Another explanation could involve something similar to aliasing, where the visual system is not processing all of the steps in the modulation by processing a small portion of the steps but not others. It would be interesting to know if the "stationary double-bars" would appear to be at one depth at one time and then at another depth at a later time; the possibility of aliasing will be explored later.

The evidence shown above suggests that the perception of an object moving in depth requires more time to process than one would expect based on the time needed to detect movement in the frontal plane. Also, the evidence discussed above, is based on an object that changes position over time on the retina of each eye, raising the question: does movement-in-depth rely on objects which actually change position over time? What would be perceived if a stimulus was altered over time to create motion-and-depth, but did not move across the retina? Would movement-in-depth be seen, and if so, would it require the same processing time as an object that did change in retinal position over time? These questions have yet to be answered.
Humans have two eyes that have separate views of the world. The fact that each eye has a different view enables the visual system to compare the two images in order to get a more complete view of three-dimensional space. Cases in which images fall on retinal points that do not correspond (Ogle, 1962, p. 223; Howard & Rogers, 1995, pp. 6-13), when one eye sees part of an image not seen by the other eye (da Vinci, 1796, pp. 178-179), or when there are differences in the image shown to each eye (Wheatstone, 1838) have been traditionally presumed to be primary contributors to stereopsis. The conditions all contain monocular cues to depth. Using random-dot images to remove monocular cues, Julesz (1960) found that depth remained visible. However, images falling on disparate retinal locations are not required for depth perception. Reduced illuminance (Cibis & Haber, 1951; Münster, 1941) or reduced contrast (Filley 1998) in the images reaching one eye can also cause a surface to appear to rotate towards the eye that receives lower illuminance or lower contrast.

Cibis & Haber (1951) interpreted depth arising from lower luminance as a result of irradiation that caused the image in one eye to be reduced in size, thus creating a geometric disparity. Their interpretation is called into question because stimuli with completely above threshold components have been found to create a perception of depth (Filley, 1998). Von Békésy (1970) showed that
lateral interactions could help to amplify the Venetian blind effect if a large dark area was near the stimulus grating.

The perception of motion developed very early within the visual system (Anstis 1970), and can arise from motion on the retina or changes in retinal position over time (Derrington, et al., 2004). Hubel & Wiesel (1962, 1968) described cells in the visual cortex that would only respond if a stimulus was moved across the visual field in a certain way. However, images do not need to physically move across the retina to create the perception of movement; Wertheimer (1912) described the \( \Phi \)-phenomenon where an image, alternatingly flashed in two separate spots, is perceived as moving smoothly from one spot to the other rather than flashing on and off in each spot. Anstis (1970) found that when using the photographic negative of the stimulus, it would appear to move in the opposite direction (reversed \( \Phi \)-phenomenon) and that the \( \Phi \) motion was visible when using random dot images. However, Braddick (1974) found that apparent motion deteriorated as distance between the shifted dots increased, suggesting that a global process may not contribute to apparent motion from the \( \Phi \)-phenomenon. Motion across space, and over time, is able to be described by a spatiotemporal energy model in which energy detectors are tuned to the change in location over time in \( x, y, t \) space (Adelson & Bergen, 1985).

Hubel & Wiesel found cells that were not only tuned to the orientation and movement of stimuli, but were controlled by input from both eyes. Stimuli shown to both eyes could, depending on the cell, cause greater response than when each eye was stimulated alone, or stimulation of both eyes could cancel the
response that would be given if each eye was stimulated alone. Barlow et al. (1967) found cells in the visual cortex tuned to specific retinal disparities; stimuli that had one disparity from the fixation point would create a large response, but if the stimulus were at a different disparity it would create a small response. Blakemore et al. (1972) found cells that, when stimulated with an object tilted in 3D space, would have a differential response depending on the orientation of the object.

Objects that have motion-and-depth could respond to changes in stimulus attributes or to changes in the stimulus itself (Regan, et al, 1979). Objects that move in depth have disparities and velocities that are different for each eye over time (Cumming & Parker, 1994). The ratio of the changes in one eye versus the changes in the other eye can be used to detect the direction of motion-and-depth (Beverley & Regan, 1973a, b). Detecting motion-and-depth is more accurate for objects that are moving away from the head, but detecting direction of motion-and-depth is more accurate if the object is on a trajectory that will hit the head (Beverley & Regan, 1975). Cynader & Regan (1978) supported the finding of Beverley & Regan (1975) by finding cells in the visual cortex that responded to a very small range of directional movements (directed towards the head). It has been suggested that detection of motion-and-depth can occur exclusively from interocular velocity differences (Shioiri et al., 2000; Fernandez & Farell 2005), but it does not indicate that other differences are not as important to the perception of motion-and-depth.
In the 1860's, Dove determined that even when illuminated for a very short time, depth could still be seen (Ogle, 1962). Julesz (1960) suggested that removal of monocular cues did not block the perception of depth but did increase the time needed to see it. Reversing depth in random-dot images can become more difficult to detect with increases in the frequency of depth reversals (White & Odom, 1985). In terms of interocular delay, when scanning across a textured surface, areas exist that are visible to one eye before they are visible to the other eye. However, perception of depth from interocular delay is only visible after delays of 70 ms (Ross, 1974); suggesting that, in this case, the visual system needs more time to register depth. Perceived slant in random-dot images is processed faster for those images that contain sharp disparity boundaries between two halves of the image; these boundaries create a reference to compare the disparity in one part of the image versus another part (Gillam et al., 1988; van Ee & Erkelens, 1996).

Since objects in depth are not processed immediately, it can be assumed that objects that do move in depth also take a certain amount of time to properly process. An object that moves left to right in the frontal plane remains visible while the speed of movement oscillations increase to frequencies beyond 20 Hz, but an object moved in depth towards or away from the viewer stops appearing to move when the frequency reaches approximately 3.2 Hz (Richards, 1951). If the image is moved in a sine wave motion, however, movement-in-depth can be seen up to frequencies between 5-6 Hz (Tyler, 1971; Richards, 1972; Regan & Beverley, 1973a, b; Beverley & Regan, 1974a, b). In certain cases, the
perception does not change directly from movement-in-depth to no depth, but changes gradually with some range where motion is disrupted but depth is still visible. Regan & Beverley (1973a) describe the breakaway point where a previously moving bar would appear to be two bars at separate depths instead of one unified bar moving in depth. The existence of a breakaway point is what would be expected if the frequency were above the limit of the visual system to detect motion-and-depth.

So, would luminance or contrast disparity changes over time create the impression of motion-and-depth through the Venetian blind effect? Second, since motion-and-depth has been found to decrease at frequencies above 1 Hz and completely stop at frequencies close to 5 Hz, if motion-and-depth can be created using the Venetian blind effect, would it decrease in the same manner as other cases of motion-and-depth? If the Venetian blind effect were found to decrease at a frequency well below 5 Hz, it would indicate that the visual system is recruited in a different way to perceive motion-and-depth from illuminance or contrast disparities than from geometric disparities. This would contradict the Cibis-Haber model, which had interpreted the Venetian blind effect as a result of geometric disparities caused by decreased illumination in on eye.
CHAPTER IX

PRELIMINARY EXPERIMENT ONE

Participants

Subjects were RSH and JJD. JJD has normal vision, while RSH has myopia, as well as a slight astigmatism in the left eye that is corrected by glasses. Both subjects were experienced observers with normal stereopsis. The Institutional Review Board of the University of New Hampshire granted approval for this study, 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

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 artificial pupils. Stimuli were presented on a LaCie electron19blueIV monitor with a refresh rate of 85 Hz at a distance of 1.58 m. At this distance one pixel took up 38 seconds of visual angle. A Power Mac G4 MDD computer running Mathematica 4.2.1.0 controlled the display; Mathematica was used to generate the animated stimuli and record responses.

15 The use of the term artificial pupil can be somewhat misleading. Each artificial pupil is several centimeters in front of each eye as opposed to the natural pupil that is the opening at the front of the eye. The artificial pupils could be better described as apertures.
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/m\(^2\) respectively, which set the optimum average luminance\(^9\) value at 44 cd/m\(^2\), and the maximum contrast value to be approximately 0.95. This range can be seen in figure 25, which plots the contrast and luminance values that can be used to generate gratings for an experimental stimulus. The monitor was \(\gamma\) corrected.

The range of luminance values was further reduced to ensure that luminance values for experimental animations remained in a range that could be generated by the monitor. As is shown in figure 26, the optimum average luminance value was set at 29 cd/m\(^2\), 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. An example is shown in figure 27. 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 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. The gratings shown in figure 27 have an overall luminance of 29 cd/m\(^2\), which is equal to the luminance of the
Figure 25. Plot range of the gratings that can be displayed on the monitor.
Figure 26. Plot range of gratings that can be used for experimental animations
Figure 27. Experimental stimulus displaying equal contrast to each eye.
background, and an overall contrast of 0.325. Above and below each grating, 0.03° nonius lines\textsuperscript{16} 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.

**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 through an aperture that blocked all parts of the screen except for the stimulus. The artificial pupils 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 artificial pupil 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 artificial pupils 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.

\textsuperscript{16} 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.
Figure 28. Adaptation image shown for 10 seconds during the inter-trial interval.
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 and vertical rectangles (Figure 28) 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 grey 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 animations were constructed with 200 experimental stimulus frames in which the gray values for the gratings were drawn so that, when animated, the average luminance of each grating would remain the same, while contrast became gradually larger and smaller in a sine wave modulation. Figures showing differences in contrast for each eye (at one point in the animation) are shown in figures 29 and 30. The sine wave modulation in one eye was \(\pi\) radians out of phase with that in the other eye, so that, as the contrast increased in the image shown to one eye, it decreased in the other eye.

The amplitude and frequency of each sine wave modulation was determined for each trial by randomly choosing from a set of pre-determined parameters (Table 1). Each randomly chosen amplitude and frequency parameter included an amplitude value between 0.1 and 1, and a frequency value between 1 and 14 cycles per 10 seconds (0.1 and 1.4 Hz). As mentioned above, the range of contrast values that could be shown was between 0.0 and

79
Figure 29. Experimental stimulus displaying greater contrast to the right eye.
Figure 30. Experimental stimulus displaying greater contrast to the left eye.
Table 1
Frequency and amplitude values used to create sine wave animations of experimental stimuli.

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0.65. Amplitude values represented how much of the range was covered by the sine wave modulation. For example, an amplitude value of 0.75 would cover 75% of the available range of contrasts. Modulations with higher amplitudes had higher contrast disparity at the peak of the sine wave that, as shown by Hetley (2005), should cause the individual bars of the fused grating to appear to rotate further in depth, making depth more visible.

To aid the subject in determining motion-and-depth, the vertical rectangles above and below each grating were also animated. All four vertical rectangles increased and decreased in luminance at the same frequency and phase as the dark bars of the left grating, but had a constant amplitude value of 0.7. Since all four rectangles were animated the same way in each eye, the subject could use the rectangles to help monitor the contrast modulation.

Subjects completed one hundred fifty individual trials. Each trial was 10 seconds in duration followed by a 10 second inter-trial interval. With the five-minute adaptation period, and 150 trials, each experimental session was a minimum of 55 minutes. Due to reaction time and rest periods, however, sessions averaged between 75 and 90 minutes. Over a five-day period, subjects JJD and RSH completed four sessions for a total of 600 trials each.

Four possible responses were made. Subjects were to respond with “1” if they saw no depth and no movement (the grating appeared to be flat), “2” if they only saw stationary depth (individual bars rotated out in depth or if smooth movement wasn’t clearly present), “3” if they saw movement of the individual bars within the grating, rotating back and forth in depth around a vertical axis.
(movement-in-depth), and "4" if they saw movement of the bars rotating around a vertical axis but the movement was not at the frequency of the sine wave modulation (aliasing). The 4th response was added after, in preliminary experiments, subjects had reported movement-in-depth that was at a frequency below that of the sine wave modulation.

Results

The results are plotted in figures 32-34. The data were plotted in the form of a density plot showing the areas where motion-and-depth and depth was visible. When plotted, each response was given a specific color; blue for a response of "1," green for "2," yellow for "3," and white for a response of "4." A legend is shown in figure 31. Areas that were not tested are marked in black. Average response data for JJD are shown in figure 32 while figure 33 shows average response data for RSH. Figure 34 is an average of all eight experimental sessions (four by JJD and four by RSH). Density plots showing response data for each individual session are shown in figures C.77-C.80 in Appendix C.

Discussion

Dynamically changing contrast disparities in vertically oriented square wave gratings can create the impression of motion-and-depth. As shown in figures C.77-C.80 in Appendix C, during each individual session for both subjects RSH and JJD, when the amplitude was above a certain level (approximate amplitude values of 3.25), the perception of motion-and-depth was diminished at frequencies that were much lower than 5 Hz. For both RSH (figures C.77 &
Figure 31. The colors used when plotting data within density plots. Yellow represents the perception of motion-and-depth. Green represents the perception of depth without movement. Blue represents the perception of a flat grating with no depth and no movement. Although not shown in the legend above, black represents a data point that was not tested, and white represents the perception of motion-and-depth at a slower rate than the frequency of the animation (aliasing).
Figure 32. Average response data as a function of contrast modulation and frequency across sessions 1, 2, 3, & 4 for JJD for preliminary experiment 1.
Figure 33. Average response data as a function of contrast modulation and frequency across sessions 1, 2, 3, & 4 for RSH for preliminary experiment 1.
Figure 34. Average response data as a function of contrast modulation and frequency across sessions 1, 2, 3, & 4 pooled across JJD and RSH for preliminary experiment 1.
C.78) and JJD (figures C.79 & C.80), the impression of motion-and-depth was visible up to approximately 1 Hz. When the perception was disrupted, choices would vary between seeing motion-and-depth, depth, or no depth. It is not clear, however, from the frequencies tested, the frequency at which the perception of depth is diminished completely. Both subjects had individual sessions where depth and even motion-and-depth were reported up to 1.4 Hz.

A fourth choice was made when a subject reported seeing what appeared to be motion-and-depth but that appeared to be moving at a frequency much below the frequency at which the contrast was increasing and decreasing in each eye (aliasing). During the four individual sessions, JJD reported cases of aliasing where the frequency was high (0.7-1.4 Hz) and when the value of contrast modulation amplitude was low (0.1 -0.5). The reports of aliasing for JJD were consistently within the range of high frequencies and low amplitude values, but reports were rarely consistent between specific frequency/amplitude combinations. RSH also reported aliasing at high frequencies and low amplitudes, but did so rarely. RSH reported aliasing in two of the four sessions (figure C.77 in Appendix C) but did so only once in one session and twice in the other. During debriefing sessions, it was discovered that RSH reported aliasing but was unsure what was visible. It was reported that the frequency of perceived motion-and-depth might have been lower than in the overall image, but that it was unclear whether it was aliasing or was “normal” motion-and-depth.
The inconsistencies between reports of aliasing for JJD and RSH suggest individual differences. If a third subject had been used, questions regarding inconsistencies in reports of aliasing may have been more clearly answered.

The presence of aliasing for JJD is an interesting finding, and may indicate that future work should attempt to specifically target and measure aliasing. It is of note that none of the previous studies of motion-and-depth report aliasing. Regan & Beverley (1973a) discussed what they called the breakaway point where, above a given frequency, the stimulus would not appear to move back-and-forth in depth but would appear to rest at one specific depth while not moving. Regan & Beverley’s report of the breakaway point is interesting, and different from the aliasing reported here, because the image would not stop moving completely, but would appear to slowly move in depth.

As a result of the inconsistent reports of aliasing, the responses where JJD and RSH reported aliasing were replaced with a response that represented a choice of depth without movement. The data were again averaged for each subject and averaged across both subjects. For cases where the choices for aliasing were replaced, figures 35 and 36 show averages for JJD and RSH respectively and figure 37 shows combined averages for both JJD and RSH.

It is clear that the perception of motion-and-depth was not consistent at frequencies above 1 Hz, but the frequency at which the perception of depth is diminished completely remains unclear. It is necessary to test frequencies above 1.4 Hz to determine the exact frequency where the perception of depth is completely diminishes.
Figure 35. Average response data as a function of contrast modulation and frequency across sessions 1, 2, 3, & 4 for JJD after removal of responses for aliasing for preliminary experiment 1.
Figure 36. Average response data as a function of contrast modulation and frequency across sessions 1, 2, 3, & 4 for RSH after removal of responses for aliasing for preliminary experiment 1.
Figure 37. Average response data as a function of contrast modulation and frequency across sessions 1, 2, 3, & 4 pooled across JJD and RSH after removal of responses for aliasing for preliminary experiment 1.
CHAPTER X

PRELIMINARY EXPERIMENT TWO

Participants

Subjects were RSH, JJD and WWS. RSH and JJD participated in preliminary experiment 1. All three subjects were experienced observers with normal or corrected vision and normal stereopsis. The Institutional Review Board of the University of New Hampshire granted approval for this study, 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

The computer, display monitor, and software were the same as was described above. Stimuli consisting of stereo pairs of vertically oriented square wave gratings were constructed in the same manor as in the first preliminary experiment (figures 27-30).

Procedure

To completely capture the fall off point for the perception of depth, the range of frequencies used to construct sine wave oscillations was increased to 2 Hz. The low end of the range was set at 0.5 Hz and the high end was increased to 2 Hz (0.5-2 Hz). The range of amplitude values was also reduced to a range of 0.1 to 1 in steps of 0.1. Table 2 shows the entire set of amplitude and frequency values used to construct the animations. Each subject completed one
Table 2
Frequency and amplitude values used to create sine wave animations of experimental stimuli for the second preliminary experiment.

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hundred twelve trials that lasted a minimum of 43 minutes. RSH, JJD, and WWS completed four experimental sessions for a total of 448 trials per subject. The procedure for a given experimental session was the same as in the first preliminary experiment.

**Results**

Average response data are shown in figure 38 for RSH, in 39 for JJD, and 40 for WWS. Figure 41 shows an average of all 12 experimental sessions (four by RSH, four by JJD, and four by WWS). Density plots showing response data for each individual session for RSH, JJD, and WWS are shown in figures D.81-D.86 in Appendix D.

**Discussion**

The goal of the second preliminary experiment was to replicate the finding from the first preliminary experiment, that the perception of motion-and-depth decreased when the frequency of contrast modulation was above approximately 1 Hz, and would not be visible when above approximately 1.4 Hz. A second goal was to determine the frequency at which perceived rotation of individual bars was no longer visible within the square wave grating.

For all subjects the perception of motion-and-depth was visible up until approximately 1 Hz. When the frequency was between approximately 1 and 1.4 Hz, the perception of motion-and-depth became more variable and was intermixed with perceptions where depth was visible without movement, or where no depth was visible at all. When the frequency was above 1 Hz but below 1.4
Figure 38. Average response data as a function of contrast modulation and frequency across sessions 1, 2, 3, & 4 for RSH for preliminary experiment 2.
Figure 39. Average response data as a function of contrast modulation and frequency across sessions 1, 2, 3, & 4 for JJD for preliminary experiment 2.
Figure 40. Average response data as a function of contrast modulation and frequency across sessions 1, 2, 3, & 4 for WWS for preliminary experiment 2.
Figure 41. Average response data as a function of contrast modulation and frequency across sessions 1, 2, 3, & 4 pooled across JJD, RSH, and WWS for preliminary experiment 2.
Hz, RSH and JJD reported motion-and-depth more often than did WWS. WWS reported motion-and-depth up until approximately 1 Hz and rarely reported seeing depth when frequencies were above approximately 1.3 Hz.

As was found in the first preliminary experiment, individual differences existed between subjects and between each experimental session. As can be seen in figures D.81 & D.82 in Appendix D, RSH reported seeing depth at higher frequencies than did JJD or WWS, but rarely did so when frequencies were above 1.9 Hz. For JJD, depth was rarely reported above approximately 1.5 Hz (figures D.85 & D.86 Appendix D) and for WWS depth was rarely reported above approximately 1.3 Hz (figures D.83 & D.84 in Appendix D).

The perception of motion-and-depth and depth in general depended on the amplitude value that was used. For all subjects, reports of motion-and-depth, depth, and no depth varied greatly at lower amplitudes and at combinations of higher amplitudes and moderate frequencies. If the amplitude was extremely low (below a value of 0.2), depth and motion-and-depth were rarely visible and became progressively more visible as the amplitude values increased. If, however, the amplitude increased (above a value of 0.9) and the frequency increased to above 1 Hz, the perception of depth also became more variable.

Again, as in the first preliminary experiment, individual differences have prevented finding the exact frequency at which the perception of depth is diminished in the Venetian blind effect. However, the frequency was much lower than was reported by Regan & Beverley (1973a), who reported that depth from
geometric disparities was diminished at frequencies that were approximately 5 Hz.
CHAPTER XI

PRELIMINARY EXPERIMENT THREE

Participants

Subjects were RSH, JJD, and WWS. The Institutional Review Board of the University of New Hampshire granted approval for this study, 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

The computer, display monitor, and software were the same as was described previously. Stimuli were stereo pairs of vertically oriented square wave gratings constructed with lighter bars that were dynamically altered to be wider in one eye than in the other (Figures 42 & 43). 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. This is shown in figure 44 where, for illustration, the pixels are colored in white. 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. The overall monocular image remained 1.6° in height and 2.8° in width.
Figure 42. Experimental stimulus for preliminary experiment 3. Right monocular image contains wider lighter bars.
Figure 43. Experimental stimulus for preliminary experiment 3. Left monocular image contains wider lighter bars.
Figure 44. Example of an experimental stimulus showing the pixels (colored in white) that were dynamically altered to make the lighter bars physically wider in one eye than they were in the other.
Procedure

To compare the performance of the visual system’s ability to detect motion-and-depth with the Venetian blind effect (where stimuli do not move on the retina) to cases where a stimulus does move on the retina, the width of three of the bars were dynamically altered to be wider in one eye than in the other. The luminance values of the white pixels, as shown in figure 44, were altered in a square wave manner. Each pixel began at a starting point of 14.5 cd/m² and either increased to 38 cd/m² (luminance of the lighter bars) or decreased to 19.6 cd/m² (luminance of the darker bars). The luminance of the individual pixels was increased in one eye and decreased in the other eye, which made the lighter bars wider in one eye than in the other. While the individual pixels were increased or decreased, the lighter and darker bars remained at a constant luminance.

The frequency at which the pixel luminance was alternated was in a range between 0.2 to 5 Hz in steps of 0.2 Hz (0.2, 0.4, 0.6, 0.8, etc). Each subject completed one hundred trials that lasted a minimum of approximately 33 minutes. Each experimental session consisted of four choices for each frequency. Two sessions were completed for each subject for a total of eight choices for each frequency. All other procedures for set up and responding were the same as in the previous preliminary experiments.
Results

The probability of reporting depth or no depth was calculated as a function of frequency and plotted for each individual subject and across subjects and are shown in figures 45-48. Probabilities are shown in figure 45 for RSH, figure 46, for WWS, 47 for JJD and across all subjects in figure 48. Standard errors are calculated using the score confidence interval (Equation 2 from Agresti & Coull, 1998; Wilson, 1927) with n = 8 and α = 0.682. Plots show the probability of detection as a function of frequency of disparity changes. Curves were fit using the cumulative distribution function for a Laplace distribution with a mean of μ and a scaling factor of β. Least-squares fits were determined using the FindFit procedure in Mathematica 6.0.1.0. The mean (μ) is the frequency that represents the threshold for detection at a given stimulus. The standard deviation can be calculated by multiplying the square root of two by β (\sqrt{2}(β)). Curves were not fit if the observer did not respond above threshold (0.5 probability).

Discussion

Regan & Beverley (1973a) and others (Richards, 1951; Tyler, 1971; Beverley & Regan, 1973a; 1973b; 1974a; 1974b; 1975; Regan & Beverley, 1973b; 1979) have suggested that the perception of depth decreases as the frequency of depth oscillations increases and will diminish completely once the frequency of disparity oscillations reaches a certain level. Regan & Beverley used geometric disparities and found that depth was no longer visible when the frequency was above about 5 Hz.
Figure 45. Probability of responding to perceived depth as a function of frequency, for RSH in preliminary experiment 3.
Figure 46. Probability of responding to perceived depth as a function of frequency, for WWS in preliminary experiment 3.
Figure 47. Probability of responding to perceived depth as a function of frequency, for JJD in preliminary experiment 3.
Figure 48. Probability of responding to perceived depth as a function of frequency, pooled across RSH, WWS, and JJD in preliminary experiment 3.
The first two preliminary experiments have suggested that the perception of motion-and-depth and depth in the Venetian blind effect decrease and are eliminated at frequencies much lower than 5 Hz. The goal of the third preliminary experiment was to determine the frequency at which perceived rotation of individual bars in a square wave grating is eliminated if a geometric disparity is present as opposed to an overall contrast or luminance disparity between the individual bars.

When geometric disparities are introduced between individual bars of a square wave grating, the frequency can be adjusted to a level of approximately 2.6 Hz before becoming disrupted and even when frequencies reach 5 Hz the perception of depth is not completely disrupted. RSH and WWS both reported depth up to frequencies of approximately 2.6 Hz without disruption. Once above 2.6 Hz, RSH (figure 45) began to report more cases where depth was not visible than did WWS (figure 46). JJD (figure 47) reported seeing depth up until approximately 4.5 Hz without disruption. When looking at each subject individually, or when the results are combined for all subjects (figure 48), the perception of depth is uninterrupted up to approximately 2.6 Hz and does not decrease completely at frequencies of 5 Hz.

These findings, along with the first two preliminary experiments, suggest that the perception of depth from geometric disparities, and from the Venetian blind effect, is not processed in the same way. This is a contradiction to the model proposed by Cibis & Haber (1951). Cibis & Haber suggested that the Venetian blind effect was a result of a geometric disparity caused by different
illuminance reaching the eye and irradiation that leads the image in one eye to be smaller. If the Cibis & Haber model was correct, and if the Venetian blind effect somehow caused a geometric disparity in the images viewed by each eye, it would be expected that the Venetian blind effect would decrease and be eliminated at frequencies comparable to cases where there is a geometric disparity. The results, however, show that the Venetian blind effect reduces at frequencies that are much lower than those where the perception of depth from geometric disparities is reduced.

It might be suggested that the amount of rotation caused by increasing the size of the lighter bars by two pixels in one eye was much more than would be seen in the Venetian blind effect. If the amount of rotation is larger, depth would more easily be seen at higher frequencies than is seen in the Venetian blind effect. The amount of slant as a function of horizontal size ratio can be found using an equation introduced by Backus, Banks, van Ee, & Crowell (1999):

\[
S = \tan^{-1} \left( \frac{2d(HSR - VSR^2)}{I \cos \gamma (HSR + VSR^2)} + \tan \gamma \right)
\]

where \( HSR \) is the horizontal size ratio, \( VSR \) is the vertical size ratio, \( d \) is the viewing distance to the target, \( I \) is the interocular distance, and \( \gamma \) is the positive azimuth. The horizontal and vertical size ratios consist of the ratio of the horizontal and vertical angles subtended by the images in each eye. The positive azimuth is the angle of lateral movement made by the both eyes away from the median plane of the head (Backus et al. 1999). For the stimuli used in
this experiment, the slant from the geometric disparity equals approximately 49° which, when looking at results from Stine & Hetley (2006) (figure 49), falls within the range of horizontal size ratios used by Stine & Hetley to determine the perceived slant angle from the Venetian blind effect. The horizontal size ratio for the lighter bars was approximately 1.05 which, as seen in figure 49, corresponds to a contrast modulation of approximately 0.5.

The computer monitor used by Stine & Hetley (2006) had the capability to generate much higher luminance values than the monitor used for the present experiments. Therefore, for Stine & Hetley, an image with a contrast modulation of 1.0 would have a 100% contrast in the image shown to one eye. Due to luminance constraints of the current monitor, an image with a contrast modulation of 1.0 would have 65% contrast in one eye. For Stine & Hetley, with an average contrast of 0.5 and a contrast modulation of 0.5, the contrast of the image in one eye would be 75%\textsuperscript{17} and would be 25% in the other. For the present experiments, the images had an average contrast of .325 so a contrast modulation of 1.0 would lead to an image with 65% contrast in one eye and 0% contrast in the other eye. When taking the ratio of the luminance values of the individual bars in each eye,\textsuperscript{18} a contrast modulation of 0.5 for Stine & Hetley (2006) would be roughly equivalent to a contrast modulation of 0.68 for the present experiments.

\textsuperscript{17} The contrast of the image in one eye can be calculated using the equation \( \text{con} = (\text{avgcon}) \times (1 \pm \text{conmod}) \), where con is the contrast of the grating in one eye, avgcon is the starting contrast of the grating, and conmod is the contrast modulation used for the two gratings.

\textsuperscript{18} lightbareye1/lightbareye2 and darkbareye1/darkbareye2
Figure 49. Graph from Stine & Hetley (2006) showing the contrast disparities necessary to cancel the perception of depth caused by specific horizontal size ratios.
The results suggest that, in this experiment, the perceived rotation from increasing the size of individual bars in the square wave grating was not larger than perceived rotation that could be created with the Venetian blind effect. Therefore, the results showing that RSH, JJD, and WWS reported that depth was visible at frequencies as high as 5 Hz when the bars were physically wider (geometric disparity) but rarely reported depth above 1.8 Hz in the Venetian blind effect (no geometric disparity) was not a result of a larger amount of rotation with the geometric disparity.
CHAPTER XII

EXPERIMENT ONE

Participants

Subjects were RSH, JJD, and WWS. The Institutional Review Board of the University of New Hampshire granted approval for this study, 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

The apparatus was the same as was used for the three preliminary experiments. Stimuli consisting of stereo pairs of vertically oriented square wave gratings were constructed in the same manner as in the first two preliminary experiments.

Procedure

Procedures were also similar to those used in the preliminary experiments. Stimuli were constructed using a reduced set of values for contrast modulation amplitude and for frequency. Amplitude values were 0.2, 0.4, 0.6, 0.8, & 1. Frequencies ranged from 0.6 to 1.8 Hz in steps of 0.1 Hz (0.6, 0.7, 0.8, etc.). Each subject completed 65 trials for a total session time of approximately 35 min. Also, each subject completed two practice sessions and a total of twelve experimental sessions. Data were again plotted in the form of density plots with
yellow representing a response of "3" when motion-and-depth was perceived, green representing a response of "2" when depth was perceived without motion, and blue representing a response of "1" when the stimulus appeared as a flat grating. Also, the probability of reporting motion-and-depth, depth alone, or no depth was calculated for both, individual, and group data.

Results

Average response data are shown in figure 50 for RSH, in 51 for JJD, and 52 for WWS. A combined density plot for all three subjects is shown in figure 53. Figures E.87- E.104, in Appendix E, show density plots for each of the twelve individual sessions for JJD, WWS, and RSH. Probabilities of reporting motion-and-depth, depth alone, or no depth, are shown in figures 54 for RSH, in 55 for JJD, in 56 for WWS, and in 57 for all three subjects. Standard errors are calculated using the score confidence interval (Equation 2 from Agresti & Coull, 1998; Wilson, 1927) with n = 12 and $\alpha = 0.682$. The plots show probability of each response for a contrast modulation of 0.6. Curves were fit using the same methods as described in the third preliminary experiment. Additional plots showing the probabilities of each response at each contrast modulation are shown in figures E.105- E.124 in Appendix E.

Discussion

Results were similar to those found in the second preliminary experiment. When amplitude values were above a specific value, motion-and-depth was reliably visible at frequencies up to 1 Hz but became more variable at frequencies between 1 and 1.4 Hz. When above 1.4 Hz, depth became rarely
Figure 50. Average response data as a function of contrast modulation and frequency across sessions 1-12 for RSH in experiment 1.
Figure 51. Average response data as a function of contrast modulation and frequency across sessions 1-12 for JJD in experiment 1.
Figure 52. Average response data as a function of contrast modulation and frequency across sessions 1-12 for WWS in experiment 1.
Figure 53. Average response data as a function of contrast modulation and frequency across sessions 1-12 pooled across RSH, JJD, and WWS in experiment 1.
Figure 54. Probability of reporting no depth (top), depth alone (middle), or motion-and-depth (bottom) at a contrast modulation of 0.6 as a function of frequency for RSH in experiment 1.
Figure 55. Probability of reporting no depth (top), depth alone (middle), or motion-and-depth (bottom) at a contrast modulation of 0.6 as a function of frequency for JJD in experiment 1.
Figure 56. Probability of reporting no depth (top), depth alone (middle), or motion-and-depth (bottom) at a contrast modulation of 0.6 as a function of frequency for WWS in experiment 1.
Figure 57. Probability of reporting no depth (top), depth alone (middle), or motion-and-depth (bottom) at a contrast modulation of 0.6 as a function of frequency for pooled across RSH, JJD, and WWS in experiment 1.
reported and was not reliably visible at frequencies close to 1.8 Hz. The frequency range in which the Venetian Blind effect becomes no longer visible is much lower than that reported by previous work in which actual geometric disparity cues were oscillated (Tyler, 1971; Richards, 1972; Regan & Beverley, 1973a, b; Beverley & Regan, 1974a, b). This result suggests that the model given by Cibis & Haber (1951) may not accurately account for perceived depth from the Venetian Blind effect.
CHAPTER XIII

EXPERIMENT TWO

Participants

Subjects were RSH, JJD, and WWS. The Institutional Review Board of the University of New Hampshire granted approval for this study, 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

The apparatus was the same as in the preliminary experiments and experiment one. Stimuli were constructed in the same manner as in the third preliminary experiment. One pixel on each side of the lighter bars of the square wave grating began at the same luminance in both monocular images. The luminance of each pixel was increased to the luminance of the lighter bars in one monocular image while being decreased to the luminance of the darker bars in the other monocular image which, when animated, created the appearance of individual bars increasing and decreasing in size in a square wave motion.

Procedure

The procedures were similar to those used in the third preliminary experiment. The frequency at which the pixel luminance was alternated was in a range between 0.2 to 5 Hz in steps of 0.2 Hz (0.2, 0.4, 0.6, 0.8, etc). Each
subject completed one hundred trials for a session time of approximately 45 minutes. Each experimental session consisted of four choices at each frequency value. Each subject completed two sessions for a total of eight choices at each frequency value. As a result of reports in the third preliminary experiment, a third response was possible. Upon finishing the third preliminary experiment, WWS and JJD reported that, in some cases, the bars would appear to smoothly rotate at a frequency much lower than the frequency at which the bars were becoming larger or smaller in each eye. It is for this reason, that during experiment two, subjects were given the opportunity to make a response of “3” if they observed aliasing during an experimental session. Probabilities of making a response of “1” for no depth, “2” for depth alternating back and forth in a square wave motion, or “3” for aliasing were plotted for each individual subject and for all three subjects combined.

**Results**

Probabilities of reporting, depth alone, no depth, or aliasing are shown in figure 58 for RSH, in 59 for JJD, in 60 for WWS, and in 61 for all three subjects combined. Aliasing was reported by WWS and JJD, but was not reported by RSH. Standard errors are calculated using the score confidence interval (Equation 2 from Agresti & Coull, 1998; Wilson, 1927) with \( n = 16 \) and \( \alpha = 0.682 \). Therefore, figure 62 shows the combined probabilities of WWS and JJD only. Curves were fit using the same methods as described in the third preliminary experiment.
Figure 58. Probability of reporting no depth (top), depth alone (middle), or motion-and-depth at a slower rate than the frequency (bottom) as a function of frequency for RSH in experiment 2.
Figure 59. Probability of reporting no depth (top), depth alone (middle), or motion-and-depth at a slower rate than the frequency (bottom) as a function of frequency for JJD in experiment 2.
Figure 60. Probability of reporting no depth (top), depth alone (middle), or motion-and-depth at a slower rate than the frequency (bottom) as a function of frequency for WWS in experiment 2.
Figure 61. Probability of reporting no depth (top), depth alone (middle), or motion-and-depth at a slower rate than the frequency (bottom) as a function of frequency pooled across RSH, JJD, and WWS in experiment 2.
Figure 62. Probability of reporting no depth (top), depth alone (middle), or motion-and-depth at a slower rate than the frequency (bottom) as a function of frequency pooled across JJD and WWS in experiment 2.
**Discussion**

This experiment was conducted by dynamically increasing the width of vertical bars within a square wave grating shown to one eye while decreasing the width of the bars in the grating shown to the other eye. Subjects perceived individual bars rotating back and forth at different rates depending on the frequency at which the bars were increased/decreased in each eye. In agreement with results from previous research (Tyler, 1971; Richards, 1972; Regan & Beverley, 1973a, b; Beverley & Regan, 1974a, b), the probability of perceiving depth decreased as the frequency increased, but was still reported in some cases at 5 Hz. This result suggests that, in preliminary experiments, and in experiment one, that perceived depth from the Venetian Blind effect (diminishes at frequencies below 1.8 Hz), does not seem to be processed in the same way as perceived depth from geometric disparities.
EXPERIMENT THREE

Participants

Subjects were RSH, JJD, and WWS. The Institutional Review Board of the University of New Hampshire granted approval for this study, 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

The apparatus was the same as in the previous experiments. Stimuli were stereo pairs of vertically oriented square wave gratings constructed in the same manner as in previous experiments.

Procedure

The procedures were similar to those used in the preliminary experiments and in the first experiment. Stimuli were constructed using the same set of values for contrast modulation amplitude and frequency used for the first experiment. Amplitude values were 0.2, 0.4, 0.6, 0.8, & 1. Frequencies ranged from 0.6 to 1.8 Hz in steps of 0.1 Hz (0.6, 0.7, 0.8, etc.). Since, in the second proposed experiment, it was found that depth decreases at frequencies well above the frequencies found in the first proposed experiment, one could ask whether or not some difference in square wave modulation (second proposed experiment) as opposed to sine wave modulation (first proposed experiments)
contributed to the perception of depth reducing at lower frequencies. Stimuli were therefore, animated by increasing and decreasing the contrast of the grating shown to each eye in a square wave motion rather than smoothly increasing and decreasing in a sine wave motion. As described above, the amplitude and frequency values were the same as was used for the stimuli animated in a sine wave motion.

Each subject completed 65 trials for a total session time of approximately 35 min. Each subject completed two practice sessions and a total of twelve experimental sessions. Data were plotted in the form of density plots with green representing a response of “2” when depth was perceived alternating back and forth, and blue representing a response of “1” when the stimulus appeared as a flat grating. It was possible for the subjects to make a response of “3” for smooth movement-in-depth but this perception was never reported. Also, the probability of reporting depth alone or no depth was calculated for both, individual, and group data.

**Results**

Average response data are shown in figure 63 for RSH, in 64 for JJD, and 65 for WWS. A combined density plot for all three subjects is shown in figure 66. Figures F.125- F.142, in Appendix F, show density plots for each of the twelve individual sessions for JJD, WWS, and RSH. Probabilities of reporting depth or no depth are shown in figures 67 for RSH, in 68 for JJD, in 69 for WWS, and in 70 for all three subjects combined. Standard errors are calculated using the score confidence interval (Equation 2 from Agresti & Coull. 1998; Wilson, 1927)
Figure 63. Average response data as a function of contrast modulation and frequency across sessions 1-12 for RSH in experiment 3.
Figure 64. Average response data as a function of contrast modulation and frequency across sessions 1-12 for JJD in experiment 3.
Figure 65. Average response data as a function of contrast modulation and frequency across sessions 1-12 for WWS in experiment 3.
Figure 66. Average response data as a function of contrast modulation and frequency across sessions 1-12 pooled across RSH, JJD, and WWS in experiment 3.
Figure 67. Probability of reporting depth at a contrast modulation of 0.6 as a function of frequency for RSH in experiment 3.
Figure 68. Probability of reporting depth at a contrast modulation of 0.6 as a function of frequency for JJD in experiment 3.
Figure 69. Probability of reporting depth at a contrast modulation of 0.6 as a function of frequency for WWS in experiment 3.
Figure 70. Probability of reporting depth at a contrast modulation of 0.6 as a function of frequency pooled across RSH, JJD, and WWS in experiment 3.
Curves were fit using the same methods as described in the third preliminary experiment, with \( n = 12 \) and \( \alpha = 0.682 \). The plots show probability of each response for a contrast modulation of 0.6. Additional plots showing the probabilities of making each response at each contrast modulation are shown in figures F.143- F.162 in Appendix F.

**Discussion**

Results were similar to those found in the first experiment. Depth was visible up to approximately 1.4 Hz but began to decrease and was completely diminished by approximately 1.8 Hz. The results of this experiment, along with the results of experiment one, show that when cues for the Venetian Blind effect are oscillated at frequencies between 1.4 and 1.8 Hz, perceived depth diminishes as the frequency increases and is completely diminished at approximately 1.8 Hz. Experiment two found that, if a geometric disparity is introduced in the type of images used in experiments one and two, depth is still perceived in some cases at 5 Hz. Taken together these three experiments suggest that, perceived depth from the Venetian Blind effect does not seem to be processed in the same way as perceived depth from geometric disparities.
EXPERIMENT FOUR

Participants

Subject JRH was not an experienced observer and was naïve to the specific details and hypotheses of the experiment. JRH has myopia, which is corrected by glasses. The Institutional Review Board of the University of New Hampshire granted approval for this study, and JRH 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

The apparatus was the same as was used for previous experiments. Stimuli consisting of stereo pairs of vertically oriented square wave gratings were constructed in the same manor as in the first two preliminary experiments and experiments one and three.

Procedure

Procedures were similar to those used in previous experiments. Stimuli were constructed using a reduced set of values for contrast modulation amplitude and for frequency. To minimize the amount of time required for JRH, only one amplitude value (0.6) was used for this experiment. Frequencies ranged from 0.6 to 1.8 Hz in steps of 0.2 Hz (0.6, 0.8, 1.0, etc.), and contrast modulations were alternated in a square wave motion. JRH completed 42 trials for a total session time of approximately 20 min. JRH completed two practice sessions and two
experimental sessions. Just as in experiment three, a response was made to each individual data point twelve times. The probability of reporting depth or no depth was calculated.

**Results**

Probabilities of reporting depth or no depth are shown in figure 71. The plots show probability of each response for a contrast modulation of 0.6. Standard errors are calculated using the score confidence interval (Equation 2 from Agresti & Coull, 1998; Wilson, 1927) with n = 12 and $\alpha = 0.682$. A curve was fit using the same methods as described in the third preliminary experiment.

**Discussion**

Results were similar to those from experiment one for JJD, RSH, and WWS. JRH reliably reported depth until approximately 1 Hz. Between 1 and 1.4 Hz depth was less reliably reported and was not reported when the frequencies began to reach 1.8 Hz. The fact that JRH was able to reliably see the Venetian blind effect at low frequencies and that the perception of depth decreased above 1 Hz and was diminished completely before 1.8 Hz gives strong support for the reliability of the results of JJD, RSH, and WWS.
Figure 71. Probability of reporting depth as a function of frequency for JRH in experiment 4.
CHAPTER XVI

EXPERIMENT FIVE

Participants

The subject was again JRH who only had experience as an observer in experiment 4 and who was naïve to the specific details and hypotheses of the experiment. The Institutional Review Board of the University of New Hampshire granted approval for this study, and JRH 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

The apparatus was the same as was used for previous experiments. Stimuli consisting of stereo pairs of vertically oriented square wave gratings were constructed in the same manor as in the third preliminary experiment and experiment two.

Procedure

Procedures were similar to those used in previous experiments. Stimuli were constructed in the same manor as in the third preliminary experiment and in experiment two. Individual pixels were increased and decreased in luminance to make the individual bars of the grating increase and decrease in size in a square wave motion at a given frequency. Frequencies ranged from 0.2 to 5 Hz in steps of 0.4 Hz (0.2, 0.6, 1.0, etc.). JRH completed 104 trials for a total session time of approximately 50 min. JRH completed two experimental sessions. Just as in
experiment two, a response was made to each individual data point sixteen
times. The probability of reporting depth, no depth, or aliasing was calculated.

Results

The probabilities of reporting depth, no depth, or aliasing are shown in
figure 72. Standard errors are calculated using the score confidence interval
(Equation 2 from Agresti & Coull, 1998; Wilson, 1927) with $n = 16$ and $\alpha = 0.682$.
Curves were fit using the same methods as described above.

Discussion

Results were similar to those from experiment 1 for JJD, RSH, and WWS.
The probability of reporting depth began to decrease between 1 and 2 Hz and
was still reported in some cases at 5 Hz. Again, these results give support for
the reliability of results from JJD, RSH, and WWS in experiment two.

In experiment two, RSH reported no cases where the bars appeared to
rotate back and forth at a slower rate than the frequency in the animation
(aliasing), JJD reported some cases, and WWS reported a large number of
cases. In this experiment, JRH did report slower movement in some cases,
which suggests that large individual differences do exist. Despite only reporting
a few cases of aliasing, JRH reported that the perception was clear; the
individual bars appeared to slowly, and smoothly, rotate back and forth at a
frequency far lower than what was indicated by the small rectangles placed in the
center of the top and bottom nonius line. As noted above, the results indicate
large individual differences. It would be of interest in future work, to further
explore what may be leading to the perception of aliasing.
Figure 72. Probability of reporting no depth (top), depth alone (middle), or motion-and-depth at a slower rate than the frequency (bottom) as a function of frequency for JRH in experiment 5.
CHAPTER XVII

OVERALL DISCUSSION

Several studies have shown that changing geometric disparities over time can create the perception of motion-and-depth (Richards, 1951; Tyler 1971; Beverley & Regan, 1973a, 1973b; Regan & Beverley, 1973a, 1973b; Shioiri et al., 2000; & Fernandez & Farell, 2005), that the responses of specific neurons can be measured in response to disparity cues (Cynader & Regan, 1978; Regan & Cynader 1982), and that, as the frequency of depth oscillations increases, the amount of depth that is perceived is reduced and eventually completely diminished (Richards, 1951; Tyler 1971; Beverley & Regan, 1973a, 1973b; Regan & Beverley, 1973a, 1973b).

Two questions were behind the current research: First, would changes in luminance or contrast disparity (not geometric disparities) over time create the impression of motion-and-depth using the Venetian blind effect? The results from experiment one (figures 50-57) show that changes in luminance or contrast disparities over time can create the impression of motion-and-depth. All three subjects reported individual bars of a square wave grating smoothly rotating back and forth around a vertical axis.

Second, since motion-and-depth has been found to decrease at frequencies above 1 Hz and completely stop at frequencies close to 5 Hz (Richards, 1951; Tyler 1971; Beverley & Regan, 1973a, 1973b; Regan & Beverley, 1973a, 1973b), if the Venetian blind effect can appear to move in
depth, would it decrease in the same manner as other cases of motion-and-depth?

The results of experiment one (figures 50-57) shows that the perception of motion-and-depth and depth 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 63-70), where the contrast of the gratings were increased and decreased in a square wave motion. With the square wave motion, the bars did not seem to smoothly rotate, but would jump back and forth from one position to another. The perception of depth again decreased when above approximately 1 Hz, and was completely diminished before 1.8 Hz.

A further question involved whether or not the perception of depth from bars that were physically larger in one eye (a geometric disparity) would diminish at approximately 5 Hz. The results of the second experiment (figures 58-62) showed that, if the size of individual square wave grating bars were alternatingly increased and decreased in one eye by two pixels, reports of depth became more variable above 1-2 Hz and was still reported at 5 Hz in some cases. Also, when comparing the results from experiment two to the results of Stine & Hetley (2006), the amount of rotation from the geometric disparity of a two pixel increase in the image shown to one eye, was not beyond the amount of rotation that could be generated by the Venetian blind effect.

The subjects for experiments 1-3 were experienced observers who knew the specific details of the experiment and the experimental hypotheses.
Experiments 4 and 5 served to determine whether a naïve subject could reliably see the Venetian Blind effect, and if so, would perceived depth diminish at the same frequencies as for JJD, RSH, and WWS. In experiment 4, JRH reliably reported depth at frequencies below 1 Hz but perceived depth became more variable above 1 Hz and was completely diminished below 1.8 Hz. In experiment 5, JRH reported depth at frequencies below 2 Hz and continued to report depth in some cases at 5 Hz. These results replicate those of experiments 2 and 3 suggesting that the results of RSH, JJD, and WWS were not a result of experience with the stimuli or knowledge of the hypotheses.

Cibis & Haber (1951) interpreted depth arising from lower luminance as a result of irradiation that causes the image in one eye to be reduced in size, thus creating a geometric disparity. Cibis & Haber's interpretation was called into question when Filley (1998) found that stimuli that were above threshold would create the perception of depth if the retinal illuminance or Michelson contrast were greater in one eye than in the other.

The results of experiments 1-3 showing that depth from the Venetian Blind effect decreases at frequencies below 1.8 Hz, whereas depth from geometric disparities can remain visible at 5 Hz, also contradicts the Cibis-Haber model. As described above, the Cibis-Haber model interpreted the Venetian blind effect as being a result of geometric disparities, caused by decreased illuminance in one eye. If irradiation creates a geometric disparity within the Venetian blind effect, then perceived depth from the Venetian Blind effect should decrease at the same
frequency as perceived depth from an actual geometric disparity. The results from experiments 1-3, suggest that Cibis & Haber's assumption is not true.

The large difference between depth perceived as a result of a geometric disparity and depth perceived as a result of the Venetian Blind effect, can be seen in figures 73-76. Figures show the critical frequency as a function of the contrast modulation amplitude for JJD (figure 73), RSH (figure 74), WWS (figure 75), and pooled across all subjects (figure 76). Plots contain dashed lines (large dashes for "depth and motion" and small dashes for "no depth") for experiment one, and a solid line for experiment three. The critical frequencies for experiment two are shown in each plot as one point at a modulation of 0.68 (contrast modulation that would be necessary to cancel perceived rotation from the geometric disparity). Critical frequencies were calculated using the cumulative distribution function for a Laplace distribution that was described above. Error bars represent the standard deviation (\(\sqrt{\frac{2}{(\beta)}}\)) for each of the curve means (\(\mu\)) at each contrast modulation amplitude. Therefore, these error bars do not represent error in estimating the threshold from the data. Rather, they represent the slope of the psychometric functions used to estimate thresholds.

There is no notable difference in critical frequency for sine wave (experiment one) and square wave (experiment three) contrast modulations. Frequencies for both modulations fall below 2 Hz, whereas the frequencies for the geometric disparity (experiment 2) range between 3.6 and 5 Hz, both of which are above the critical frequency for the Venetian Blind effect. It is of interest that there are no differences between sine and square wave Venetian
Figure 73. Critical frequency for threshold as a function of contrast modulation amplitude, for JJD. (a) Critical frequency as a function of contrast modulation amplitude for perception of depth and motion (large dashes) and "no depth" (small dashes) in experiment one. (b) Critical frequency as a function of contrast modulation amplitude for "no depth" (solid line) in experiment three. (c) Critical frequency for a geometric disparity (single data point) in experiment two.
Figure 74. Critical frequency for threshold as a function of contrast modulation amplitude, for RSH. (a) Critical frequency as a function of contrast modulation amplitude for perception of depth and motion (large dashes) and "no depth" (small dashes) in experiment one. (b) Critical frequency as a function of contrast modulation amplitude for "no depth" (solid line) in experiment three. (c) Critical frequency for a geometric disparity (single data point) in experiment two.
Figure 75. Critical frequency for threshold as a function of contrast modulation amplitude, for WWS. (a) Critical frequency as a function of contrast modulation amplitude for perception of depth and motion (large dashes) and "no depth" (small dashes) in experiment one. (b) Critical frequency as a function of contrast modulation amplitude for "no depth" (solid line) in experiment three. (c) Critical frequency for a geometric disparity (single data point) in experiment two.
Figure 76. Critical frequency for threshold as a function of contrast modulation amplitude, pooled across JJD, RSH, and WWS. (a) Critical frequency as a function of contrast modulation amplitude for perception of depth and motion (large dashes) and “no depth” (small dashes) in experiment one. (b) Critical frequency as a function of contrast modulation amplitude for “no depth” (solid line) in experiment three. (c) Critical frequency for a geometric disparity (single data point) in experiment two.
Blind effect critical frequencies because, even at higher frequencies, it is not difficult to tell the difference between the two as an observer; stereo-motion is perceived with the sine-wave modulation but not with the square-wave modulation. Both sine wave and square wave modulations are driven by the wave's fundamental frequency, but the square wave modulation is also composed of a set of higher harmonics; frequencies that are three or more times the fundamental. Therefore, the stereo system is somehow able to respond to frequencies of at least 4.5 Hz in the harmonics in order to respond to stereo-motion though the stereo system is limited to 1.5 Hz for perceived depth; the critical frequencies for square wave and sine wave modulations do not differ. Further, the critical frequencies are much higher for perceived depth from a geometric disparity.

Regan et al. (1979) attempted to determine possible mechanisms underlying the perception of stereo-motion. One possibility is that an object moving in depth would activate binocular depth cells tuned to detect position in depth; objects moving in depth would "successively activate a sequence of binocular depth cells" which could enable an observer to detect motion in depth. Also, that these cues for depth could be "neurally compared to give an estimate of the object's direction of motion in depth (p. 492)," but that the direction of motion and depth signal would not be precise, and would take a long time to process. A second possibility they suggest is a mechanism specifically tuned to the direction of motion in depth, which would be more precise and would allow an individual to detect an object moving directly towards the head more rapidly.
Regan et al. (1979) recorded form 101 units in area 18 of cat visual cortex. Twenty-nine of the 101 cells were found to be sensitive to the direction of motion in depth over a small range of directions. Despite being sensitive to direction of motion in depth, the cells were not, or were only minimally, sensitive to position in depth. Also, some of the cells showed a directionally selective inhibition where "with binocular stimulation, the 'silent' eye strongly inhibited the responses of the active eye. (p. 491)." They conclude that these types of cells enhanced information about stereo-motion in depth "at the expense of positional information," and therefore, that there are separate subsystems for position in depth and motion in depth.

Regan et al. (1979) do not discuss how fast the visual system might detect stereo-motion in depth, but do suggest that it would be much faster than detection of stereo-motion in depth with cells dedicated to stereo-position in depth. It might be that in the current experiments with geometric disparities and with the Venetian Blind effect, the higher harmonics are being picked up by the cells specifically tuned to the direction of motion in depth and that the information regarding position in depth is being picked up by stereo-position in depth cells (described in detail below). The quick jump in perceived depth with the square wave modulation (containing the higher harmonics) might give cues for an object moving towards the head, which would be determined using the detectors for stereo-motion in depth described by Regan et al. and, if the conclusion is correct, would be processed at a much faster rate by cells specifically tuned to the direction of stereo-motion in depth.
A basic goal of this research has been to better understand the factors that lead to a perception of depth from the Venetian Blind effect. It remains unclear what neural mechanisms generate the effect, and how they relate to the mechanisms responsible for edge-based stereopsis. As noted above, the Cibis & Haber (1951) model predicts that the mechanisms for the Venetian blind effect are the same as those for edge-based stereopsis. For edge-based stereopsis, a stimulus with a larger retinal image in one eye than the other eye is interpreted as a depth cue and the observer would perceive depth.

Cibis & Haber suggested that decreases in overall illuminance to an eye would decrease the size of the image in that eye. They assumed that factors similar to modulation transfer function of the eye (e.g., Williams, Brainard, McMahon, & Navarro, 1994) that was demonstrated several years later, would lead the image falling on that retina to have smaller energy distribution (figure 12) than the image on the other retina. The model proposed by Cibis & Haber relied on the assumption that the dark area surrounding the two white squares was below both a sensory and perceptual threshold. The results of Filley (1998) contradicted this model because all of the bars within the square wave gratings were above threshold and yet rotation was perceived. Above threshold images should not lead to a smaller image in the way that had been proposed by Cibis & Haber. The visual system must somehow feed information regarding illuminance or contrast disparities into the stereo system, which then must assign a depth value at the edges to create the perceived rotation.
The question then arises: how does illuminance and contrast information "feed in" to the stereo system? A simple model could assume that, for perceived depth from a geometric disparity, a binocular cell that monitors disparity information would have a differential response depending on the relative disparity in the image falling on each retina. The results described above in experiments three and four, and those from previous work (Richards, 1951; Tyler 1971; Beverley & Regan, 1973a, 1973b; Regan & Beverley, 1973a, 1973b), suggest that depth responses can be made even as the frequency of disparity reversals approaches 5 Hz. For the Venetian Blind effect, the stereo system is gaining information about disparities in illuminance or contrast at a much slower rate. One might suggest that, like the binocular cells that monitor geometric disparities, there may be binocular cells that monitor disparities in illuminance or contrast (cells for the Venetian Blind effect (VB cells)).

When viewing a rotated object, binocular cells that monitor geometric disparities could detect the disparity and make the appropriate depth response, without a need for cells to monitor disparities in illuminance or contrast. It seems then that a VB cell might not hold a primary role in depth perception. VB cells may, however, serve a supportive role. As noted above, in a majority of cases, geometric disparities serve as the primary cues for depth perception, and illuminance and contrast cues would be much less relevant. However, since results from Cibis & Haber (1951) and Hetley (2004) have both shown that perceived depth from a geometric disparity can be cancelled with a disparity in
illuminance or contrast, these disparities clearly influence the perception of rotation.

If specific VB cells exist, then why would they have a slower time course? It was suggested above that a VB cell might serve a supportive role since most stimuli (if rotated) would have a geometric disparity that would be a stronger cue for depth. VB cells might serve to enhance the perception of depth by giving a deeper, richer, perception of depth. A cell of this nature would not necessarily need a fast time course; typical binocular cells would detect the geometric disparity quickly and VB cells would enhance the perception.

A major question would be why these cells have not been discovered previously. It is possible that no one has looked. Cells not responding to a geometric disparity would not necessarily be tested in previous experiments, and the stimuli that are used might not necessarily have a disparity in illuminance or contrast. If, while recording the responses of a single binocular cell, responding changed when a disparity in luminance or contrast were present, then support for the existence of a VB cell might have been found.

At least three things can be said about the perception of depth. First, depth from geometric disparities can be cancelled with a luminance (Cibis & Haber, 1951; Hetley, 2005) or contrast disparity (Hetley, 2005). Second, the perception of depth can occur when there are (Wheatstone, 1838), or are not (Julesz, 1960), monocularly visible differences between the images seen by each eye. Third, the perception of depth can occur solely as a result of a luminance (Cibis & Haber, 1951) or contrast disparity between the two eyes (Cibis & Haber,
1951; Filley, 1998; Hetley, 2005). When a luminance or contrast disparity exists, there are no monocular edge differences between the two images; therefore, some component of the visual system must be feeding information into the stereo system about differences in illuminance or contrast between the two eyes and assigning a depth value for the edges that leads to the perception of depth. This component may take longer to "feed in" the luminance or contrast information, which would explain why depth from geometric disparities is visible up to 5 Hz, whereas depth from the Venetian blind effect is no longer visible at frequencies slightly below 2 Hz.
LIST OF REFERENCES


APPENDICES
APPENDIX A

APPROVAL FOR USE OF HUMAN SUBJECTS
Stine, William  
Psychology  
Conant Hall  
Durham, NH 03824  

**IRB #:** 2937  
**Study:** The Venetian Blind Effect and Binocular Contrast & Luminance Summation  
**Review Level:** Expedited  
**Approval Expiration Date:** 18-Apr-2008  

The Institutional Review Board for the Protection of Human Subjects in Research (IRB) has reviewed and approved your request for time extension for this study. Approval for this study expires on the date indicated above. At the end of the approval period you will be asked to submit a report with regard to the involvement of human subjects. If your study is still active, you may apply for extension of IRB approval through this office.

Researchers who conduct studies involving human subjects have responsibilities as outlined in the document, *Responsibilities of Directors of Research Studies Involving Human Subjects*. This document is available at [http://www.unh.edu/osr/compliance/irb.html](http://www.unh.edu/osr/compliance/irb.html) or from me.

If you have questions or concerns about your study or this approval, please feel free to contact me at 603-862-2003 or Julie.simpson@unh.edu. Please refer to the IRB # above in all correspondence related to this study. The IRB wishes you success with your research.

For the IRB,

![Signature]

Julie F. Simpson  
Manager  

cc: File
Exempt Review

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46.101(b)(6) Taste and food quality evaluation and consumer acceptance studies, (i) if wholesome foods without additives are consumed or (ii) if a food is consumed that contains a food ingredient at or below the level and for a use found to be safe, or agricultural chemical or environmental contaminant at or below the level found to be safe, by the Food and Drug Administration, or approved by the Environmental Protection Agency, or the Food Safety and Inspection Service of the U.S. Department of Agriculture.

Protocol is approved as presented in the category checked

Protocol is approved with the following contingencies/comments (attach sheets if necessary)

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Protocol cannot be approved as presented (cite reasons on separate sheet)

DRC Reviewer:  Date: 7/4/17
APPENDIX B

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A17. Journal_Year: 1960
A18. Journal_Volume: 39
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A20. Copy_Pages: Figures 1, 2, and 3
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Author: Gillam, Barbara; Chambers, Deborah; Russo, Thomas
Publication: Journal of Experimental Psychology: Human Perception and Performance
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Date: May 1, 1988

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APPENDIX C

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PRELIMINARY EXPERIMENT TWO INDIVIDUAL DATA
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Contrast Modulation Amplitude

RSH Session 2

Contrast Modulation Amplitude

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