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The Venetian blind effect, binocular luster, and binocular rivalry

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THE VENETIAN BLIND EFFECT, BINOCULAR LUSTER, AND BINOCULAR RIVALRY

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ABSTRACT

THE VENETIAN BLIND EFFECT, BINOCULAR LUSTER, AND BINOCULAR RIVALRY

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When one views a square-wave grating and changes the average luminance or contrast of the monocular images relative to each other, at least three perceptual phenomena occur. These are the Venetian blind effect, or a perceived rotation of the bars around individual vertical axes; binocular luster, or a perceived shimmering; and binocular rivalry, or an alternating perception between the views of the two eyes. In this paper, it is shown that increasing the dichoptic luminance modulation leads to these three phenomena in sequence, while increasing dichoptic contrast modulation generally only leads to perceived rotation.

It is also shown that average luminance and contrast are not the deciding factors in when the three perceptual phenomena occur. Perception of luster and rivalry occur when the light bars in the grating dichoptically straddle the background luminance, with little impact of the dark bars, as demonstrated when light bars or dark bars are presented in isolation. Also when presented in isolation, perceived rotation ceases when the bars dichoptically straddle the background luminance. The deciding factor is shown not to be the adaptation level of the participant and instead to be this relation of the monocular images to the background.

The patterns for perceived rotation versus binocular luster and binocular rivalry suggest separate mechanisms in the visual system. Possible mechanisms are suggested, and experimental manipulations are proposed that would discriminate between them.

CHAPTER I

INTRODUCTION

Humans and other organisms use two eyes, set some distance apart, to extract information about the environment. Some visual information can be utilized by just one eye, such as the luminance or contrast[1] in an image. However, using binocular vision allows us to detect differences between the two eyes' views, extracting unique types of information known as binocular disparities.

Geometric disparities are perhaps the best understood type, resulting when objects in front of the observer appear in different positions and orientations in each eye's view. We use these disparities to create a fused image with depth and three-dimensional (3-D) orientation. Presenting viewers with geometric disparities is the principle behind classic methods of generating 3-D images (see, e.g., Howard & Rogers, 1995, chapter 1).

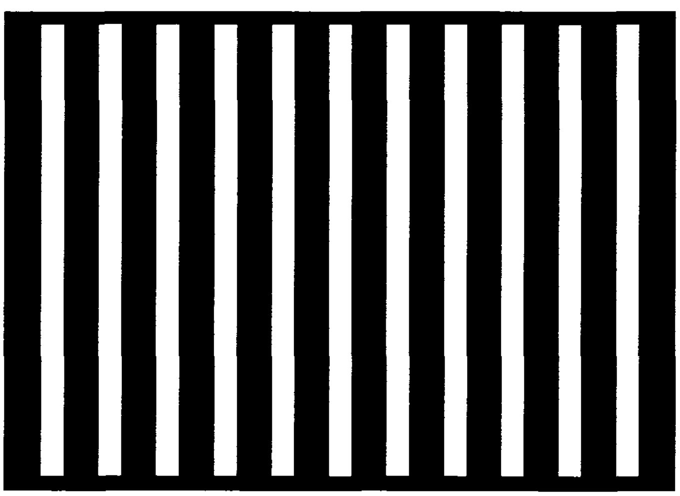

Figure 1. Square-wave grating for demonstrating the Venetian blind effect. See text.

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[1] All references to contrast in this paper are to *Michelson contrast,* defined by the equation

$$C = (L_{max} - L_{min})/(L_{max} + L_{min}),$$

where L_{max} and L_{min} are the maximum and minimum luminance values in the image (Michelson, 1927, p. 40).

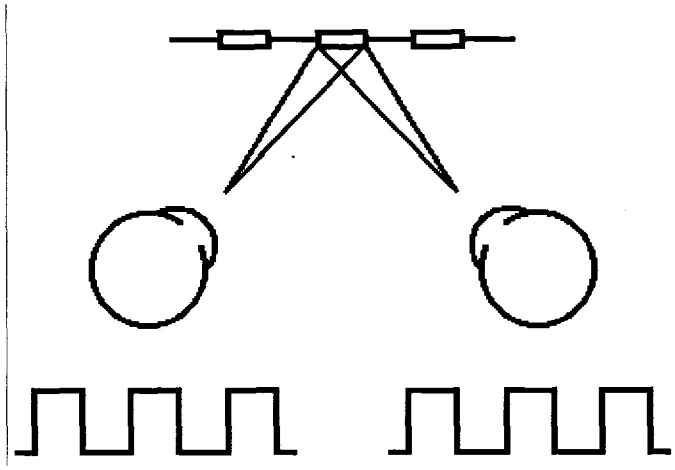

Figure 2. Viewing a square-wave grating with no disparity. Ordinary viewing of Figure 1 leads to identical luminance profiles in each retina for every bar. There is no perception of rotation in depth. See Figure 3.

Münster (1941) discovered that luminance disparities are also important, a fact independently rediscovered by Cibis and Haber (1951), who named what they found the Venetian blind effect. The Venetian blind effect can be observed by viewing a flat image of vertical light bars and dark bars (a square-wave grating; Figure 1) with a neutral density filter over one eye. If the right eye receives the image dimmed by the filter, then the light bars appear to be rotated around individual vertical axes such that their rightmost edge slants out (Figure 2-4, also Figure 5 described in the perceived rotation section, p. 7). The effect is symmetrical when the left eye has the filter, and when observers focus on the dark bars they may appear to be slanted opposite from the light ones (Cibis & Haber, 1951). Filley (1998) discovered that this perceived rotation also occurs

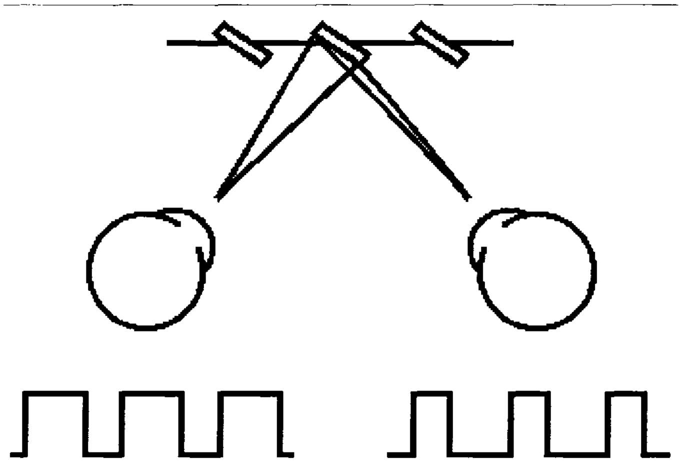

Figure 3. Viewing a square-wave grating with a geometric disparity. Rotated bars would result in narrower luminance profiles in one eye than the other. Thus, geometric disparities are important to perceived rotation. See Figure 4.

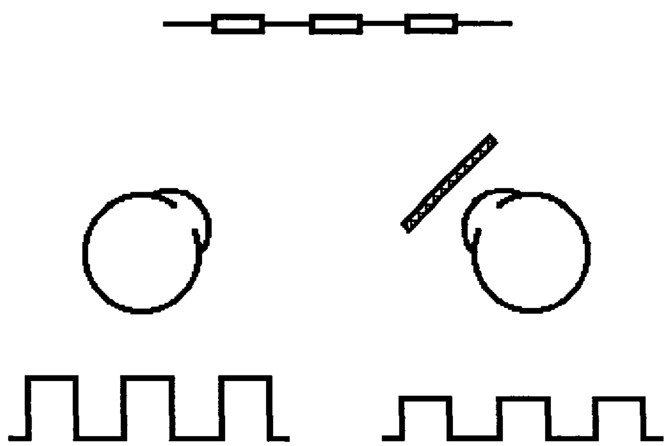

Figure 4. Viewing a square-wave grating with a luminance disparity. Viewing Figure 1 with a neutral density filter in front of one eye leads to different heights, not widths, in the luminance profile. There is a resultant perception of rotation in depth.

for contrast disparities, where lowering the contrast in one eye's image is analogous to putting a neutral density filter in front of that eye.

These examples with a luminance or contrast disparity, occurring with no geometric disparity, involve an extra dimension: though the viewer experiences a perception of rotation in depth just as with geometric disparities, the viewer must also experience some brightness[2] or perceived contrast. In my master's thesis (Hetley, 2005) I demonstrated that these two perceptions, perceived rotation on the one hand and brightness or perceived contrast on the other, could be described by repartitioning the disparity information. With disparity fundamentally depending on information "input" from the two eyes, the two "output" perceptions could arise by effectively summing the "input" to get brightness or perceived contrast and taking the difference to get perceived rotation[3]. More detail is available in the thesis.

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[2] *Brightness* is the briefer and more common term for perceived luminance. There does not seem to be an accepted briefer term for *perceived contrast.*

[3] More precisely, brightness or perceived contrast in a grating with a luminance or contrast disparity can be described by a norm,

$$\|D\|_p = \left(L^p + R^p\right)^{\frac{1}{p}},$$

where L and R are the average luminance or contrast of the left and right monocular images, and D is the ordered pair (L, R) and represents the binocular image. $\|D\|_p$ is the "pth" norm of D. A second

However, further perceptions are possible beyond these. Dove (1851) discovered a phenomenon which, in the translated works of Helmholtz (1873, 1910/1925), is called stereoscopic or binocular luster. Under similar circumstances to those which cause the Venetian blind effect, i.e., when there is an adequate luminance disparity in an image, the image appears to have a luster like the shimmer on a body of water or reflective piece of metal (Figure 14-15, described in the binocular luster section, p. 19). Informal observations during my master's thesis (Hetley, 2005) suggested that this could also occur for an image with a contrast disparity, but it was more commonly noticed with luminance at that time.

Scientists have also undertaken extensive research on the phenomenon of binocular rivalry (see, e.g., Alais & Blake, 2005). Though generally discussed in terms of geometric disparity and, occasionally, even disparity in color or other submodalities of vision, further observations during my master's thesis (Hetley, 2005) indicated rivalry could occur for an image with a luminance disparity. In rivalry, it becomes nearly impossible to maintain a fused image as perception wavers back and forth between the two eyes' views (Figure 20, described in the binocular rivalry section, p. 32). It may not be meaningful to discuss rivalry with a contrast disparity since one monocular image with very low contrast may be wholly suppressed while the other image dominates perception without alternation.

Some researchers (e.g., Julesz and Tyler, 1976) feel that luster and rivalry co-occur. Some (e.g., Helmholtz, 1873, 1910/1925) feel that luster appears only when there

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grating that has no disparity and is at an average luminance or contrast defined by $\|D\|_p$ will match the original grating on brightness or perceived contrast. To describe perceived rotation, one may replace the summation with a difference, taking care to subtract the smaller number from the larger. In all cases, there are also constants to fit the equation to data from individual viewers, and the value for p may vary.

is no rivalry. And some (e.g., Howard, 1995) feel that the relationship depends on other factors such as the size of the images in question. The relationship between perceived rotation and these other two perceptual phenomena does not seem to have been studied.

Given that the perceived rotation and the brightness or perceived contrast in gratings (Hetley, 2005) may now be describable as phenomena occurring in "parallel," it is possible that perceived rotation, luster, and rivalry occur in "serial." That is, one could imagine a single mechanism in the visual system that would respond to increasing disparity with each of the latter three phenomena, requiring different threshold disparity levels for each one. Alternately, given that luster and rivalry do seem to relate (though the nature of the relationship has not been settled), it is possible that the three phenomena reduce to two independent mechanisms. That is, one could imagine one mechanism in the visual system that would respond with a perception of rotation when certain conditions were met, and a second that independently would respond with luster and/or rivalry when certain conditions were met. I will argue that there must be at least two mechanisms, and that the "conditions" concern both the disparity between the images received by the two eyes and the relation between these images and their background. It is possible that these two mechanisms relate to the two "parallel" perceptions addressed in my master's thesis. I will now discuss terminology used in this paper, then review the literature on these three perceptual phenomena and other relevant topics, and then describe my research into their relationship.

Notes on Terminology

To discuss images, I use certain terminology conventions from Macknik and Martinez-Conde (2004). *Binocular image* and *monocular image* refer to an image presented to two eyes or to one eye, respectively. By definition, a binocular image is composed of a pair of monocular images, so a binocular image can be discussed in terms of both its binocular and monocular qualities. *Dichoptic image* refers to a binocular image that has a disparity or disparities in its two monocular images. *Monoptic image*, being the opposite of dichoptic, refers to an image that has no such disparity. It is important to note that the terms monocular and monoptic are therefore not the same. *Fused image*, a term not used by Macknik and Martinez-Conde, refers to a participant's unified perception of the presentation.

To discuss luminance and contrast disparities, it is first necessary to have a common measure of disparity magnitude. I have adopted *dichoptic luminance modulation* and *dichoptic contrast modulation*, which were developed to specify experimental grating images. Dichoptic luminance modulation appears in the equation

$$avglum = (baselum) * (1 \pm lummod),$$

where *avglum* is the average luminance of one monocular image in cd/m^2 (e.g., the average luminance of the light bars and dark bars in one monocular grating)[4], *baselum* is the base luminance for the binocular image (which is the average luminance of the two monocular images together), and *lummod* is the dichoptic luminance modulation. One monocular image therefore averages above the base luminance and the other averages below, with a magnitude determined by the modulation. The same general equation

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[4] When considering types of monocular images that only incorporate one luminance value instead of alternating bars, *avglum* becomes *lum*.

holds for dichoptic contrast modulation, in Michelson contrast, describing monocular contrasts relative to a base contrast.

Perceived Rotation

Cibis and Haber (1951) gave empirical data on the Venetian blind effect, or perceived rotation, as it results from a luminance disparity. The basic effect can be demonstrated by stereoscopic viewing of Figure 5. Cibis and Haber did not use stereoscopic viewing, and instead used two white squares, 2.6 minutes of visual angle[5] each, both visible to each eye. The luminance from these squares could be estimated[6] at around 100 cd/m^2, and the participants viewed the squares with various strengths of neutral density filters in front of one eye or the other. The filters resulted in from 0.00 to 0.99 dichoptic luminance modulation. By using a cancellation method, i.e., physically rotating the squares until they appeared flat despite the Venetian blind effect, Cibis and Haber found that the

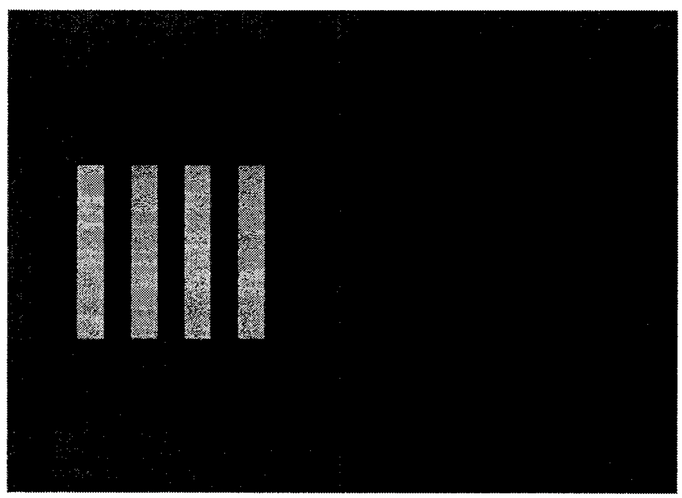

Figure 5. Dichoptic square-wave grating with a luminance disparity. This binocular image has dichoptic luminance modulation of 0.4, and leads to perceived rotation of each bar when perceptually fused.

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[5] Visual angle is the angle subtended by a stimulus in an eye's view, where 1 degree is composed of 60 minutes, and 1 minute is composed of 60 seconds.

[6] Actual luminance values were not given. I estimated this number by projecting light from a Mag-Lite flashlight onto plain white paper in a darkened room, then measuring the light with a Minolta LS-110 photometer. The light used in this study was "a projector," and the material of the squares was not specified.

perceived rotation increased with the disparity up to a plateau at the highest filter strengths. It is worth noting that this "plateau" becomes linear when looking at modulation as the measure of disparity[7].

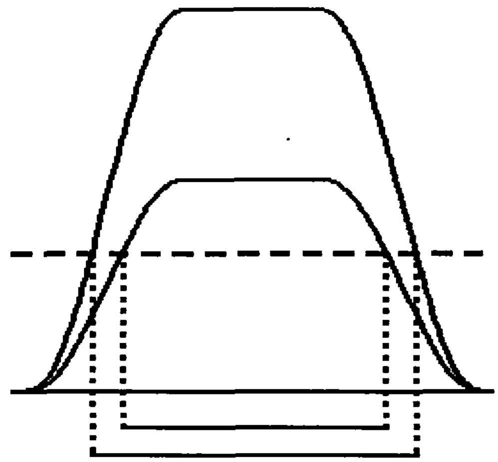

Figure 6. The Cibis & Haber (1951) explanation for the Venetian blind effect. The two curves are luminance profiles for a light bar with and without dimming. The horizontal dotted line is the absolute threshold. The two solid lines at the bottom show the detected width of each bar. See text.

Cibis and Haber (1951) explained the Venetian blind effect as, essentially, the result of an illusory geometric disparity (Figure 6)[8]. Due to the modulation transfer function of the eye (see, e.g., Williams, Brainard, McMahon, & Navarro, 1994), the edges in a square-wave pattern become blurred in their luminance profile on the retina. If the darkest parts of the image are below the absolute threshold for detection, then these blurred edges will cross that threshold at a different point from where a sharp edge would. With the luminance in one monocular image uniformly lowered, the total area detected in that image narrows. As discussed (see Figure 2-3), such geometric disparities are a standard way to generate 3-D images, and in fact Ogle (1952) criticized Cibis and Haber for even giving such a

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[7] For example, the original filter strengths were measured in log units, where a change from 0 to 1 to 2 log units means going from no loss of luminance, to cutting the luminance to a tenth, to cutting the luminance to a hundredth. In dichoptic luminance modulation, this change is from 0 to 0.82 to 0.98, thus compressing and straightening any plateau that would be visible at higher log units.

[8] Figure 6 is adapted from Cibis and Haber's original within Fair Use under U.S. Copyright Law. See Appendix A.

phenomenon a new name. Regardless of the name or the theorist, the Cibis and Haber explanation has been the most common one given for the Venetian blind effect (e.g., Howard & Rogers, 1995, p. 310; Ogle, 1962, pp. 302-303).

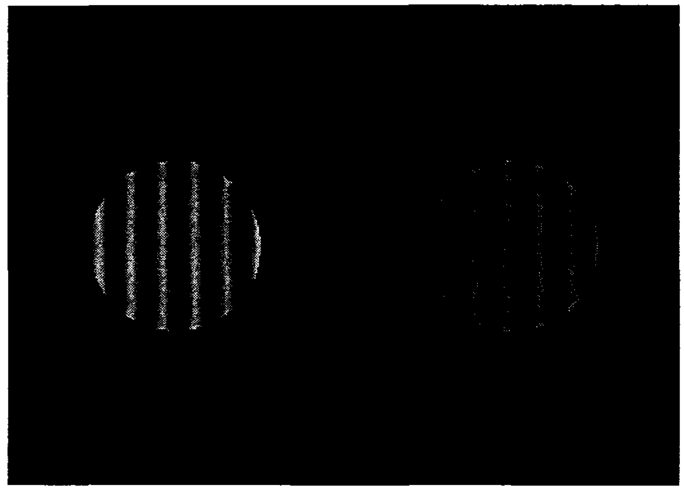

Figure 7. Dichoptic sinewave grating with a contrast disparity on a black surround. This binocular image has dichoptic contrast modulation of 0.5, and may lead to perceived rotation of the entire sinewave pattern when perceptually fused. As discussed in the text, this may be an artifact.

Fiorentini and Maffei (1971), amidst other research, gave a different explanation for the Venetian blind effect based on their findings with contrast disparities. They used sinewave gratings instead of square-wave, which when presented with a contrast disparity and fused appeared to rotate about a single vertical axis. A separate oscilloscope presented one image to each eye, averaging 3 cd/m^2 in luminance, through an aperture 7° in diameter within a black cardboard surround (similar to Figure 7, though this image presents a higher luminance than in the original, and the original did not actually provide a graphic). The gratings had a spatial frequency[9] of either 2 or 6 cycles per degree, with one grating (for either the left or right eye) at 0.5 contrast and the other at various lower contrasts, resulting in from 0.00 to 0.90 dichoptic contrast modulation. By using a matching method, i.e., physically rotating a cardboard rectangle until it appeared parallel

[9] The spatial frequency of a repeating pattern is the number of cycles in a given area, or, more informally, how rapidly its bars repeat.

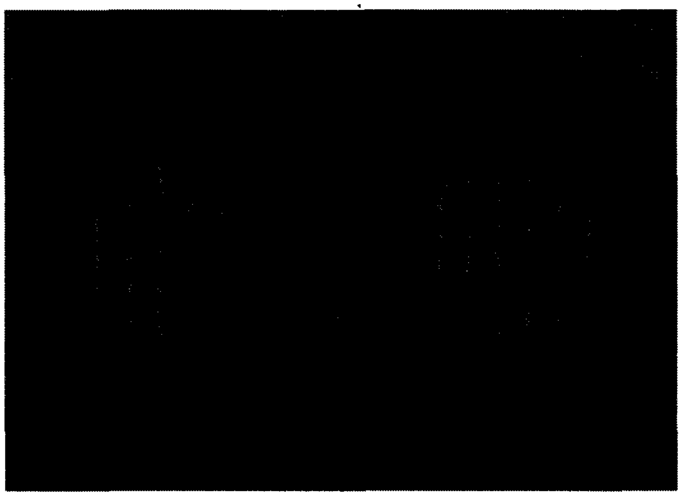

Figure 8. Dichoptic sinewave grating with a spatial frequency disparity. The left monocular image has a spatial frequency of about 2 cycles per degree and the right about 2 1/3 cycles per degree when held at arm's length. This leads to perceived rotation of the entire sinewave pattern when perceptually fused.

to the fused image, Fiorentini and Maffei found that the perceived rotation increased with the contrast disparity up to a plateau.

As the images were sinewaves and only their contrast varied, Fiorentini and Maffei (1971) felt they had eliminated all detectable edges and edge-based explanations. Instead, they explained the perceived rotation in terms of spatial frequency. Previous researchers, notably Blakemore (1970), had shown that spatial frequency disparities lead to a perception of single-axis rotation, such that if the right monocular image has higher spatial frequency then the right edge of the fused image appears closer (Figure 8). Fiorentini and Maffei proposed that a spatial frequency operator in the brain takes the two eye inputs and responds if there is a spatial frequency disparity. An image with weaker contrast would result in a weaker signal to this operator, likewise causing an imbalance and ultimately a perception of rotation (Fiorentini & Maffei, 1971).

Blake and Cormack (1979) were unable to replicate Fiorentini and Maffei's (1971) results, and indeed it may be difficult to perceive rotation in images like Figure 7. However, it is possible that Blake and Cormack did not allow the participants enough time to view the images. A more compelling concern came from Filley (1998), Filley

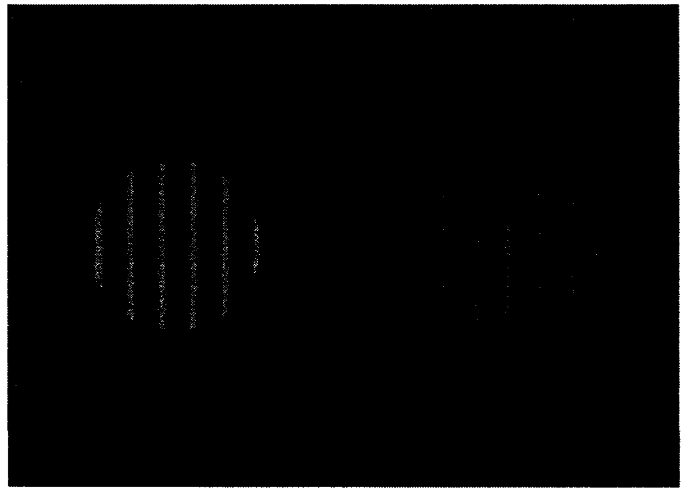

Figure 9. Dichoptic sinewave grating with a contrast disparity on a gray surround. This binocular image has the same dichoptic contrast modulation (0.5) as in Figure 7, but is less likely to lead to perceived rotation of the entire sinewave pattern when perceptually fused. See text.

and Stine (1998), and Stine and Filley (1998), who essentially argued that Fiorentini and Maffei's results were an artifact of their setup. By using a sharp aperture with a sudden drop in luminance, Fiorentini and Maffei introduced a sudden luminance and contrast change at the edges that would not be present against a background of average luminance (compare Figure 7 to Figure 9). Therefore, each entire circular image could be the equivalent of a square from Cibis and Haber's (1951) research, requiring no explanation beyond the Cibis and Haber model for the resulting perceived rotation (Filley, 1998; Filley & Stine, 1998; Stine & Filley, 1998).

Further, Filley's (1998) research demonstrated that the Cibis and Haber (1951) model itself is not tenable. Filley presented participants with numerous square-wave gratings that had luminance and/or contrast disparities (the effect of a contrast disparity on perceived rotation can be demonstrated by stereoscopic viewing of Figure 10). Filley's stimuli were rectangles 2.92° in width and 6.56° in height with a spatial frequency of 1.2 cycles per degree, presented stereoscopically and viewed through 3 mm artificial pupils. Either the left or right monocular image was at an average luminance of

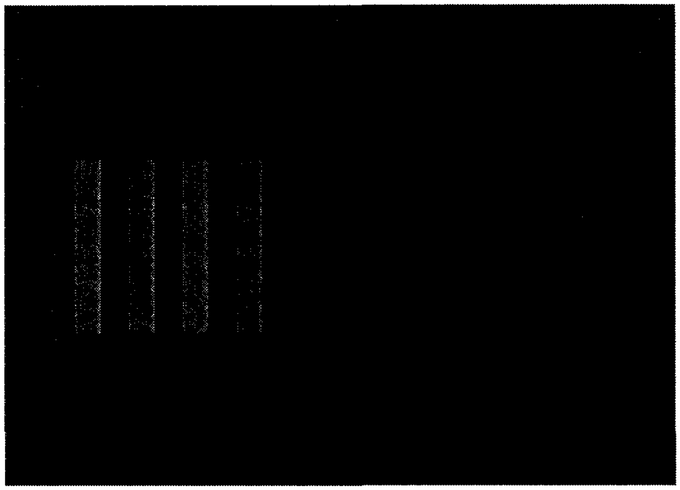

Figure 10. Dichoptic square-wave grating with a contrast disparity. This binocular image has dichoptic contrast modulation of 0.5, and leads to perceived rotation of each bar when perceptually fused.

26.7 cd/m^2 (77.63 photopic td)[10] and 0.5 contrast, while the other monocular image had any of several combinations of luminance and/or contrast values, resulting in dichoptic luminance and/or contrast modulation from 0.00 to near 0.50. Cibis and Haber's model depends on portions of the image falling below the absolute threshold for detection, and predicts that no perceived rotation should occur for stimuli above threshold, yet perceived rotation reliably occurred in this study despite all images being wholly above threshold (Filley, 1998). Likewise, it can be observed that there are no parts in either Figure 5 or Figure 10 that are "undetectable."

Lacking a model that fully explains the Venetian blind effect, I (Hetley, 2005) performed further experiments to at least describe the effect, as Filley (1998) did not actually measure magnitude of perceived rotation. The basic stimulus was akin to that shown in Figure 11. Each monocular image was 0.6° of visual angle in width, 0.4° in height, at 5.7 cycles per degree, and presented stereoscopically through 3 mm artificial

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[10] The *troland* is a unit of retinal illuminance, calculated by multiplying pupil area in millimeters to luminance in cd/m^2 (see, e.g., Boynton, 1966, pp. 284-285). However, using the pupil and luminance values given by Filley, the retinal illuminance should be 188.75 td. The reason for the discrepancy is unclear.

pupils. The vertical dark nonius lines shown in Figure 11 were simply to aid in fusing[11]. The background gray, and also the base luminance (the average luminance of the light and dark bars from both monocular images, as mentioned in the notes on terminology), was 37.9 cd/m^2 (268 photopic td), and the monocular images had a base contrast of 0.5 (Hetley, 2005).

Figure 11. Sample Experiment I image with no disparity. This sample is akin to that used in Hetley (2005), described in the text. This sample was generated with the code from my current research, and will be discussed as the neutral condition in Experiment I (p. 47).

Among other experiments, I measured the magnitude of perceived rotation in the Venetian blind effect with a cancellation method. I presented participants with images that had pixels shifted between the two monocular square-wave patterns, resulting in geometric disparities like those that would be detected in real rotated images (see Figure 3). These disparities were either 12.2, 24.3, 36.5 or 48.7 seconds of visual angle. The task was to find a level of dichoptic luminance or contrast modulation that resulted in a Venetian blind effect strong enough to counteract the perceived rotation from the geometric disparity. For luminance, modulation between around 0.30 and 0.90 provided

[11] This use of the term *nonius line* is adapted from the technique described in Ames, Ogle, and Gliddon (1932). In my research, I use it to refer to a line that appears in each monocular image and that falls on corresponding parts of the retina when the images are fused.

cancellation depending on condition[12]; for contrast, modulation between around 0.25 and 0.75 provided cancellation (Hetley, 2005).

Since then, further work (Stine & Hetley, 2006) has provided a model for the magnitude of perceived rotation based on a contrast disparity. Although not discussed in that publication, the model also applies moderately well to a luminance disparity. This model is based on data from my past work (Hetley, 2005) and ideas from two other studies.

First, Sclar, Maunsell, and Lennie (1990) modeled the response of neurons in macaque monkey (*Macaca fascicularis*) striate cortex to the contrast of a sinewave grating. Neuron response in this area, as well as various others, followed a Naka-Rushton equation,

$$R(C) = \frac{R_{\max} C^n}{C^n + \sigma_{50}^n} + M ,$$

where R is the response, C is the contrast, $R_{\max}$ is the maximum possible response, M is the spontaneous rate of response, σ_{50} is the contrast that causes half of the maximum response, and n is a parameter that adjusts the steepness of the response (Sclar et al., 1990).

Second, Backus, Banks, van Ee, and Crowell (1999) provided a convenient measure of the geometric disparity in a rotated image called *horizontal size ratio* (HSR), the ratio of the visual angle of the left monocular image and the right monocular image. Backus et al. discussed how a viewer's use of the HSR, along with other quantities

[12] Modulation was not permitted to go beyond 0.90.

including the similar *vertical size ratio*, unambiguously allow for determination of rotation around a vertical axis.

With Backus et al.'s (1999) definition, the HSR's canceled by the Venetian blind effect in my thesis (Hetley, 2005) ranged from 0.857 to 1.17. With the constants that Sclar et al. (1990) used for striate cortex complex cells, we (Stine & Hetley, 2006) described the magnitude of perceived rotation by comparing the responses of two different neurons, one responding to the left monocular image and the other to the right. This followed the equation

$$PercHSR(C_l,C_r) = gain_l R_l(C_l - shift) - gain_r R_r(C_r + shift),$$

where the subscripts l and r indicate the neuron and image under consideration, *gain* is a parameter that adjusts the range of perception, *shift* is a parameter that adjusts the bias between the left and right responses, and *PercHSR* is the perceived horizontal size ratio (Stine & Hetley, 2006). Though not discussed, the same equation can be used with luminance input to describe perceived rotation.

In total, perceived rotation from luminance or contrast disparities may not be well-explained, but it is well-described. The leading explanation based on the detection of blurred edges at an absolute threshold (Cibis & Haber, 1951; Howard & Rogers, 1995, p. 310; Ogle, 1962, pp. 302-303; see Figure 6) is untenable, as perceived rotation is detected above threshold (Filley, 1998; Filley & Stine, 1998; Stine & Filley, 1998; see Figure 5 and 10). However it occurs, perceived rotation can arise from stimuli of many different sizes and base luminance and contrast values, and the magnitude of rotation increases with the magnitude of dichoptic luminance or contrast modulation over a wide range, up to 0.99 modulation in some cases (Cibis & Haber, 1951; Filley, 1998;

Fiorentini & Maffei, 1971; Hetley, 2005). Despite this body of information, though, there are concerns about exactly what is being manipulated that are addressed in the following subsection.

Light Bars and Dark Bars Versus Average Luminance and Contrast - There may be other fundamental approaches to the Venetian blind effect (and eventually the next phenomena discussed here). A grating stimulus may be defined in two mathematically interchangeable ways. The first is to state the maximum and minimum luminance values in the grating, which are the luminance values of the light bars and dark bars. The second is to state the average luminance and contrast, where the average luminance gives a "starting point" and the contrast specifies how "spread out" the light bars and dark bars are. I have been using the latter so far, but the question is whether there is a reason to choose one mathematical definition over the other.

Gottesman, Rubin, and Legge (1981), after doing a study pertaining to contrast, asked whether contrast is really its own sensory dimension worth studying or whether it is some form of combination of sensory responses to the light and dark bars. Later, Legge and Kersten (1983) explicitly compared the different definitions of a grating, including multiple types of contrast. They presented participants with images on a computer screen that had either a rectangular or Gaussian luminance profile, and were either 0.1°, 1°, or 10° in width and 16° in height, with one condition at 0.1° width and 4° height. These images were either increments or decrements relative to a 340 cd/m^2 background, and so were considered to represent "light bars" or "dark bars." Participants viewed pairs of increments or decrements one after another on the screen and judged

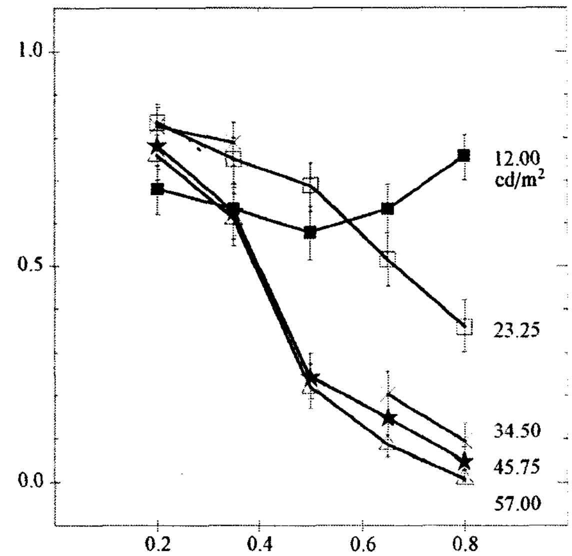

Figure 12. Data from Filley (1998). Probabilities that the monocular image which is manipulated (left or right) corresponds to the edge of each bar that appears closer to the viewer (left or right), for different contrast (on axis) and/or average luminance values (separate lines) of the manipulated image.

whether the first or second presentation involved the most contrast against the background (Legge & Kersten, 1983).

As with other research that they cited, Legge and Kersten (1983) found there are some differences between how light bars and dark bars are perceived; differences which would be overlooked when using average luminance and contrast as the definition of a grating. For one, the absolute detection threshold for dark bars is at a smaller contrast than for light bars, meaning a smaller disparity from the background is necessary to detect dark bars. However, looking at discrimination and not detection, they found that increments and decrements have equivalent effects. Further, discrimination functions plotted based on the contrast between an isolated bar and the background, specifically the Michelson contrast, follow the same shape for each type of stimulus. The functions even follow the same shape as contrast discrimination functions in intact sinewave gratings. This result suggests that one may consider Michelson contrast as a standard in defining gratings for discrimination tasks, and Legge and Kersten provided a physiological explanation: photoreceptor response to light is proportional to the logarithm of the intensity over a moderate range, and Michelson contrast is roughly equivalent to a logarithm transformation over a moderate range.

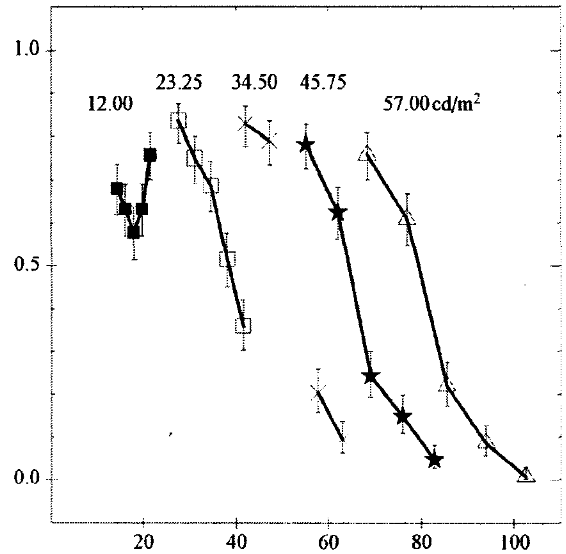

Figure 13. Data from Filley (1998) replotted against the luminance of the light bars. These are the same probabilities shown in Figure 12.

In years since, science has typically defined gratings in terms of average luminance and contrast, though there are some increment and decrement imbalances such as those noted by Legge and Kersten (1983). A new analysis of Filley's (1998) research suggests that the light bars and dark bars may again be important when considering the Venetian blind effect. Filley's participants stated which edge of the bars in square-wave gratings appeared to be rotated closer to the viewer (in stimuli with dichoptic luminance and/or contrast modulation, as discussed), and their responses showed an interaction (Figure 12)[13]. When average luminance is raised in one monocular image, contrast can predict which edge appears closer. That is, with the right monocular image at a higher average luminance, if the left or right image has lower contrast, then each left or right edge (respectively) appears closer. However, when average luminance is lowered, the edge appearing closer is unaffected by contrast. That is, with the right monocular image at a lower average luminance, the right edge of each bar always appears closer (Filley, 1998).

[13] Figure 12 is adapted with permission of the original author. See Appendix A. This figure mainly differs from the original in that the score estimator is used to create standard error bars. The score estimator was first defined by Wilson (1927), and the formula is presented in the methods for data analysis section of the general methods (p. 45).

The nature of this interaction is made more clear when Filley's (1998) data are replotted based on the luminance of the light bars, not the average luminance (Figure 13)[14]. With very few exceptions, all the perceived rotation data follow the same shape when plotted in this manner. Thus, using part of the same argument as Legge and Kersten (1983), considering the light bars and dark bars separately may be necessary when defining Venetian blind stimuli. The usefulness of this approach to binocular luster and binocular rivalry in addition to perceived rotation will be discussed in my experiments.

Binocular Luster

Helmholtz (1873, 1910/1925) summarized both his and Dove's (1851) phenomenological study of binocular luster. For grayscale images, the basic effect can be demonstrated well by stereoscopic viewing of crystal-shaped images composed of lines and fields (Figure 14; Helmholtz described this but did not actually provide a graphic) or, here taken after McCamy (1998), Mondrians[15] (Figure 15)[16]. When corresponding monocular components differ greatly in luminance, the fused image appears to shine like it is reflecting light, making Helmholtz's example appear like a crystal of graphite on a lustrous background. By comparison, identical components (such as many in the Mondrian) appear dull, just as the original monocular images printed on paper do (Helmholtz, 1873, 1910/1925).

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[14] Figure 13 was not in Filley's original work, and instead is generated with permission from raw data provided by the original author. See Appendix A.

[15] The term *Mondrian* for such images was first used by Land (1983), referring to geometric designs of different patches that resemble paintings by the artist Piet Mondrian.

[16] Figure 15 is adapted with permission of John Wiley & Sons, Inc. See Appendix A.

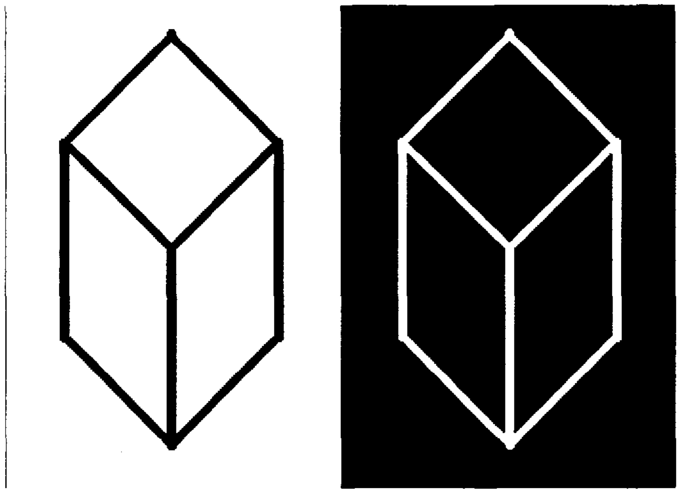

Figure 14. Dichoptic crystal image for demonstrating binocular luster. See text.

Similar luster can be generated by dichoptic viewing of an image through colored filters that differ a moderate amount in the wavelengths they pass[17]. The effect can also be generated purely monocularly, either through rapid succession of differing images, or through an optical setup that presents the two images at slightly different perceptual depths (Helmholtz, 1910/1925).

This concept of depth is central to Dove's (1851) explanation for luster, namely that luster is due to our perceiving conflicting images as two separate lights, one shining through the other (Helmholtz, 1910/1925). The perception of color in an object depends both on specular reflection of light off the surface and diffuse reflection from within the material[18], which

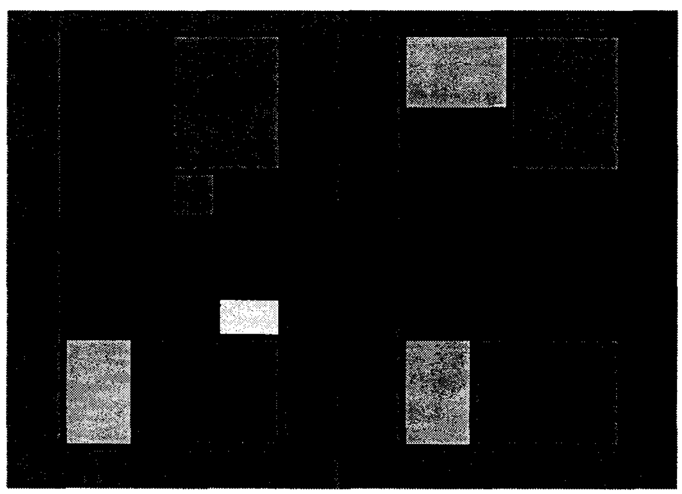

Figure 15. Dichoptic Mondrian image for demonstrating binocular luster. Note luster is visible in three components of the fused image. See text.

[17] The nature or magnitude of the difference was never precisely defined in Helmholtz (1910/1925), stating only that the colors must not be "too different," otherwise binocular rivalry might occur instead.

Dove (1851) felt are perceived at different depths. Thus, for luster based on color, he felt the viewer divides up the two monocular images to two sources. For black and white images, different intensities of light are known to lead to different pupil contraction, and contraction generally goes along with lens accommodation, so he felt that black and white examples likewise lead to different perceptual depths based on feelings of accommodation (Helmholtz, 1910/1925).

Helmholtz (1910/1925) disagreed. For black and white images, examples such as the Mondrian in Figure 15 are nearly identical and have little reason to lead to different pupil contraction. Also, because pupil contraction changes the amount of light let in, if contraction were to occur when viewing Figure 15 then all the monoptic components should also show binocular luster, the Venetian blind effect, or some other effect (this argument was not mentioned by Helmholtz). The use of artificial pupils in modern research, such as my master's thesis (Hetley, 2005), is to eliminate pupil contraction as a factor.

However, Helmholtz (1910/1925) felt the concept of specular reflection was indeed relevant, though misused by Dove (1851). When a surface is particularly reflective, light from a single source reflects in a single direction. This can lead to one eye receiving a very intense reflection while the other does not (Figure 16-17). Dull surfaces do not reflect as well, so when the visual system receives monocular images that do differ in intensity it is logical to have a special perception of reflectivity to distinguish

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[18] *Specular reflection* and *diffuse reflection* are modern terms that were not used by Helmholtz. When light strikes a surface, some light goes through specular reflection where the angle of incidence of the light equals the angle of reflection. Some light also goes through diffuse reflection where the light enters the material and exits in random directions. Further, in diffuse reflection only certain wavelengths are actually released by the material, while in specular reflection the light remains unchanged.

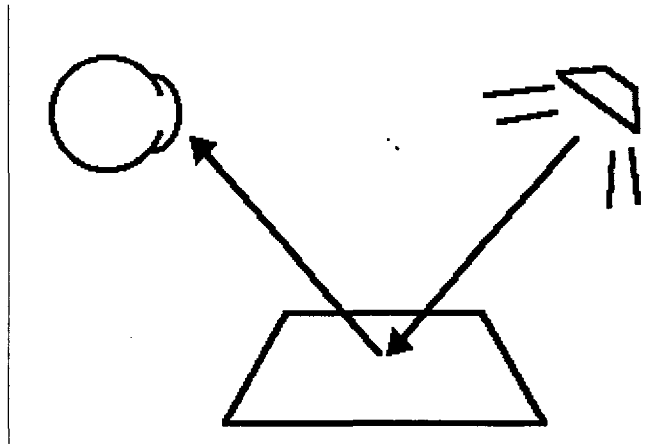

Figure 16. Side view of specular reflection. A light reflects off of a surface and goes directly to one eye, resulting in an image of the world that has a bright spot on that surface. See Figure 17.

this surface property (Helmholtz, 1910/1925). This explanation was also supported, with more diagrams depicting specular reflection, by McCamy (1998).

Helmholtz's (1873, 1910/1925) discussions of binocular luster were within larger discussions of binocular rivalry (the latter described in the next section here, p. 32), where he noted a distinction between the two. He observed that luster did not depend on the shifts in perception over time that occur in rivalry, as luster can be perceived in images illuminated by a spark that lasts only one-four-thousandth of a second[19]. Instead, he felt that luster was a result of a stable perception of a fused image. The stability of luster can be

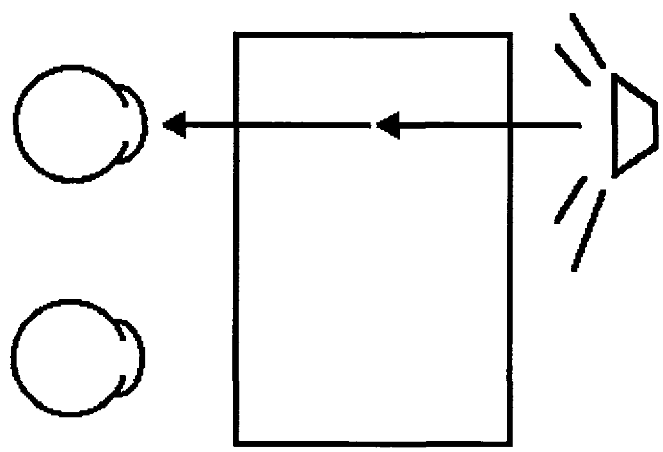

Figure 17. Top view of specular reflection. As light travels straight, only one eye detects the bright spot as being at that exact location, leading to a luminance disparity and, it is proposed, binocular luster. See text.

[19] These discussions did not address the persistence of vision after the spark. Tyler (2004), however, stated that luster is still detectable in an image presented for 2 ms between two presentations of masking stimuli.

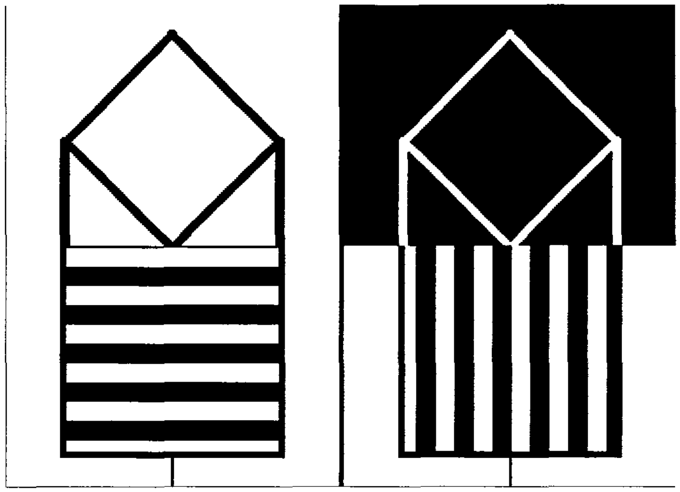

Figure 18. Dichoptic half-crystal, half-gratings image. This binocular image leads to binocular luster in the top half and binocular rivalry in the bottom half when perceptually fused.

compared to the defining instability of rivalry in images like Figure 18-19, where the upper and lower halves of the stereoscopic drawings differ (the bottom halves are identical to Figure 20, also described in the next section, p. 32). However, he passed along the observation by Dove (1851) that the two phenomena can be concurrent, as Dove found luster in rivaling images during the precise moments where perception was shifting from one monocular image to the other (Helmholtz, 1873, 1910/1925).

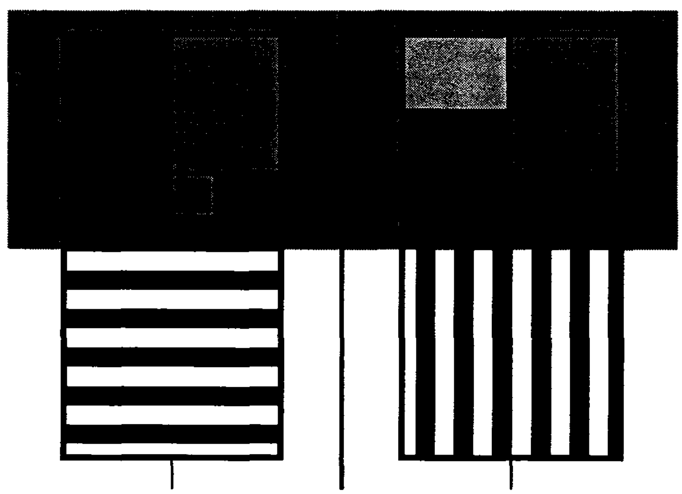

Figure 19. Dichoptic half-Mondrian, half-gratings image. This binocular image leads to binocular luster in two components of the top half and binocular rivalry in the bottom half when perceptually fused.

Hering (1879-1883/1942, chapter 15, 1920/1964, section 52) likewise briefly described the effect phenomenologically. However, as has been repeatedly noted (e.g., Ludwig, Pieper, & Lachnit, 2007; McCamy, 1998; Tyler; 2004), there has been very little modern investigation into binocular luster, including both psychophysical and physiological. As with Hering, work by Julesz and Tyler (1976) and McCamy (1998) mentioned luster mainly to say that it exists. However, Julesz and Tyler's phrasing was subtly different, stating that luster regularly occurs when images rival, but not when images are fused. It is possible that this brief analysis overlooked the more complicated situation of a fused image with great disparity.

McCamy (1998) and Tyler (2004), in summarizing many phenomena, stated that binocular luster involves some indeterminate impression of depth. Tyler's description suggested that this would not be much depth information, because, although research participants can use luster to inform them when a stereographic image has a binocular disparity, luster alone has little use in judging what depth is simulated in the image[20]. The implications for Dove's (1851) explanation of luster, based on perceived depth, are unclear.

Tyler (2004) also stated that luster is wholly different from rivalry and does not involve fluctuation, agreeing with Helmholtz (1873, 1910/1925). However, this view on fluctuation seems to be a point of contention between researchers, as both of these contradict Julesz and Tyler's (1976) statements discussed earlier. Agreeing with both Tyler and Helmholtz, Ludwig et al. (2007) stated that luster is as stable a perception as color. On the other side, Birnkrant, Wolfe, Kunar, and Sng (2004) described luster as "dynamic" in the same way rivalry is.

Experimental data came from Wolfe and Franzel (1988), who included luster in a study on binocular information and visual "pop out." In general, basic features such as color and form are thought to be processed in parallel by the visual system, resulting in

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[20] The task described was judging whether a random-dot stereogram of a spiral was pointing towards or away from the viewer.

extremely fast detection of objects uniquely defined by those features (e.g., Treisman & Gelade, 1980). Wolfe and Franzel asked participants to search for a stimulus among distractors based on binocular rivalry, binocular luster, or other qualities to determine if any would likewise "pop out." They presented from 2 to 32 stimuli dichoptically such that at most one target was uniquely defined by one of the above qualities and measured the time until a participant reported on the target's presence or absence (Wolfe & Franzel, 1988).

For rivalry, Wolfe and Franzel (1988) presented squares or spots 1.6° in visual angle, incorporating rivalry like that in Figure 20, or rivalry based on color, or no rivalry at all, estimated[21] as averaging around 50 cd/m^2 in luminance. They found that reaction time increased linearly with the number of distractors. For luster, they presented spots 1.6° in visual angle with grayscale values that differed relative to the estimated[22] 50 cd/m^2 background. Noting that the effect seems most compelling when one monocular image is more luminant than the background and the other is less luminant, nonlustrous stimuli were presented monoptically at around either 20 cd/m^2 or 95 cd/m^2, while lustrous stimuli had one monocular image at each luminance, thus dichoptically straddling the background. With those estimates, these stimuli would have a dichoptic luminance modulation around 0.65. Reaction time to detect targets based on luster was hardly

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[21] Actual luminance values were not given. I estimated this number given that computer monitors, such as the Apple ColorSync Display for my experiments, tend to produce from 2 to over 100 cd/m^2. The display used in this study was a monitor from an arcade game viewed with a built-in shutter stereoscope, and the grating images for the rivalry experiments were described as having "high contrast."

[22] I estimated this and following luminance values based on the gamma value for my experiments, assuming the maximum luminance that Wolfe and Franzel could display was 100 cd/m^2. The background for the luster experiments was described as having a grayscale value of 175 out of 255, with the spots at 100 or 250 out of 255.

affected by the number of distractors, suggesting luster but not rivalry is a basic feature supporting parallel search (Wolfe & Franzel, 1988).

This result is particularly interesting because other phenomena labeled "basic features," such as color, are generally extracted early in visual processing (Wolfe & Franzel, 1988). The essential placement of luster as a binocular phenomenon is supported by Birnkrant et al.'s (2004) research with monoptic images. They monoptically presented participants with spheres 4.5° in visual angle that either contained information about reflectivity, such as a bright highlight which would occur from specular reflection, or lacked it, such as a scrambled version, and averaged an estimated[23] 10-20 cd/m^2 in luminance. Search for stimuli defined by monoptic "shininess" increased with the number of distractors. Therefore, though luminance information is available early in vision, and a reflection has an effect on luminance, reflectivity is not key in aiding search when not perceived as binocular luster (Birnkrant et al., 2004). Perhaps, as Wolfe and Franzel suggested, the "list of basic features" needs to be based on perception, not level of processing.

The minimal total amount of research on binocular luster makes it difficult to draw conclusions. The effect may be explained as the visual system's natural response when presented with an image of high luminance disparity, i.e., to perceive the object as reflective (Helmholtz, 1873, 1910/1925; McCamy, 1998; see Figure 16-17). Hypothetically, this explanation may be relevant to the Venetian blind effect. Specular reflection would occur differently on surfaces at different rotations, and luster has been

[23] Actual luminance values were not given. I estimated these numbers by displaying stimuli from a PDF file of the authors' poster on my experimental Apple ColorSync Display monitor, then measuring the light with a Minolta LS-110 photometer.

described as involving some impression of depth (Dove, 1851; McCamy, 1998; Tyler, 2004), but this has not been explored. At the least, luster can be expected around extreme levels of dichoptic luminance modulation (pure black and white images; Helmholtz, 1873, 1910/1925) and moderate ones (Wolfe & Franzel, 1988). There does not seem to be research on binocular luster and contrast disparities.

However, there are other important aspects of the conditions in which luster is and is not perceived, which the following subsections address. These will include research showing luster can also be expected around low levels of modulation in the right circumstances (Anstis, 2000).

The Relation between Stimuli and the Background - It is worth expanding the discussion of Wolfe and Franzel's (1988) use of images dichoptically straddling the background luminance when studying binocular luster. Fry and Bartley (1933), in researching the perception of brightness that results from luminance disparities, specifically avoided having one monocular image above and the other below the background luminance as this led to rivalry that made data collection impossible. Their stimuli were rectangles 2.38° in width by 1.2° in height, with one monocular image maintaining 10.8 cd/m^2 in luminance and the other varying[24], resulting in dichoptic luminance modulation from 0.00 to 1.00 in different experiments. The implications of this may seem unclear because Wolfe and Franzel, as well as Filley (1998) and myself (Hetley, 2005), were able to collect data despite using images that dichoptically straddled the background luminance.

[24] I believe that Fry and Bartley made a typographical error. The luminance value they gave was 10 times that stated here, but the higher number does not agree with their graphs or their other experiments.

However, the presence of binocular rivalry does not preclude other perceptual phenomena based in binocular vision, which will also be discussed in the section on binocular rivalry (p. 34, 36) and my experiments. Anstis (2000) demonstrated that dichoptic straddling is the ideal condition for inducing a perception of luster. Anstis presented participants with two columns of five squares, one column to each eye, with each square 0.75° of visual angle. The squares either were presented dichoptically with luminance disparities just like with the other research considered here, or were completely monoptic but flickered between two luminance values, which is a possible way to generate luster mentioned by Helmholtz (1910/1925), as discussed. The squares were at luminance values ranging from 34.35 cd/m^2 to 192.36 cd/m^2, always in pairs 0.15 log units apart, which when presented dichoptically were at levels of dichoptic luminance modulation of 0.17 or 0.18 (Anstis, 2000). Note that these modulation values are much below the 0.65 estimated in the discussion of Wolfe and Franzel (1988).

The key manipulation in Anstis (2000) was the background luminance, which ranged from 41.22 cd/m^2 to 160.3 cd/m^2, interleaved between the luminance values chosen for the squares. Participants gave numerical ratings from 0 to 10 for their subjective experience of the luster in each fused image of a square in all combinations of conditions. Ratings were highest (close to if not exactly 10) when the dichoptic squares straddled the background luminance and when the flickering squares flickered above and below the background luminance, regardless of the absolute value of the background luminance. Luster was still perceived when the squares were very close to the background without straddling it, but ratings decreased with increasing distance in luminance, and the decrease was symmetrical with distance above and with distance below the background luminance (Anstis, 2000).

Perhaps the relation between binocular luster and binocular rivalry, though discussed as being a point of contention between researchers (e.g., Birnkrant et al., 2004; Helmholtz, 1873, 1910/1925; Julesz & Tyler, 1976; Ludwig et al., 2007; Tyler, 2004), ties in here. It seems reasonable to conclude that both luster and rivalry arise from images that dichoptically straddle the background luminance, though just how much "straddling" is necessary may vary. Wolfe and Franzel (1988), after all, did not state that their luster stimuli also seemed to be rivaling, and the stimuli used in my master's thesis (Hetley, 2005) only rivaled at the most extreme luminance disparities.

Fluorence - The issue of the relation between dichoptic images and the background as discussed with Wolfe and Franzel (1988) and Anstis (2000) prompts consideration of another phenomenon outside of binocular vision, namely fluorence. Evans (1959) defined *fluorence* as the perceptual counterpart of fluorescence, in the same way that brightness is the perceptual counterpart of luminance. Fluorence is, therefore, an experience of a glowing image, and it may arise in some similar circumstances to binocular luster. It is worth discussing fluorence to understand how it may impact the study of luster, but as will be seen, these are two distinct perceptual phenomena.

Evans (1959) performed two experiments, where the first provided impetus for the study of fluorence in the second. In the first experiment, participants made matches between lights of certain wavelengths, intensities, and purities[25], to a comparison light on

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the same surround, where the instruction was to match the amount of gray in the two lights. Evans found that there are several combinations of intensity and purity that work to make matches, such that at higher purity a lower intensity is needed. Increasing intensity of grayscale images tends to make them seem closer to white, so these results mean that a matching light could seem as "gray" as "white light" (i.e., not gray at all) while itself being much dimmer than the white light, provided that the purity were raised. These results naturally led to the question of what would happen if a light appeared to be as "gray" as "white light" and then were increased in intensity (Evans, 1959).

Thus, in Evans' (1959) second experiment, participants viewed a blank wall or panel that appeared white under illumination of either 308.36 cd/m^2, a half of that, or a quarter of that. In that wall was a hole, 1.75° in width by 2° in height, with light shone from the other side through various filters. This hole was generally perceived as being continuous with the actual solid surface of the wall, so the hole could be called a "center" and the wall a "surround." Sometimes, a comparison gray patch was placed within the surround. The hole and the patch were viewed binocularly with no dichoptic components, unlike the other studies discussed in this paper. The participants viewed several intensity values in the center, all of which were greater than those determined in the first experiment to match "white" for different purity levels (Evans, 1959).

Evans (1959) found that increasing intensity beyond the point of whiteness causes participants to feel that the center image is fluorescing. The conclusion was that the perceptual experience of fluorence and grayness are "positive" and "negative" around a

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[25] *Purity* refers to the narrowness of the band of wavelengths present in a light. It roughly corresponds to the perceptual experience of saturation, so light that appears as a very vivid red likely has high purity, while light that appears as a weak pink likely has low purity. Grayscale images, such as those in my experiments, have the least purity.

sort of white zero point. Also, when increasing luminance of the center from near zero, perception reaches several noteworthy points in a sequence: first, a grayness match to any comparison gray patch in the surround; second, the minimum threshold for fluorence (the "white zero point"); then the point where the light has a brightness match to the surround; then the threshold where the light stops looking like it is a physical part of the surround and instead appears as its own separate illuminant, at which point fluorence vanishes. For lights that appear gray or white, i.e., those of the least purity, the minimum threshold for seeing fluorence is closer to the brightness match to the surround than for any light of higher purity (Evans, 1959).

The fact that fluorence appears in lights close to a brightness match to the surround brings to mind the discussion of Anstis (2000). Anstis showed that the perception of binocular luster is strongest when dichoptic stimuli, with monocular components that need not be very different in luminance, straddle the background luminance. It is possible that fluorence was being seen during some of the experiments discussed here for luster.

However, though fluorence may indeed have been seen, it is not the same thing as binocular luster. Given the pattern of thresholds discussed by Evans (1959), perception of fluorence is asymmetrical around a brightness match to the surround. Anstis (2000), as discussed, found symmetrical perception of luster as image luminance moves away from the background. Also, for grayscale images, intensity must be very close to the brightness match to the surround before fluorence will appear. An image such as Figure 14 involves luminance values that are at or far below the "white" paper's background, and Figure 15 involves luminance values that are moderately far from the background gray, and yet both result in a perception of luster. Lastly, fluorence vanishes as intensity goes up and the image no longer seems "solid." During my master's thesis (Hetley, 2005), participants viewing images with strong rivalry would often informally note what appeared to be bars floating in space that were themselves "lustrous." Therefore, fluorence needs to be kept in mind when considering the stimuli in a study of luster, but will not be given further theoretical consideration here.

Binocular Rivalry

Binocular rivalry is the alternation of perception between the monocular components of a dichoptic image that cannot be fused. The basic effect can be demonstrated by stereoscopic viewing of Figure 20, here taken after Panum (1858) who introduced gratings into the study[26]. A full review of binocular rivalry will not be attempted here, as it has undergone systematic research for almost 200 years. In fact, according to Wade (2005), the existence of the phenomenon has been described for almost 2000 years. For more information, the most recent writings wholly devoted to rivalry include Levelt (1965b), Lack (1978), and Alais and Blake (2005).

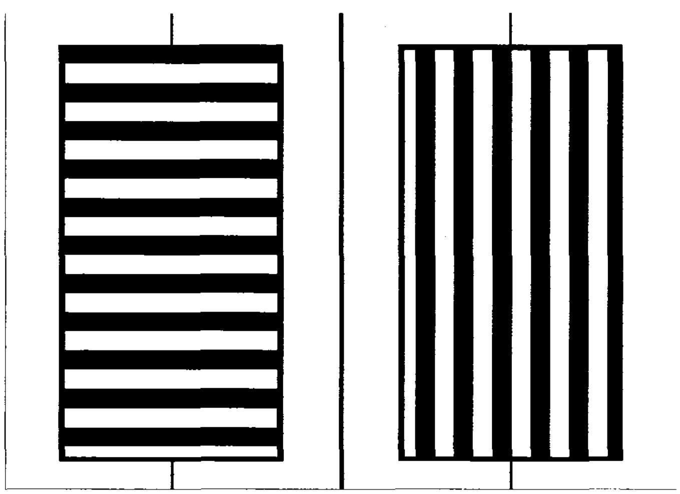

Figure 20. Dichoptic gratings for demonstrating binocular rivalry. See text.

Wheatstone (1838), reported in his paper where he

[26] Technically, Panum's gratings were at diagonals instead of horizontal and vertical.

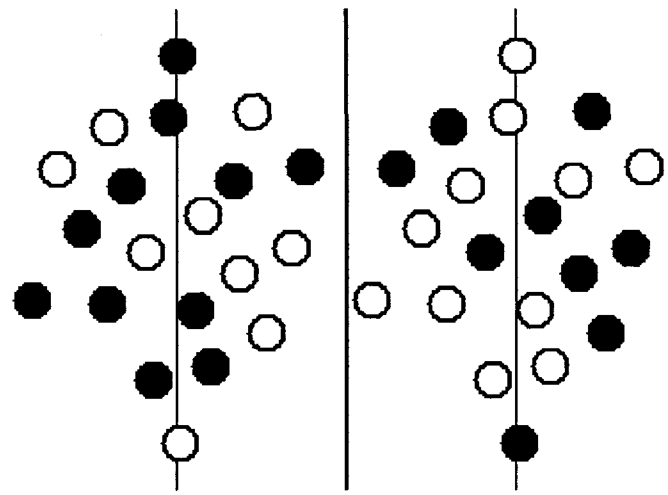

Figure 21. Dichoptic circles for demonstrating unitary rivalry. When perceptually fused at arm's length, these binocular images lead to unitary binocular rivalry and the sieve effect. See text.

introduced the stereoscope, performed the first systematic study of binocular rivalry and made three observations. First, when perception changes from one monocular image being dominant to the other, the two images often fragment. In Figure 20, instead of just perceiving horizontal bars and then just perceiving vertical bars, the viewer tends to perceive a fractured mosaic between periods of dominance. Second, voluntary control of the alternations by the observer appears impossible. This conclusion actually raises a point of contention and likely involves individual differences, as Helmholtz (1873, 1910/1925) felt he could arrest rivalry by means of attention to one image, and Lack (1978) provided experimental evidence that naïve observers could exhibit limited control. Third, manipulating features of the images, including luminance, affects the alternations. For example, the monocular image with less luminance is dominant for a shorter period of time relative to the other (Wheatstone, 1838).

These observations have been refined. Various sources (e.g., Fox, 2005; Howard and Rogers, 1995, p. 327; Ludwig et al., 2007; Wolfe & Franzel, 1988) have described how the mosaic or piecemeal dominance during transitions only occurs for larger images.

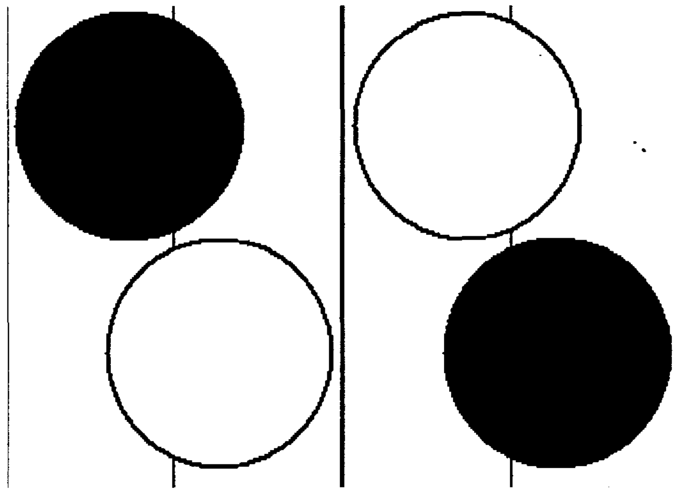

Figure 22. Dichoptic circles for demonstrating mosaic rivalry. When perceptually fused at arm's length, these binocular images lead to mosaic binocular rivalry and binocular luster. See text.

For images 1° in visual angle or smaller, exclusive or unitary rivalry may occur where perception changes as a whole.

Howard (1995; see also 2005) drew a connection between stimulus size, binocular rivalry, and binocular luster in an experiment on depth perception. Circles smaller than 1°, with one monocular image black and the other white, result in unitary rivalry and a perception of being more distant than their surroundings, which he called the sieve effect (Figure 21)[27]. Circles larger than 1° result in mosaic dominance and also binocular luster with an indeterminate depth (Figure 22). As mentioned in the subsection on the relation between stimuli and the background (p. 28), the presence of rivalry does not preclude other perceptual phenomena based in binocular vision. Howard proposed that the perception of luster occurs in this situation because binocular brightness summation is possible during mosaic dominance. Previous research (e.g., Levelt, 1965a) had shown that, when an image is presented that has a strong contour in one monocular image, the luminance near that one contour tends to control the binocular brightness near the contour. With mosaic dominance, however, there are larger areas far from contours that could be more easily compared between the two eyes (Howard, 1995). It should be noted that this explanation

[27] Figure 21, as well as Figure 22-23, is adapted with permission of Pion Limited, London. See Appendix A.

for the relationship between rivalry and luster would conflict with my participants (Hetley, 2005) informally noting luster, as all my images were less than 1° in size.

Desaguliers (1716) and Helmholtz (1873, 1910/1925) made a distinction between contour or form rivalry, described so far, and color rivalry. In color rivalry, a dichoptic image differs in the wavelengths of light received by each eye, and the color perceived can rival without necessarily any difference in the image's form (Helmholtz, 1873, 1910/1925). One may observe the phenomenon by viewing a blank area in this paper with a red filter over one eye and a green filter over the other eye, attempting to judge the color of the blank area. Wolfe and Franzel (1988) said research has found color and contour rivalry to be somewhat independent phenomena. Andrews, Sengpiel, and Blakemore (2005) argued, on the basis of single neuron recordings of their own and other researchers, that the mechanism for rivalry may vary in anatomical position in the visual system for each submodality of vision, including submodalities like motion in addition to contour and color.

Contour rivalry is more relevant to this paper and will be addressed further. Blake (2005) summarized several classical papers on the properties of the images that influence alternations, bearing on the third of Wheatstone's (1838) general observations. It is possible to separately influence the overall speed of alternations and the relative predominance of one image. The deciding factor is *stimulus strength*, defined by Levelt (1965b, chapter 5) to include the relative amount of contours in an image and their average luminance, contrast, and blur.

Levelt (1965b, chapter 5) formally stated the impact of stimulus strength in four propositions: starting from a monoptic binocular image, monocular increases in strength increase the relative predominance for that image; monocular increases in strength do not affect the absolute average duration of dominance for that image; monocular increases in strength increase the alternation rate; and binocular increases in strength increase the alternation rate. Levelt's famous second proposition is important because, in light of the other propositions, it leads to two unintuitive conclusions: one, that a monocular increase in strength lowers the duration of dominance for the *other* image; two, that a subsequent change in the strength of the weaker image *would* affect its *own* duration. This means that the weaker image has an important role, which may explain other phenomena such as the ability of an abrupt change in a suppressed weaker image to suddenly command perception (Blake, 2005). Note that this interplay between images is another situation where rivalry does not preclude the use of information from both images.

Andrews et al. (2005) noted that the majority of rivalry research has involved orthogonal gratings, such as in Figure 20. Solid black and white images, like the circles in Figure 21-22 discussed by Howard (1995), do not conflict at their contours but may also be varied in terms of Levelt's (1965b, chapter 5) stimulus strength, e.g., in luminance. Researchers have noted that using images that are not black and white, but are instead some dichoptic combination of grays (i.e., different luminances), are less likely to induce rivalry (Figure 23). Howard, for instance, stated that rivalry completely gives over to luminance summation during these circumstances.

In this context, it is worth addressing Fry and Bartley (1933) again. As discussed in the subsection on the relation between stimuli and the background (p. 27), they presented uniform lit rectangles with certain luminance disparities, and avoided luminance values that dichoptically straddle the background luminance as these give rise

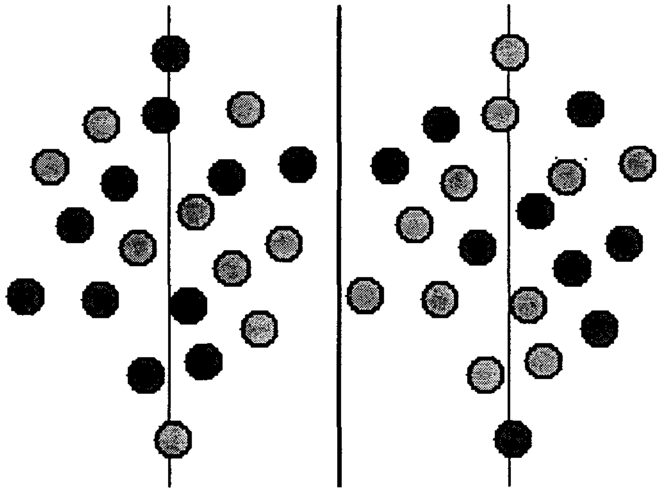

Figure 23. Dichoptic circles with a less intense luminance disparity. These binocular images generally do not lead to binocular rivalry (compare to Figure 21). *See text.

to rivalry. As was also discussed, Anstis (2000) showed that images that dichoptically straddle the background give rise to luster, though the monocular images may not be very different in luminance. If there were a relationship between binocular luster and binocular rivalry, then one would expect that circles like those in Figure 23 could rival given a different relation to the background.

Still, it remains interesting that rivalry generally did not impede research in my master's thesis (Hetley, 2005) despite my use of square-wave gratings with average luminance values above and below the background. It is possible that the use of gratings of light and dark bars differs from the use of solid rectangles. In fact, as suggested in the subsection on light bars and dark bars versus average luminance and contrast (p. 16), there may be more than one way to define images and their relationship. This will be discussed more in my experiments.

Explanations for the cause of binocular rivalry vary. Blake (2005) observed there are two general approaches to explaining rivalry: some researchers view rivalry as an issue of perceptual interpretation like with any ambiguous stimulus (Figure 24); other researchers feel explanations can be found by considering the activity of neurons inhibiting each other. Helmholtz (1873, 1910/1925), as noted, felt that attention is

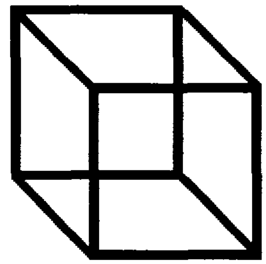

Figure 24. Ambiguous cube image. This is a classic image which can be perceived as a cube in two different orientations based on the attention of the viewer. This stimulus is generally called a Necker cube after Necker (1832), but that source actually used a rhomboid, and Wheatstone (1838) was the first to use a cube.

involved in selecting an image, with rivalry taking over when the individual puts no conscious effort forth. On the other hand, electrical recordings, such as that of Andrews et al. (2005), throughout the visual system clearly demonstrate neural interactions. Further, the underlying mechanism may vary based on submodality.

Therefore, it is not the purpose of this paper to identify the single "cause" for rivalry. Instead, the circumstances under which binocular rivalry occurs are more relevant. In summary, monocular images that are very different in form, i.e., that have great geometric disparities, undergo contour rivalry (Helmholtz, 1873, 1910/1925; Panum, 1858; Wheatstone, 1838). Images with great disparities in the wavelength of light undergo color rivalry (Desaguliers, 1716; Helmholtz, 1873, 1910/1925), and there may be different types and mechanisms of rivalry for different visual submodalities (Andrews et al., 2005). The predominance of one monocular image in perception, and the rate of alternations, may somewhat be manipulable by attention (Helmholtz, 1873, 1910/1925; Lack, 1978), but they are certainly related to stimulus strength (Levelt, 1965b, chapter 5). The relation between images and the background is important (Fry & Bartley, 1933), while notes such as that by Howard (1995) suggest that there is a minimum amount of disparity necessary for rivalry to occur. Observations by participants in my research (Hetley, 2005) suggest that rivalry can occur at high (but unmeasured) dichoptic luminance modulation, but as mentioned at the outset, it may not be meaningful to discuss rivalry with dichoptic contrast modulation. Far more information is available in these sources (e.g., Alais & Blake, 2005) and their references.

Literature Summary and Rationale for Current Research

The phenomena of the Venetian blind effect, binocular luster, and binocular rivalry have been researched to varying extents, rarely in combination with each other. It has been known since Münster (1941), Cibis and Haber (1951), and Filley (1998) that square-wave gratings presented with a luminance or contrast disparity result in a perception of rotation, or the Venetian blind effect. This rotation increases across most possible values of dichoptic luminance or contrast modulation (e.g., Hetley, 2005). Binocular luster is also known to depend on luminance disparities, with Dove (1851) and Helmholtz (1873, 1910/1925) using dichoptic luminance modulation values of 1.00 (pure black and white images) and others, such as Wolfe and Franzel (1988) and Anstis (2000), using lower modulation. Though research on binocular rivalry has often used square-wave gratings that have a strong geometric disparity (e.g., Panum, 1858), the use of black and white images (e.g., Howard, 1995) again shows the relevance of luminance disparities.

Discussions of these phenomena bring up hints of relationships. The Venetian blind effect is a phenomenon of depth perception, specifically rotation; research on binocular luster has indicated that luster brings some indeterminate impression of depth (Howard, 1995; McCamy, 1998; Tyler, 2004); and binocular rivalry also can be used as information about depth (Howard, 1995). Luster can be perceived during rivalry (Dove, 1851; Helmholtz, 1873, 1910/1925; Howard, 1995), and luster (Anstis, 2000) and/or rivalry (Fry & Bartley, 1933) are often perceived in images where the components dichoptically straddle the background luminance. The fact that the Venetian blind effect was measurable during my master's thesis (Hetley, 2005), despite informal observations of binocular luster and/or binocular rivalry, suggests that all these effects may intermingle.

My current research better quantifies the relationship between the Venetian blind effect, binocular luster, and binocular rivalry. After the upcoming general methods section, I present three experiments where I determined threshold values for the three perceptual phenomena on different types of stimuli. The discussions for each of the first two experiments present the rationale for the following experiment, and address by parts what the underlying mechanism or mechanisms may be for these perceptual phenomena. The central concept is that, if two perceptual phenomena are determined to arise in similar circumstances and/or to co-vary, then it is reasonable to presume they arise from similar underlying mechanisms. To judge this, one must precisely determine what "the circumstances" are in the first place, or what aspects are "co-varying."

In Experiment I, the stimulus was a square-wave grating, presented with either dichoptic luminance modulation or dichoptic contrast modulation. The purpose was simply to "map out" thresholds using a stimulus similar to past research (e.g., Cibis & Haber, 1951).

In Experiment II, the stimulus was composed of three "plain bars" taken from the square-wave gratings of Experiment I. The purpose was to determine whether or not luminance and contrast really form the proper way to define stimuli for these perceptual phenomena, by studying isolated "light bars" or "dark bars" (see, e.g., Legge & Kersten, 1983).

In Experiment III, the stimulus was again composed of plain bars taken from the square-wave gratings of Experiment I, but the background luminance was varied, as was the adaptation level of the participant. The purpose was to determine whether or not the relation between stimuli and the background, specifically the isolated light bars or dark bars and the background, determines the perception (see, e.g., Anstis, 2000).

CHAPTER II

GENERAL METHODS

I performed three experiments with the same participants and apparatus, except as noted. In all experiments, I used the method of constant stimuli to determine the circumstances under which the participants perceived the three phenomena of interest: perceived rotation (the Venetian blind effect), binocular luster, and binocular rivalry.

Participants

All participants are adult males in the University of New Hampshire Psychology Department, and have had experience with stereoscopic viewing. Participants WWS and JJD have normal vision, while participant RSH has myopia as well as an astigmatism in the left eye, which are corrected by glasses. Institutional Review Board clearance was acquired beforehand (see Appendix B) and all participants gave informed consent.

Apparatus

All experimental sessions were performed in a darkened room. One participant at a time was seated, bit onto a bite bar, and viewed stimuli through 3 mm artificial pupils. The experiment was controlled by a program running in *Mathematica* 4.0.2.1 on a Power Mac G4, displayed on an Apple ColorSync Display. Vertical baffles were in place along the participant's line of sight to separate the views for the two eyes. The display was around 1.62 m in front of the participant and a single pixel had a width of around 46.2 seconds of visual angle. The entire viewing area was around 3.8° in width (7.7° in total, separated for the two eyes and with a small amount covered by the baffles) and 4.6° in height, surrounded by a cardboard mask. Each monocular image was centered in the left or right half of the screen with a vertical dark nonius line above and below (to aid in fusing) and with other characteristics that varied based on the experiment. All experimental images were on a background of uniform gray which was at around 42.5 cd/m^2 (300 photopic td) in the first two experiments and which varied in the third.

Procedure

Before all sessions there was a period of setup with the lights on and a sample stimulus on the display. The participant bit onto the bite bar and aligned each artificial pupil so that it appeared centered on the relevant monocular image. The participant then set up a sight (one for each eye) composed of a pair of vertical wires so that their tips formed a direct line to the center of each monocular image. The experimenter (or a trained participant) viewed back along these lines to judge the position of each pupil and made any necessary adjustments before removing the sights. The experimenter and participant then adjusted the baffles in tandem to ensure unobstructed and equal views of the two halves of the display. The participant was allowed to set up music or other auditory background, the experimenter left the room, and the lights were turned off.

Each experimental session began when the participant entered a key on a keypad. The sample stimulus was replaced with a uniform gray (which was at the background luminance in the first two experiments but varied in the third) for a five-minute adaptation period. Experimental trials began afterwards. The participant was shown a binocular image for 5 seconds, which was chosen pseudorandomly (using the computer's own functions) from the available conditions for that experiment. The stimulus was then replaced with the uniform gray again and the participant was prompted to respond. After the response was entered on the keypad, the uniform gray remained on the screen for an interstimulus interval of 5 seconds, and then the next trial began. At the end of a session (each session lasting one hour or less), data were automatically output to a computer file.

The participant's task was to make three judgments for each binocular image, reporting whether the image appeared to have a rotation in depth (the Venetian blind effect), binocular luster, and/or binocular rivalry. For perceived rotation, direction of rotation was not measured. For binocular luster, note Dove's (1851) observation that luster is sometimes observed during the alternations in rivalry but not during steady periods of dominance, and so participants were instructed to responded to a "glow," regardless whether it was perceived as stable luster or as transient luster tied to alternations in rivalry. Also note fluorence may be perceived in images very close to the background luminance, as discussed by Evans (1959), and so some "glow" detected by participants in images close to the background may actually have been fluorence. For binocular rivalry, participants were instructed to respond to either unitary or mosaic rivalry (see, e.g., Howard and Rogers, 1995, p. 327).

Participants performed practice sessions until they felt comfortable and responses stabilized, which in all cases was three or fewer sessions for each experiment. They then performed formal sessions until 12 trials were completed for every condition in that experiment. Because of varying numbers of conditions, this meant the total number of sessions differed across experiments.

Methods for Data Analysis

The data were plotted as the probability of responding "present" to each perceptual phenomenon across the 12 trials for each condition, using standard error bars based on the score estimator. The score estimator was first described by Wilson (1927) and, as has been discussed in detail by Agresti and Coull (1998) and Agresti and Caffo (2000), provides relatively accurate confidence intervals for proportions even when the set of data is small. The endpoints of a score confidence interval are calculated with the equation

$$\frac{\hat{p} + \frac{z_{\alpha/2}^2}{2n} \pm z_{\alpha/2}\sqrt{\frac{\hat{p}\hat{q} + \frac{z_{\alpha/2}^2}{4n}}{n}}}{1 + \frac{z_{\alpha/2}^2}{n}},$$

where $\hat{p}$ is the estimated probability or proportion, $\hat{q}$ is equal to $1 - \hat{p}$, $z_{\alpha/2}$ is the z-score (or number of standard errors) for a confidence interval of the size desired, and n is the number of observations (Agresti & Coull, 1998, p. 120). Here, n was always 12 as stated, and $z_{\alpha/2}$ was always 1.

Thresholds for the perception of each phenomenon were calculated by fitting curves to the data. These curves were the cumulative density function of a Laplace distribution, fit using the *FindFit* function in *Mathematica* 5.0.0.0. When there was no fit found to the data, the results of this function were not plotted. Note that in the plots (Figure 27-29, Figure 34-36, Figure 40-42) some of the fits appear more sharp or steplike than necessary to fit the data. These fits were checked by varying the starting values for the *FindFit* function.

CHAPTER III

EXPERIMENT I

I performed Experiment I to determine thresholds for the three perceptual phenomena on a grating stimulus, as stated in the literature summary and rationale for current research (p. 40). I predicted that increasing levels of dichoptic luminance or contrast modulation would be necessary for each perception, where perceived rotation would require the least modulation, binocular luster the next, and binocular rivalry the most. I did not expect rivalry to be perceived at all for images with a contrast disparity. My initial predictions did not take into account the individual light bars and dark bars: this will be addressed in the upcoming discussion and in Experiment II.

Stimuli

Experiment I used square-wave gratings made up of three light bars and four dark bars at a spatial frequency of around 1.5 cycles per degree. Each monocular image was around 2.3° in width and 1.5° in height. The images varied from a monoptic "neutral" state, with

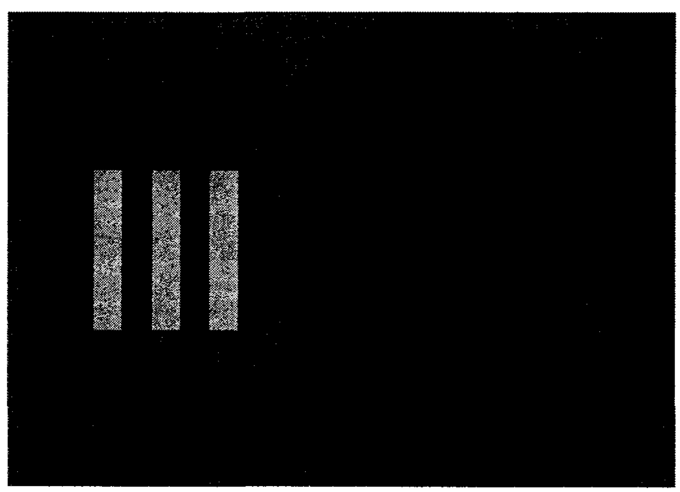

Figure 25. Sample Experiment I (grating) image, luminance disparity condition. This image has dichoptic luminance modulation of 0.4, as in Figure 5. This is also an image in the left "eye" condition, where the left image has higher luminance. See text.

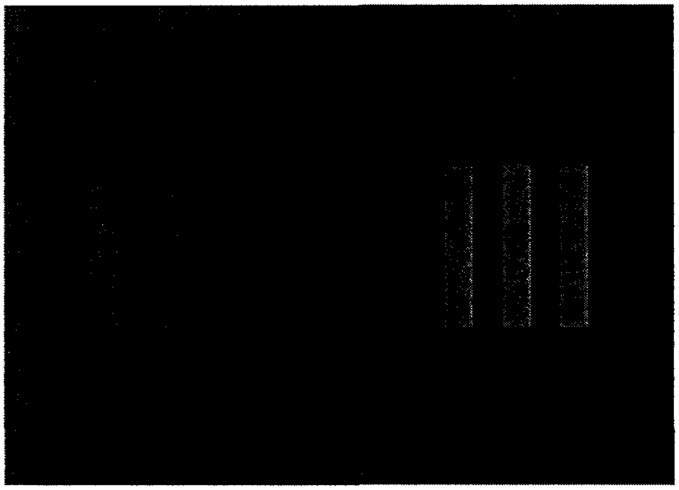

Figure 26. Sample Experiment I (grating) image, contrast disparity condition. This image has dichoptic contrast modulation of 0.5, as in Figure 10. This is also an image in the right "eye" condition, where the right image has higher contrast. See text.

no dichoptic luminance or contrast modulation, where the light and dark bars averaged 42.5 cd/m^2 (the base luminance) and had a contrast of 0.5 (the base contrast). Some images had dichoptic luminance modulation and some had dichoptic contrast modulation. The remaining area on the screen was at the background luminance of 42.5 cd/m^2.

There were three independent variables: whether dichoptic luminance modulation or dichoptic contrast modulation were being used, the amount of the modulation, and whether the left or right eye received the image with higher luminance or contrast. Possible modulation values for either luminance or contrast varied in 0.10 increments from 0.10 to 0.90, with an extra neutral condition that had no modulation (Figure 25-26, also see Figure 11 for the neutral condition). Each combination of values, including the neutral condition, appeared four times in one session. Participants performed three sessions, therefore completing 12 trials for each condition.

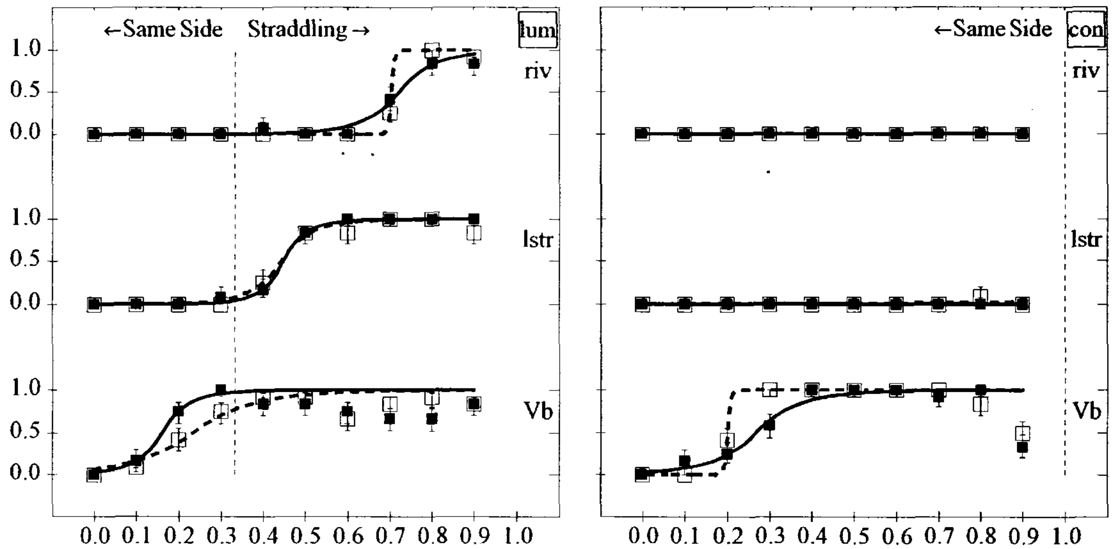

Figure 27. Experiment I data for JJD. From bottom to top, probability of detecting rotation ("Vb"), luster ("lstr"), and rivalry ("riv") at different modulations. The left chart is for luminance ("lum") and right is for contrast ("con"). Filled boxes are for the left "eye" condition and empty boxes for right "eye." The vertical dotted line is the point of monocular equality to the background, where the light bars in one monocular grating are at the background luminance. See text.

Results

Data are shown in Figure 27-29, plotting the probability of responding "present" to each perceptual phenomenon with one figure for each participant. The meaning of the vertical dotted lines will be addressed in the upcoming discussion (p. 52). For most participants and most perceptual phenomena, the phenomena seem to become visible at separate threshold modulation values, with perceived rotation requiring the least and binocular rivalry the most. Note that participant WWS may not have a bottom threshold for perceiving the Venetian blind effect and, in fact, informally stated that there is almost always a rotation in the same direction (with the right edge of each bar appearing closer to the participant). Differences in thresholds for the "eye" conditions (being whether the left or right eye received the image with higher luminance or contrast) are not always

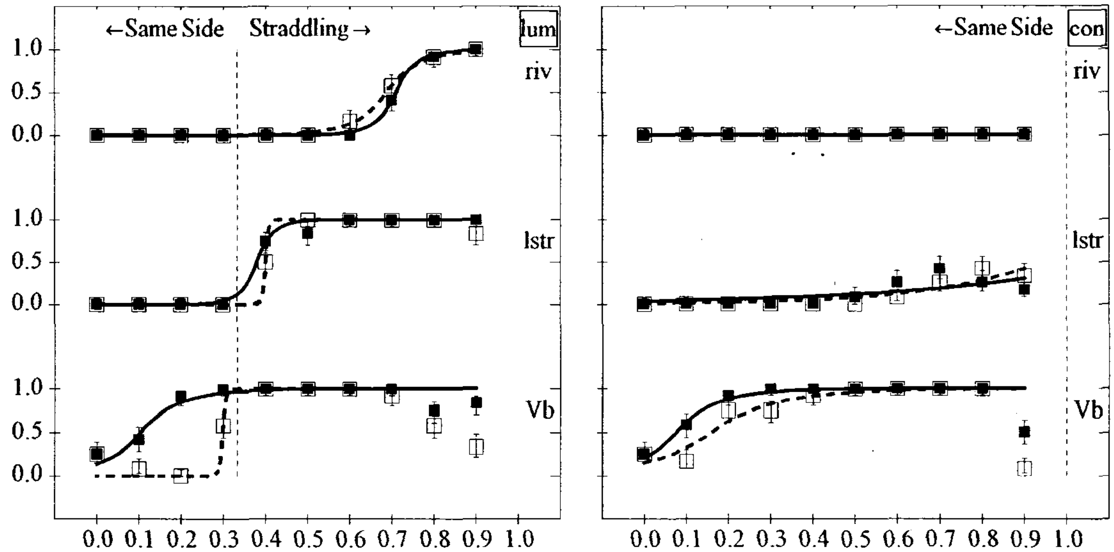

Figure 28. Experiment I data for RSH. From bottom to top, probability of detecting rotation ("Vb"), luster ("lstr"), and rivalry ("riv") at different modulations. The left chart is for luminance ("lum") and right is for contrast ("con"). Filled boxes are for the left "eye" condition and empty boxes for right "eye." The vertical dotted line is the point of monocular equality to the background, where the light bars in one monocular grating are at the background luminance. See text.

very pronounced but also differ with the phenomenon in question, where the most noticeable ocular dominance occurs with perceived rotation.

There are differences based on the type of modulation. Numerically, the threshold modulation values for perceived rotation are nearly the same when considering luminance and contrast, but the meaning of such a comparison is uncertain across these different characteristics of a grating. Thresholds for luster clearly differ when considering luminance and contrast, with neither participant JJD nor WWS perceiving contrast-based luster, and participant RSH only approaching a 50% probability of perception at higher modulation. There is no detectable contrast modulation threshold for binocular rivalry, meaning that the monocular images are never perceived as alternating back and forth. Instead, there apparently comes a point where one image wholly

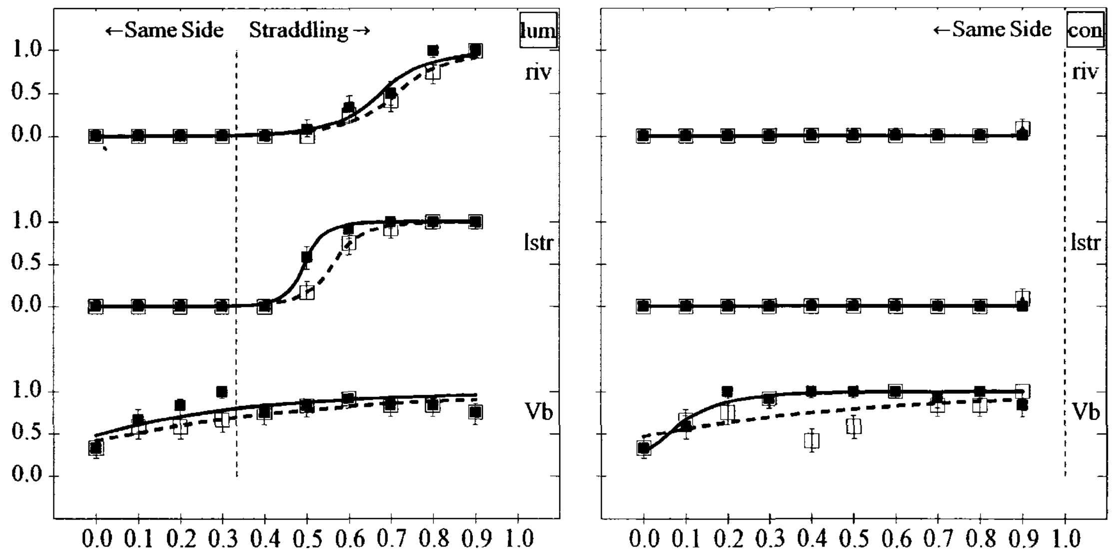

Figure 29. Experiment I data for WWS. From bottom to top, probability of detecting rotation ("Vb"), luster ("lstr"), and rivalry ("riv") at different modulations. The left chart is for luminance ("lum") and right is for contrast ("con"). Filled boxes are for the left "eye" condition and empty boxes for right "eye." The vertical dotted line is the point of monocular equality to the background, where the light bars in one monocular grating are at the background luminance. See text.

dominates the other, as can be seen in the data at high modulation values where rotation ceases to be perceived for JJD and RSH.

There are multiple observations to make from informal discussions with the participants. As dichoptic luminance modulation increases, the light bars sometimes seem to float out in space, and be rotated in depth, for periods of time within an otherwise rivalrous presentation. Participants responded that they did perceive rotation during these situations, and, as seen in the data, at even higher modulation values this perceived rotation ceases. This experience of "floating" is interesting in light of similar observations during my master's thesis (Hetley, 2005), which, at the time, were explained as a conflict between geometric and other forms of disparity. This explanation is not relevant for these geometrically identical stimuli.

Different participants informally described the experience of binocular luster differently, including using such terms as "sheen" or "transparency." As seen in the data, it is interesting to note that luster (at least based on dichoptic luminance modulation) does tend to arise at similar modulation values despite these differences in verbal descriptions.

Also informally, experiences during binocular rivalry are complex. Generally, all rivalry with these images is mosaic rivalry, which is to be expected given the images are larger than 1° in visual angle (see, e.g., Howard & Rogers, 1995, p. 327). In line with Dove's (1851) observation, binocular luster is sometimes observed as a transient phenomenon during the alternations in rivalry but not during steady periods of dominance, and sometimes luster is indeed steady. This transient luster seems to occur at higher dichoptic luminance modulation values.

Discussion

In a basic sense, the results from Experiment I address the question that led to it, namely what the thresholds are for the Venetian blind effect, binocular luster, and binocular rivalry in a grating stimulus. However, a chance observation shows a revealing coincidence touching on the work of Legge and Kersten (1983), originally discussed in the subsection on light bars and dark bars versus average luminance and contrast in the introduction (p. 16).

With luminance modulation, the modulation value of 0.20 is a short distance below the threshold for binocular luster, at least for participant RSH. With contrast modulation, the modulation value of 0.60 is slightly below the point where participant RSH approached a 50% probability for perceiving luster. Though these modulation values are seemingly unrelated, the light bars in the dichoptic stimuli are identical between the modulation types. That is, a stimulus with a dichoptic luminance modulation of 0.20 (starting from 42.5 cd/m^2 base luminance and 0.5 contrast, as discussed) has light bars at 51.0 cd/m^2 in one monocular image and 76.5 cd/m^2 in the other. A stimulus with a dichoptic contrast modulation of 0.60 has exactly the same light bars. The dark bars, however, are not the same across modulation type, and in fact they swap which monocular image has higher dark bar luminance: with luminance modulation, the monocular image that has higher light bar luminance also has higher dark bar luminance; with contrast modulation, the other monocular image does.

This discovery prompts further consideration. The vertical dotted lines in Figure 27-29 mark another meaningful point which I call the *point of monocular equality to the background.* In grating stimuli, this point is the modulation value such that one monocular grating's light bars are at exactly the background luminance. That is, a grating with a dichoptic luminance modulation of 0.33, or a grating with a dichoptic contrast modulation of 1.00, has light bars at 42.5 cd/m^2 in one monocular image and 85.0 cd/m^2 in the other. On one side of the dotted line all the light bars are above the background luminance, while on the other side they dichoptically straddle the background. For all participants, this point of monocular equality to the background must be crossed before luster and rivalry reach above threshold. The dark bars, however, are always below the background luminance and therefore do not seem to relate to the perception of luster and rivalry.

This relation between individual bars and perception suggests that considering the light bars versus the dark bars may be central in describing the phenomena. If true, then this provides a second argument against Legge and Kersten's (1983) suggestion that average luminance and contrast provide a more useful definition for grating stimuli. (The first argument came when looking at replotted data from Filley, 1998; see Figure 12-13)

Further, the point of monocular equality to the background for the light bars brings to mind the discussion of Wolfe and Franzel (1988), Fry and Bartley (1933), and Anstis (2000) in the subsection on the relation between stimuli and the background in the introduction (p. 27). It is strange that luster and rivalry seem to arise with a predictable relation to the background while perceived rotation does not. But then, perceived rotation also seems to differ from the other two perceptions in that ocular dominance was detectable or was more pronounced. Thus, the evidence so far suggests that there are two mechanisms behind these three perceptions: one that handles binocular luster and binocular rivalry, and one that handles perceived rotation. Though luster and rivalry do not have exactly identical thresholds, it is reasonable to group them in this manner because the thresholds are in the same relationship to each other for each participant, i.e., luster arises sooner.

However, this understanding is incomplete. For instance, the discussion of individual bars in Filley's (1998) images specifically pertained to perceived rotation, and the evidence from individual bars here mostly pertains to luster and rivalry. Therefore Experiment II was designed to elaborate on the role of the individual bars in describing the phenomena, while Experiment III was designed to elaborate on the relation to the background.

CHAPTER IV

EXPERIMENT II

I performed Experiment II to determine whether the most useful way to mathematically define stimuli for the three perceptual phenomena is in terms of average luminance and contrast, or in terms of the luminance values of the light bars and dark bars. I predicted that all three perceptions would arise in the patterns shown in Experiment I when participants were presented with isolated light bars, while the phenomena would either not occur or at least would not occur with the same pattern when participants were presented with any other related image. My initial predictions did not take into account the relation between the individual bars and the background, which will be addressed in the upcoming discussion and in Experiment III.

Stimuli

Experiment II used what I am calling "plain bars" images, which contained three dichoptic bars on a uniform field of the background luminance (Figure 30-33), 42.5 cd/m^2 as before. The three bars were of the same dimensions and position as the three light bars in a grating stimulus in Experiment I, each being around 0.3° in width and 1.5° in height, separated by one bar width from each other. The background gray continued between the bars.

The plain bars varied in one of four ways, and the source of the luminance values for the bars was one independent variable, as discussed below. In the "average luminance" condition, the images varied from a monoptic "neutral" state, where they were at the base luminance of 42.5 cd/m^2 (no figure is provided as these bars would simply blend into the background). Non-neutral images had luminance values taken from the average luminance of a square-wave grating from Experiment I. That is, in Experiment I, some images had dichoptic luminance modulation that varied in 0.10 increments from 0.10 to 0.90, and this modulation value was used to determine the average luminance of each monocular image. In the "average luminance" condition in Experiment II, the plain bars were at those average luminance values (Figure 30). There was no equivalent "contrast" condition because there were no dichoptic "other bars" in these plain bars images with which there would be contrast.

In the "light luminance bars" (Figure 31) and "light contrast bars" (Figure 32) conditions, the plain bars were at the luminance values of the light bars of a square-wave grating which had dichoptic luminance modulation or dichoptic contrast modulation, respectively. That is, they had a monoptic "neutral" state where they were at the luminance values of the light bars in a grating at 42.5 cd/m^2 average luminance and 0.5 contrast, and non-neutral images followed the luminance of the light bars in a

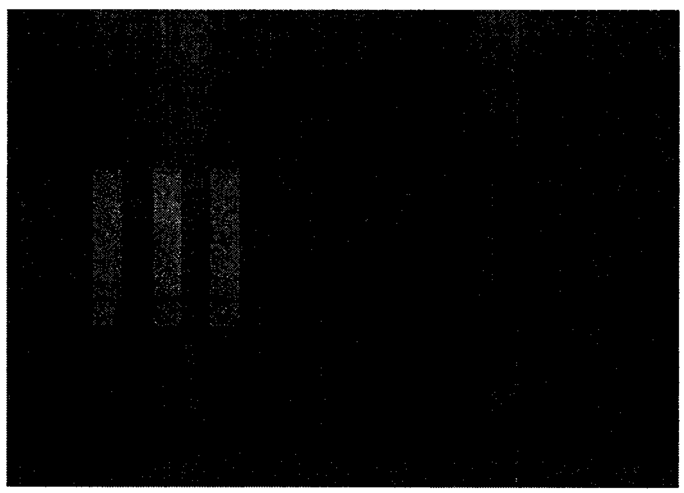

Figure 30. Sample Experiment II (plain bars) "average luminance" image. Each monocular set of bars is at a luminance equal to the average luminance of one monocular image in Figure 25, i.e., in a grating with dichoptic luminance modulation of 0.4. This is also in the left "eye" condition. See text.

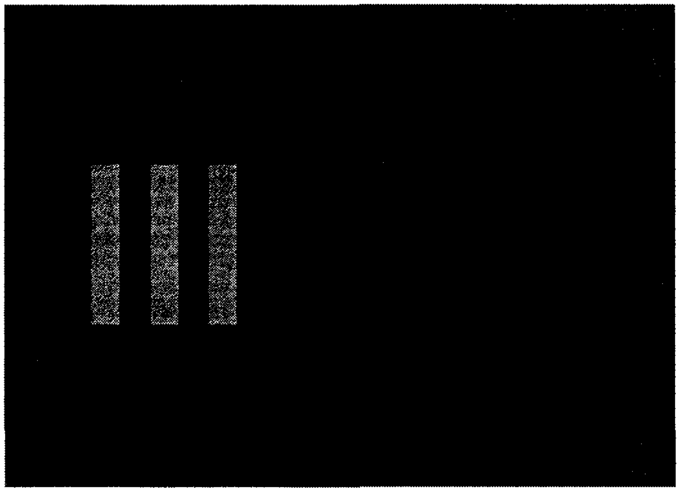

Figure 31. Sample Experiment II (plain bars) "light luminance bars" image. The bars are identical to the light bars in Figure 25, i.e., in a grating with dichoptic luminance modulation of 0.4. This is also in the left "eye" condition. See text.

grating that varied in its modulation. For both of these conditions, modulation of the grating from which the plain bars were taken varied in 0.10 increments from 0.10 to 0.90.

In the "dark bars" condition (Figure 33), the images were at the luminance values of the dark bars in a square-wave grating. The original grating stimuli swapped which monocular image had higher dark bar luminance when swapping between dichoptic luminance and contrast modulation, but the values for luminance themselves did not differ, and so there was only one "dark bars" condition. The modulation values again varied in 0.10 increments from 0.10 to 0.90. Though there were four dark bars in each original grating, only three were presented here in order to make the stimuli more comparable across conditions.

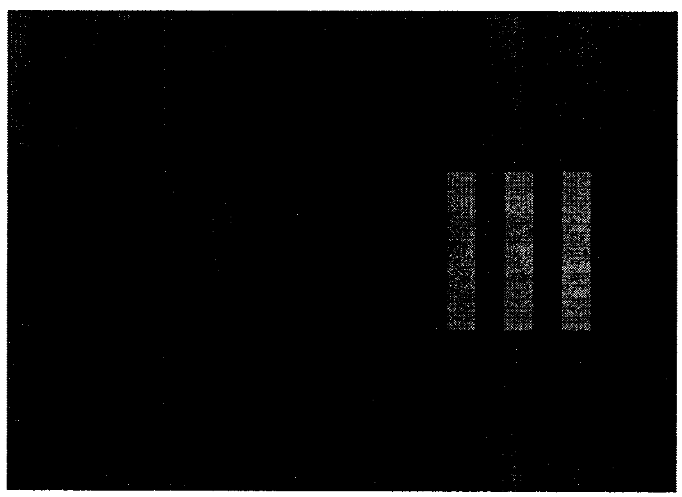

Figure 32. Sample Experiment II (plain bars) "light contrast bars" image. The bars are identical to the light bars in Figure 28, i.e., in a grating with dichoptic contrast modulation of 0.5. This is also in the right "eye" condition. See text.

Though this idea of "luminance source" means a

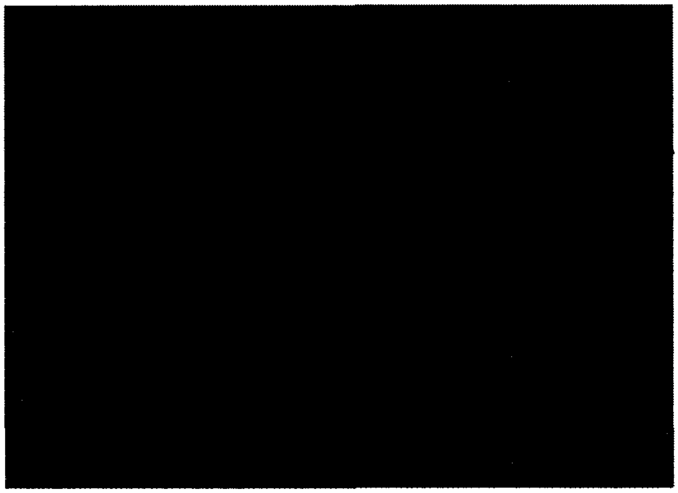

Figure 33. Sample Experiment II (plain bars) "dark bars" image. The bars are identical to the dark bars in Figure 25, i.e., in a grating with dichoptic luminance modulation of 0.4. This is also in the left "eye" condition. See text.

complex derivation for the luminance values in these images, once calculated they are simple to understand. Each of these four types of images is now effectively a new dichoptic stimulus with its own base luminance, and can be defined in terms of dichoptic luminance modulation. The average luminance of gratings with a luminance disparity was always centered around the base of 42.5 cd/m^2, and so the "average luminance" plain bars always had that base luminance. The light bars of gratings with either a luminance or contrast disparity always averaged 63.75 cd/m^2, and so the "light luminance bars" and "light contrast bars" images always had that base luminance. The dark bars of gratings with either a luminance or contrast disparity always averaged 21.25 cd/m^2, and so the "dark bars" images always had that base luminance.

It turns out that the "average luminance," "light luminance bars," and "dark bars" images can likewise be said to have dichoptic luminance modulation from 0.10 to 0.90 around their respective base luminance. The one exception is the "light contrast bars" condition, where the newly calculated dichoptic luminance modulation proceeds from 0.03 to 0.30 in increments of 0.03.

In total, there were three independent variables: the source of the luminance values, the amount of the modulation, and whether the left or right eye received the image with higher luminance. Each combination of values was one condition, and there were also three neutral conditions: one for "average luminance," one for both "light luminance bars" and "light contrast bars" (as these would be identical if there were no modulation), and one for "dark bars." Note that the neutral condition for "average luminance" is a screen that is blank gray except for nonius lines, and so even though this condition was presented, it will not be plotted in this experiment. Each combination of values, including the neutral conditions, appeared twice in one session. Participants performed six sessions, therefore completing 12 trials for each condition.

Results

Data are shown in Figure 34-36, again plotting the probability of responding "present" to each perceptual phenomenon with one figure for each participant. Note that the modulation values at the bottom of each plot are the dichoptic luminance or contrast modulation values in the original grating images of Experiment I, allowing direct comparison of these plots to those in Figure 27-29. That is, the "average luminance" and "light luminance bars" plots can be compared to the plots for images with dichoptic luminance modulation; the "light contrast bars" plots can be compared to the plots for images with dichoptic contrast modulation; and the "dark bars" plots can be compared to either.

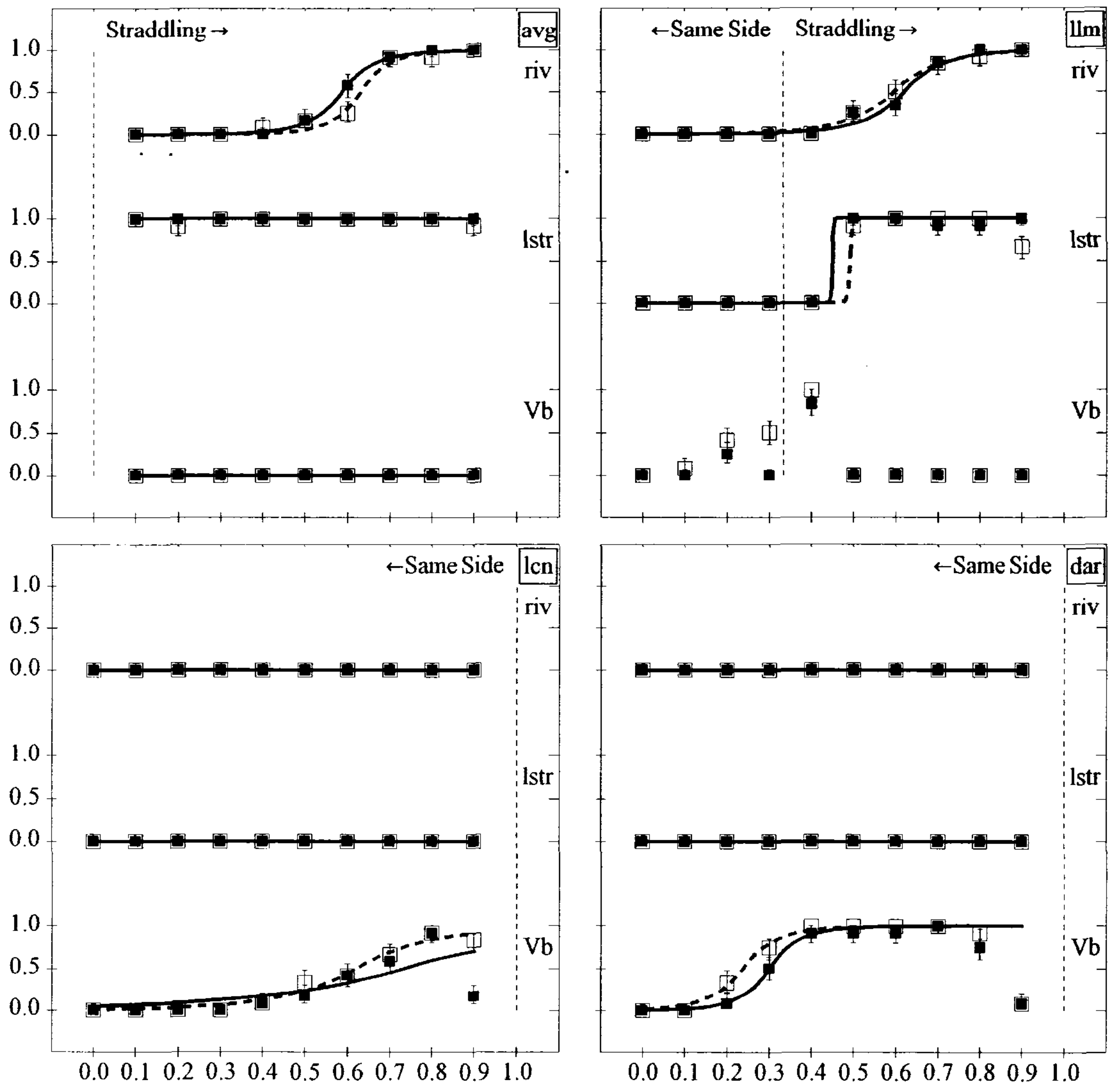

Figure 34. Experiment II data for JJD. From bottom to top, probability of detecting rotation ("Vb"), luster ("lstr"), and rivalry ("riv") at different modulations. The top left chart is for "average luminance" ("avg"), top right "light luminance bars" ("llm"), bottom left "light contrast bars" ("lcn"), and bottom right "dark bars" ("dar"). Filled boxes are for the left "eye" condition and empty boxes for right "eye." The vertical dotted line is the point of monocular equality to the background, where one monocular image is at the background luminance. See text.

The "light luminance bars" and "light contrast bars" plots show thresholds for the initial perception of rotation, binocular luster, and binocular rivalry that mirror those in Experiment I. Ocular dominance does not perfectly match across these two experiments,

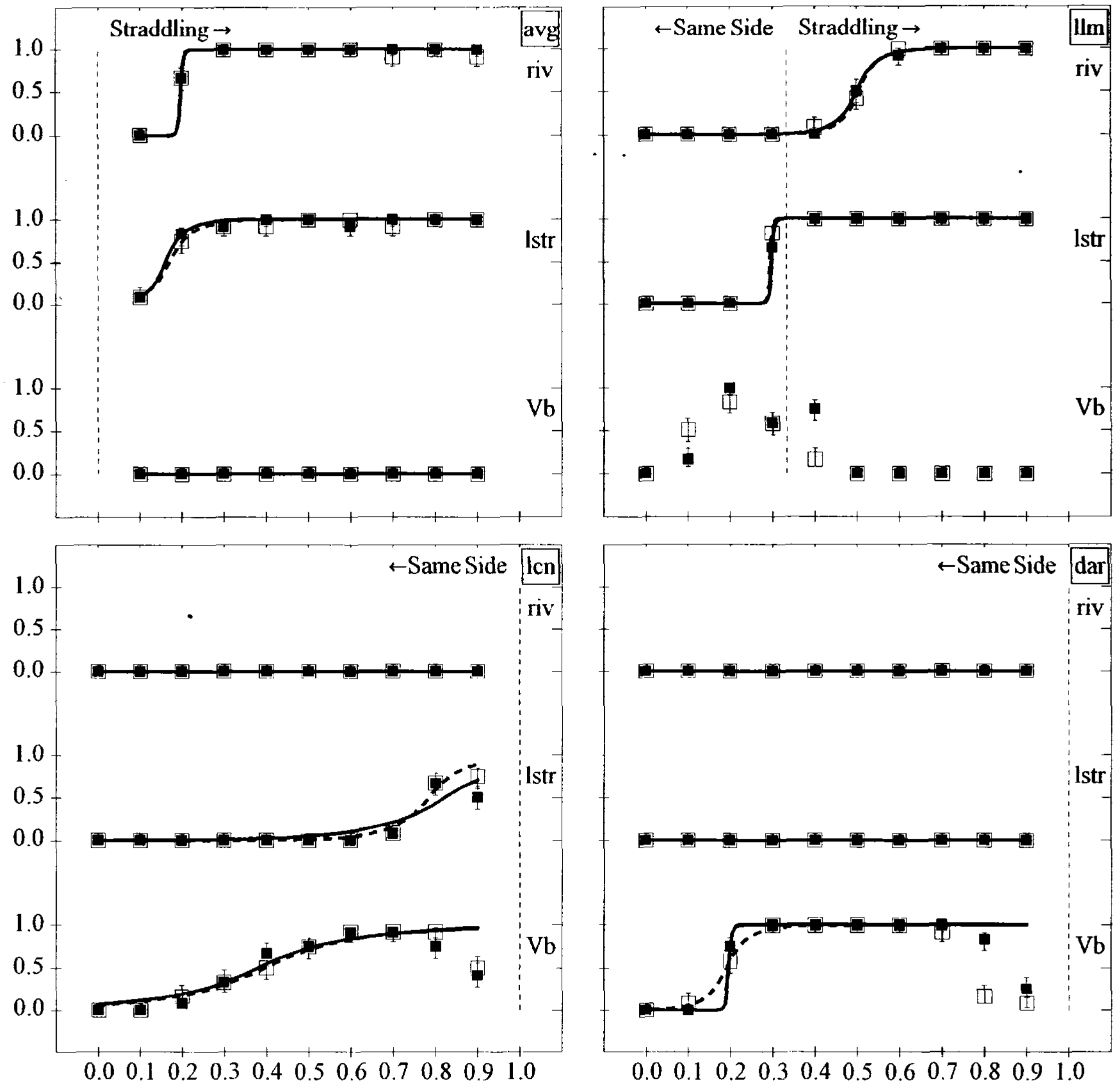

Figure 35. Experiment II data for RSH. From bottom to top, probability of detecting rotation ("Vb"), luster ("lstr"), and rivalry ("riv") at different modulations. The top left chart is for "average luminance" ("avg"), top right "light luminance bars" ("llm"), bottom left "light contrast bars" ("lcn"), and bottom right "dark bars" ("dar"). Filled boxes are for the left "eye" condition and empty boxes for right "eye." The vertical dotted line is the point of monocular equality to the background, where one monocular image is at the background luminance. See text.

but it is worth noting that, again, differences in thresholds for the "eye" conditions were more common with perceived rotation.

The vertical dotted lines are the point of monocular equality to the background, and the meaning of this point is similar to before, being where one monocular image is

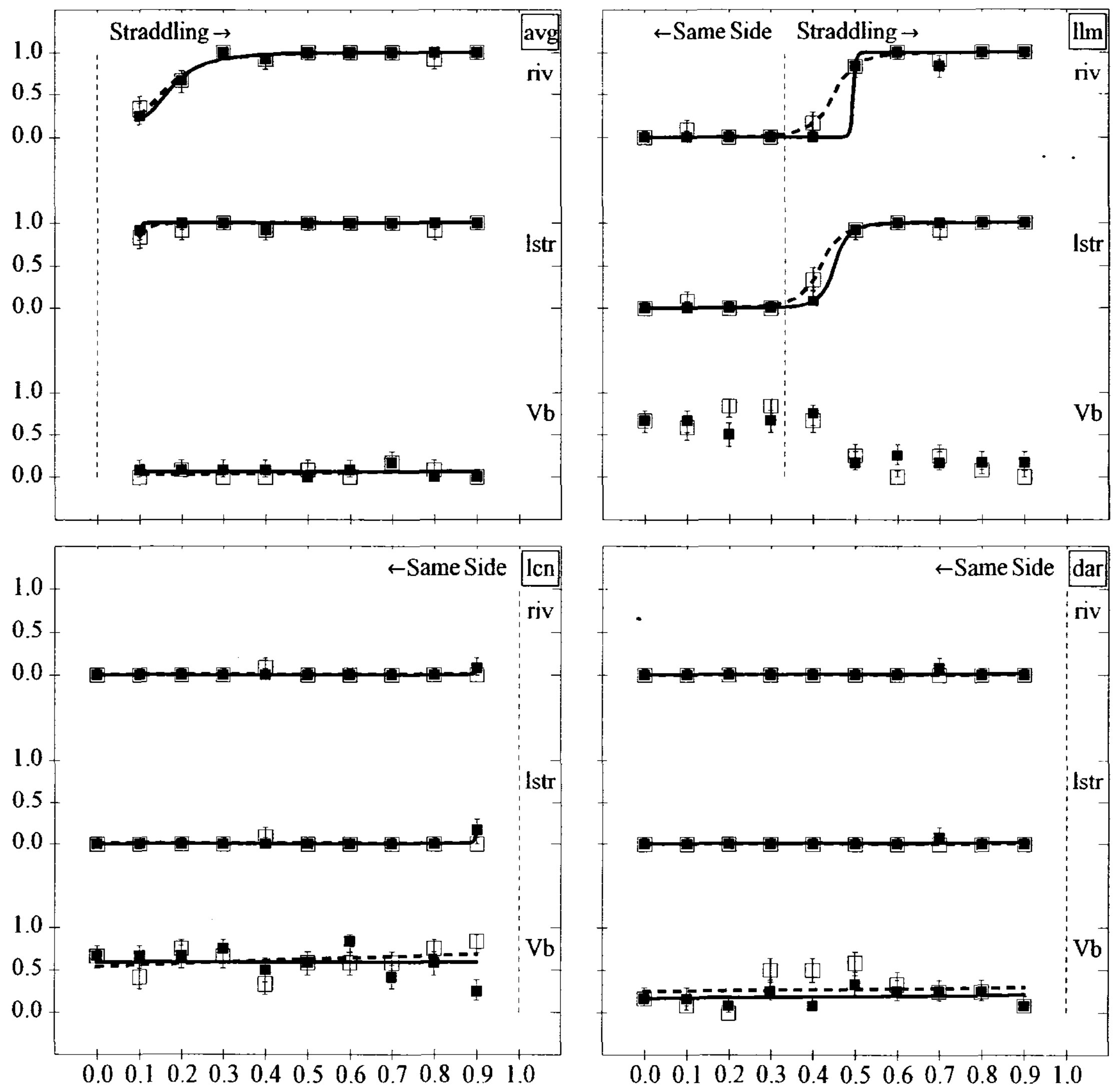

Figure 36. Experiment II data for WWS. From bottom to top, probability of detecting rotation ("Vb"), luster ("lstr"), and rivalry ("riv") at different modulations. The top left chart is for "average luminance" ("avg"), top right "light luminance bars" ("llm"), bottom left "light contrast bars" ("lcn"), and bottom right "dark bars" ("dar"). Filled boxes are for the left "eye" condition and empty boxes for right "eye." The vertical dotted line is the point of monocular equality to the background, where one monocular image is at the background luminance. See text.

exactly at the background luminance (in Experiment I, it was the point where the light bars had this relation to the background; see p. 52). It can be seen that, in nearly all cases, luster and rivalry appear only once the stimulus begins dichoptically straddling the background. As such, luster and rivalry occur the most for stimuli in the "average luminance" condition, and do not occur at all for stimuli in the "dark bars" condition. In fact, this relation to the background makes some sense of data from RSH, who was the only participant to report often seeing luster in grating images with a contrast disparity: this participant generally seems to see luster with less modulation than the other participants, and a comparison of the "light luminance bars" and "light contrast bars" plots reveals the initial threshold is in a similar location relative to the vertical line.

The pattern followed by perceived rotation, however, is unexpected. For participant JJD and RSH in the "light luminance bars" condition, the initial threshold for perceiving rotation is similar to that in Experiment I but the perception is not maintained over nearly as large a range of modulation values. In fact, after a peak near the point of monocular equality to the background, perceived rotation ceases at about the same point that rivalry begins[28]. There likewise is a lack of perceived rotation in the "average luminance" condition, where the bars always dichoptically straddle the background. This cessation of rotation even occurs for participant WWS, who reported rotation in almost every image from Experiment I.

It is also worth making some notes that relate to informal observations. Despite this similarity between all three participants on the cessation of perceived rotation, WWS has much lower probabilities for seeing rotation in the "dark bars" condition. The participant stated that for some entire sessions the dark bars seemed to remain flat while for others they seemed rotated.

It can be seen that the slope for participant JJD's perception of rivalry in the "average luminance" condition is shallower and less curved than others. The participant

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[28] As a result of the peak in the perception of rotation, Laplace fits would generally appear as flat horizontal lines and are not plotted in Figure 34-36.

informally observed he seemed to be shifting his criteria for responding to the phenomenon across sessions, in that over time he was more willing to respond "present." Given that this threshold is even lower in the subsequent Experiment III, it would seem that the new criteria are more stable.

Beyond this instance with JJD, there is much more variability in the relationship between luster and rivalry thresholds in this experiment than in Experiment II. One issue may be that in the "average luminance" condition, both monocular images could be much closer to the background than in other conditions. As discussed in the subsection on fluorence in the introduction (p. 29), Evans (1959) discovered it is possible for grayscale images to seem to glow under circumstances similar to these. Participant RSH informally noted there did seem to be some very low modulation values in that condition where a "glow" appeared that did not feel exactly the same as luster, and might have been fluorence. Therefore, there is some extra uncertainty in the luster thresholds in this condition.

Lastly, these individual bars, which are less than 1° in width but more than 1° in height, seem to only undergo mosaic rivalry and not unitary rivalry (see, e.g., Howard & Rogers, 1995, p. 327). Therefore, there is no more information available here on the relationship between these two forms of rivalry and the other perceptions.

Discussion

In most cases, the predictions for this experiment are met. The thresholds for the initial perception of rotation, binocular luster, and binocular rivalry are not detectably different when considering intact square-wave gratings versus considering the light bars alone, suggesting that the light bars are central to the overall perception. There is no detectable luster or rivalry when considering the dark bars alone. There is indeed perceived rotation, but given that the dark bar luminance values are identical in images with a dichoptic luminance disparity or dichoptic contrast disparity and yet would be expected to give rise to different directions of rotation, it seems reasonable to presume that the dark bars do not drive the overall perception. When considering the average luminance of the original square-wave gratings, perception simply did not follow any of the patterns from Experiment I.

A natural conclusion is that average luminance and contrast are not as useful in defining stimuli for these three perceptual phenomena as are the luminance values of the individual bars. The monocular sets of light bars being both on the same side of the background luminance, versus dichoptically straddling the background, determines when observers will perceive rotation, luster, and rivalry. This goes contrary to the conclusion of Legge and Kersten (1983) that considering discrimination functions based on contrast is more useful than considering the individual bars, but perhaps it is not a complete conflict with their discussion of detection. As stated in the subsection on light bars and dark bars versus average luminance and contrast in the introduction (p. 16), there are several imbalances in how the visual system treats light and dark bars, including how luminance decrements are more detectable than luminance increments. The initial detection of rotation, luster, and rivalry are clearly another situation for considering individual bars, though it is interesting that the light bars seem to drive rotation more than the dark in this situation.

The discussion so far on the importance of dichoptically straddling the background is in accord with Wolfe and Franzel (1988), Fry and Bartley (1933), and Anstis's (2000) observations in the subsection on the relation between stimuli and the background in the introduction (p. 27). However, these sources discussed the occurrence of binocular luster and binocular rivalry in straddling images, while the present results show there is also a cessation of perceived rotation. The fact that perceived rotation was often detected in Experiment I even when images were rivaling, even when the bars themselves seemed to float out in space, and even when beyond the point where perceived rotation ceased in Experiment II, is curious.

At a minimum, these results mean that luster and rivalry arise in similar circumstances and co-vary, while perceived rotation follows different rules. This insight, in turn, lends more weight to the idea of a connection between luster and rivalry, which was first discussed with Dove's (1851) observation that the two phenomena can be concurrent in the section on binocular luster in the introduction (p. 23), and to the idea that there are two mechanisms behind these three perceptions (one for luster and rivalry, one for perceived rotation), first supported in Experiment I (p. 53).

It is unclear why perceived rotation would occur so differently in the two experiments, though, suggesting that perceived rotation is dependent on the relation between the light bars and the dark bars in a way not considered so far. Perhaps rotation is indeed dependent on the light bars, but the dark bars around them form a special sort of "local background." With that in mind, it could be that a participant's adaptation to the background luminance is interacting with this "local background," and so adaptation level may need to be considered along with background luminance. Alternately, it could be a coincidence that perceived rotation, luster, rivalry, and the cessation of rotation related to the point of monocular equality to the background in this one experiment, and this point of transition is an artifact of the changes in the stimulus (e.g., the change in size). To be certain that the relation to the background is indeed key to the circumstances that give rise to these three perceptions, and to more precisely measure how perception "shifts" between the three, it is necessary to adjust two components so far untouched in these experiments: the background luminance and the adaptation level of the participant. Therefore, Experiment III was designed to elaborate on the relation to the background.

CHAPTER V

EXPERIMENT III

I performed Experiment III to determine whether or not the relation between binocular images and the background is central to the occurrence of binocular rivalry and binocular luster, and to the cessation of perceived rotation. In doing so, there could be a confound in that changing the background a participant is observing will also change the adaptation state of the participant. Therefore, I independently manipulated the luminance of the uniform gray adaptation image and the luminance of the background of the stimuli. I predicted that the thresholds for all three perceptual phenomena, and the threshold for cessation of perceived rotation, would shift to match changes in the background of the stimuli but would be unaffected by adaptation state. I also predicted that the shifts in the thresholds would be symmetrical with shifts in the background luminance, given that Anstis (2000) found symmetrical effects when considering subjective ratings of luster.

Stimuli

Experiment III used images that contained three dichoptic bars on a uniform field of the background luminance, i.e., "plain bars" images just as in Experiment II (see Figure 30-33). Instead of varying "luminance source," just one type of image was used: the "average luminance" plain bars. These bars, as before, varied in the amount of dichoptic luminance modulation from a monoptic "neutral" state where they were at the base luminance of 42.5 cd/m^2. Non-neutral images had modulation that varied in 0.10 increments from 0.10 to 0.90. This type of image was chosen because it was centered towards the middle of the available luminance values for the monitor, and so would be the most efficient in showing whether shifts in the background led to symmetrical effects.

Background luminance (cd/m^2)	Adaptation luminance (cd/m^2): 21.25	42.5	63.75
21.25	Ex. III		Ex. III
42.5		Ex. II	
63.75	Ex. III		Ex. III

Figure 37. Adaptation and background luminance conditions for Experiment III. Cells marked "Ex. III" denote combinations that were used. The center cell is marked "Ex. II" to emphasize how all stimuli in Experiment II involved this combination.

When "average luminance" plain bars were used in Experiment II, stimuli appeared as in Figure 30. Participants had adapted to 42.5 cd/m^2 and then saw 42.5 cd/m^2 as the background for each stimulus. In Experiment III, adaptation luminance and background luminance were two independent variables, and their values were either 21.25 cd/m^2 or 63.75 cd/m^2, as shown in the table in Figure 37 (stimuli against these backgrounds are shown in Figure 38-39). These values were arbitrary and could of course have been anything, but 21.25 cd/m^2 and 63.75 cd/m^2 were chosen because they were the average luminance of the dark bars and of the light bars, respectively, in gratings (as was discussed in Experiment II, p. 57). Also, the base luminance of the stimuli remained unchanged at 42.5 cd/m^2 for the entire experiment, and when such plain bars had dichoptic luminance modulation of 0.50 the monocular images were at exactly 21.25 cd/m^2 and 63.75 cd/m^2, making comparison between conditions more simple.

Figure 38. Sample Experiment III image, 21.25 cd/m^2 background luminance. (Values will differ on paper.) The bars are identical to the bars in Figure 30, i.e., in an "average luminance" image with dichoptic luminance modulation of 0.4. See text.

In total, there were four independent variables: adaptation luminance, background luminance, the amount of dichoptic luminance modulation, and whether the left or right eye received the image with higher luminance. Adaptation and background combinations were given shorthand labels of "2-2," "6-2," "2-6," and "6-6," where the two numbers were the tens digits of the luminance values, first being adaptation luminance and second being background luminance. Thus, in the "6-2" condition, a participant would adapt to a uniform gray of 63.75 cd/m^2 before the stimuli appeared, then see each stimulus against a background of 21.25 cd/m^2 for 5 seconds, then see 63.75 cd/m^2 again while making a response and during each 5 second interstimulus interval. Only one of the four combinations was done on an individual session.

Figure 39. Sample Experiment III image, 63.75 cd/m^2 background luminance. (Values will differ on paper.) The bars are identical to the bars in Figure 30, i.e., in an "average luminance" image with dichoptic luminance modulation of 0.4. See text.

Each combination of modulation value and "eye" conditions appeared six times in one session, so two sessions were performed at every adaptation and background combination to provide 12 trials for each combination of all conditions. A total of eight sessions were run, and for each participant a list was generated pseudorandomly (using the computer's own functions) to determine the order in which the adaptation and background combinations would be used. Participants, of course, knew which adaptation condition and background condition they were observing on a given session.

Results

Data are shown in Figure 40-42, plotting the probability of responding "present" to each perceptual phenomenon with one figure for each participant, with fits for the luster and rivalry data as described in the methods for data analysis section of the general methods (p. 45). For the occurrence and cessation of perceived rotation, two separate cumulative density functions of a Laplace distribution were used in order to fit the shape. For the calculation, the *FindFit* function in *Mathematica* 5.0.0.0 was given a list of data points that ceased at the modulation value where the peak of the graph appeared to occur, with all probability values after that peak replaced with the value 1.00. Each cutoff is visible in Figure 40-42 as the point where each curve ends, being a modulation value of 0.3, 0.4, or 0.6 depending on the condition.

Note that the point of monocular equality to the background is always at a modulation of 0.5, but this value has a different meaning for these images with a varying background. In the "2-2" and "6-2" conditions, the background was below the base luminance of the plain bars, and so when the plain bars were not dichoptically straddling

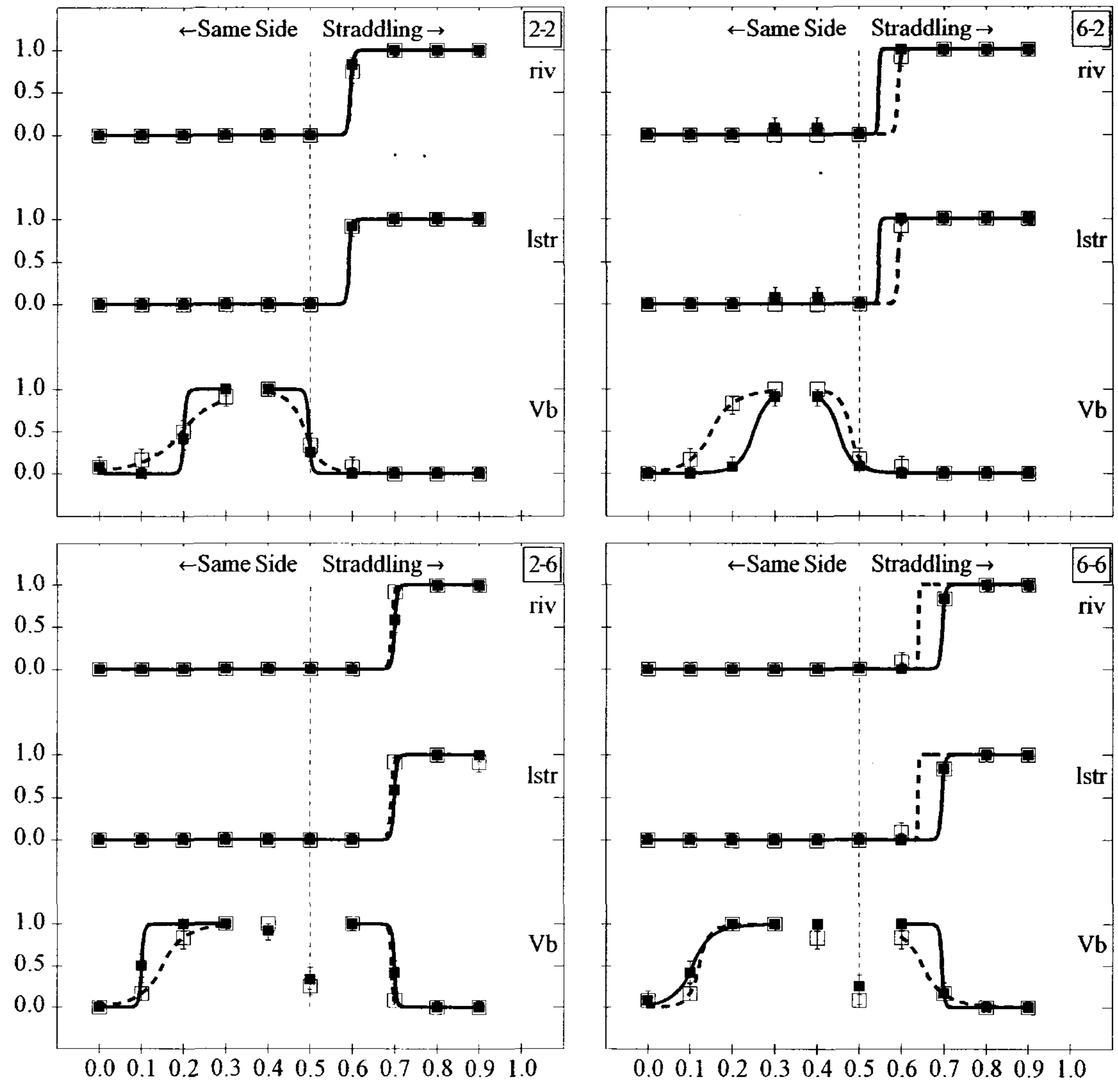

Figure 40. Experiment III data for JJD. From bottom to top, probability of detecting rotation ("Vb"), luster ("lstr"), and rivalry ("riv") at different modulations. The left column of charts is for adaptation luminance of 21.25 cd/m^2 ("2-2," "2-6"), and right for 63.75 cd/m^2 ("6-2," "6-6"). The top row of charts is for background luminance of 21.25 cd/m^2 ("2-2," "6-2"), and bottom for 63.75 cd/m^2 ("2-6," "6-6"). Filled boxes are for the left "eye" condition and empty boxes for right "eye." The vertical dotted line is the point of monocular equality to the background luminance, where one monocular image is at the background luminance. See text.

the background they had higher luminance than the background. In the "2-6" and "6-6" conditions, the background was above the base luminance of the plain bars, and so the opposite was true when the plain bars were not straddling the background.

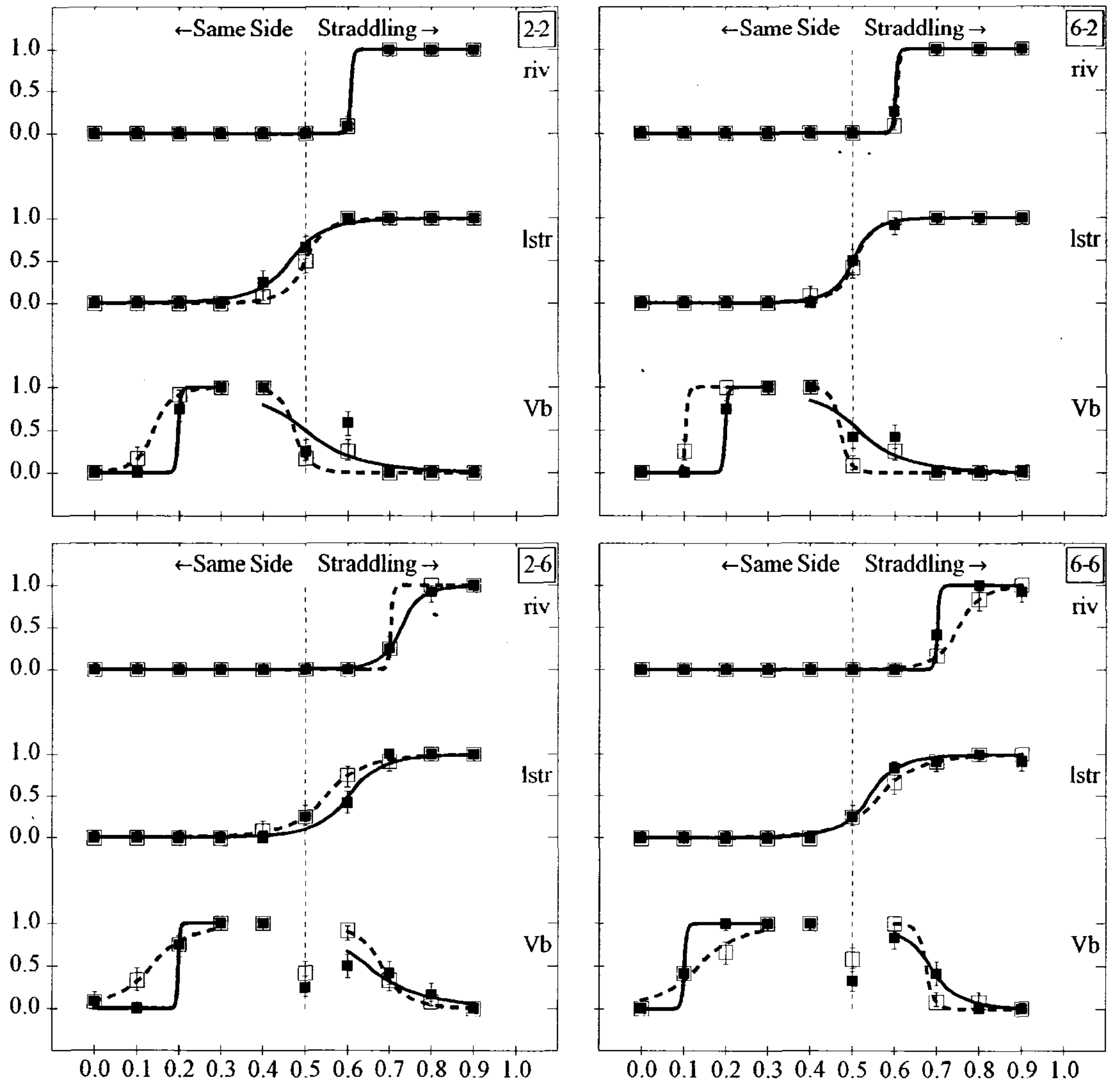

Figure 41. Experiment III data for RSH. From bottom to top, probability of detecting rotation ("Vb"), luster ("lstr"), and rivalry ("riv") at different modulations. The left column of charts is for adaptation luminance of 21.25 cd/m^2 ("2-2," "2-6"), and right for 63.75 cd/m^2 ("6-2," "6-6"). The top row of charts is for background luminance of 21.25 cd/m^2 ("2-2," "6-2"), and bottom for 63.75 cd/m^2 ("2-6," "6-6"). Filled boxes are for the left "eye" condition and empty boxes for right "eye." The vertical dotted line is the point of monocular equality to the background luminance, where one monocular image is at the background luminance. See text.

Figure 43-45 show the modulation values calculated for these four thresholds, namely occurrence of perceived rotation, binocular luster, binocular rivalry, and cessation of perceived rotation. To judge the effects of adaptation luminance, background luminance, and their interaction, analysis of variance (ANOVA) was used. One ANOVA

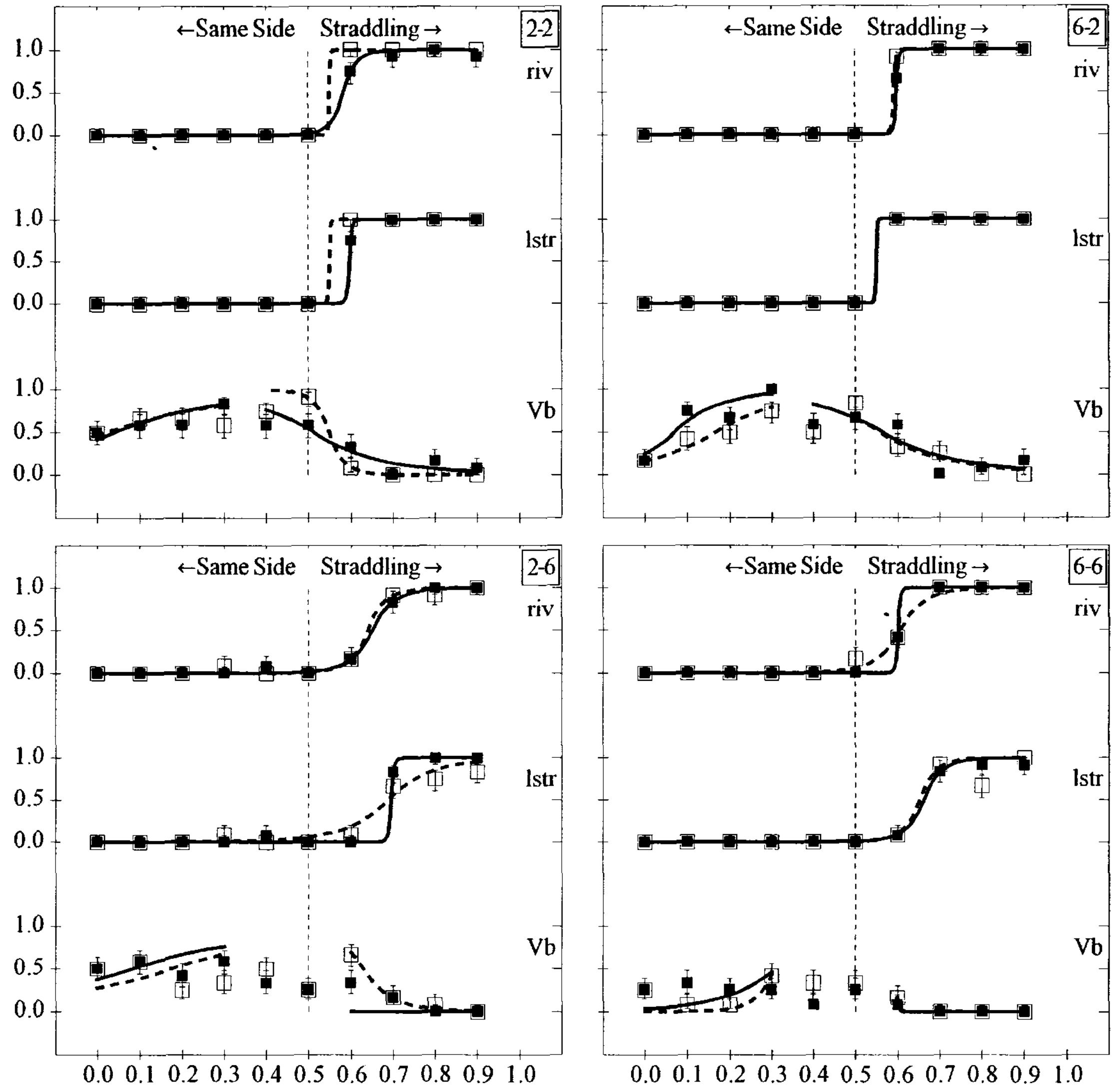

Figure 42. Experiment III data for WWS. From bottom to top, probability of detecting rotation ("Vb"), luster ("lstr"), and rivalry ("riv") at different modulations. The left column of charts is for adaptation luminance of 21.25 cd/m^2 ("2-2," "2-6"), and right for 63.75 cd/m^2 ("6-2," "6-6"). The top row of charts is for background luminance of 21.25 cd/m^2 ("2-2," "6-2"), and bottom for 63.75 cd/m^2 ("2-6," "6-6"). Filled boxes are for the left "eye" condition and empty boxes for right "eye." The vertical dotted line is the point of monocular equality to the background luminance, where one monocular image is at the background luminance. See text.

was performed for each of the four thresholds. Including "eye" condition as a third factor, each ANOVA was a randomized block factorial 2 x 2 x 2 design.

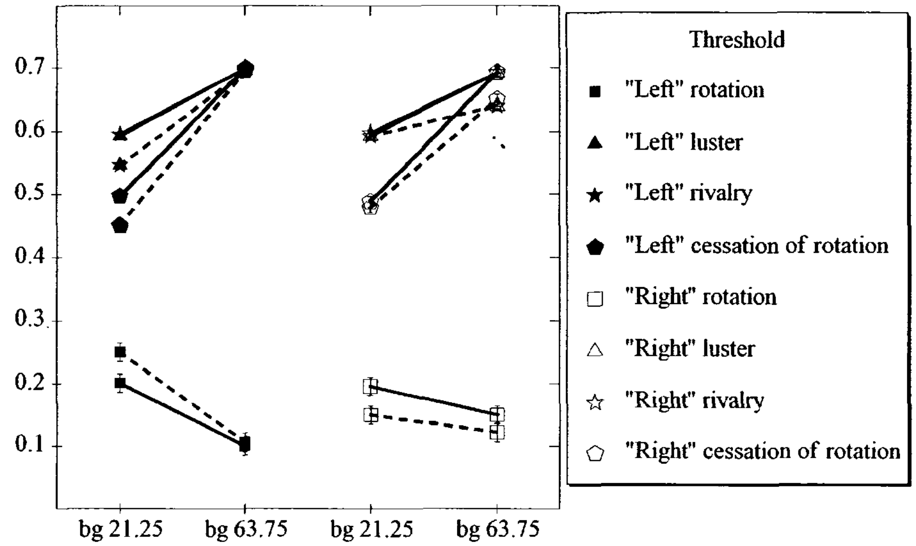

Figure 43. Experiment III thresholds for JJD. Modulation values are plotted for the occurrence of rotation, luster, rivalry, and cessation of rotation, as noted in the legend. Filled symbols are for the left "eye" condition and empty symbols for right "eye." Solid lines are for the adaptation condition of 21.25 cd/m^2 and dashed lines for 63.75 cd/m^2. "bg" refers to the "background" condition, also 21.25 cd/m^2 or 63.75 cd/m^2. See text.

Within each ANOVA, preliminary tests were performed as described in Kirk (1995, pp. 408-411) to determine the appropriateness of the terms in the ANOVA model. Starting from the most complex interaction and proceeding to the main effects, terms that failed to meet significance at the 0.25 level were pooled with the error term. For occurrence of perceived rotation, all terms pooled. For binocular luster, all interactions except the background luminance by "eye" condition interaction pooled, leaving all main effects in the model. For binocular rivalry, all terms except the main effect of background luminance and main effect of participants pooled. For cessation of rotation, all terms except the main effect of background luminance pooled.

The mean square residual, after preliminary testing, was used to generate the standard error bars in Figure 43-45. Significance of the results of each ANOVA was judged using Holm's (1979) sequentially rejective test based on the Šidák (1967)

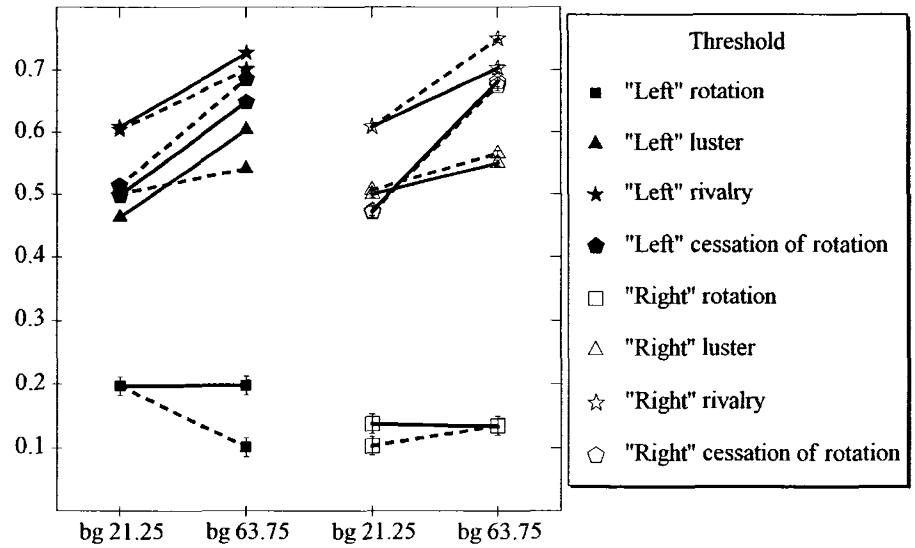

Figure 44. Experiment III thresholds for RSH. Modulation values are plotted for the occurrence of rotation, luster, rivalry, and cessation of rotation, as noted in the legend. Filled symbols are for the left "eye" condition and empty symbols for right "eye." Solid lines are for the adaptation condition of 21.25 cd/m^2 and dashed lines for 63.75 cd/m^2. "bg" refers to the "background" condition, also 21.25 cd/m^2 or 63.75 cd/m^2. See text.

multiplicative inequality, as described in Kirk (1995, pp. 140-144), with a family-wise α level of 0.05. This method was chosen because it maintains the family-wise α level while providing more power than other procedures, as described in Kirk. Effect size for main effects and interactions was calculated as partial omega squared, and effect size for participant effects was calculated as partial intraclass correlation (Kirk, 1995, pp. 259-264).

The effect of adaptation luminance is nonsignificant for all thresholds, with the plots suggesting there may be some minimal effect on the perception of rotation that varies from one participant to the next. There is no significant interaction between adaptation luminance and background luminance, or for any other interaction, for all thresholds. There is a significant effect of participant when considering binocular luster ($F_{2,17} = 47.9866$, MSRES = 0.0005184, $p = 1.0198*10^{-7}$, $\rho_I = 0.9400$) and binocular

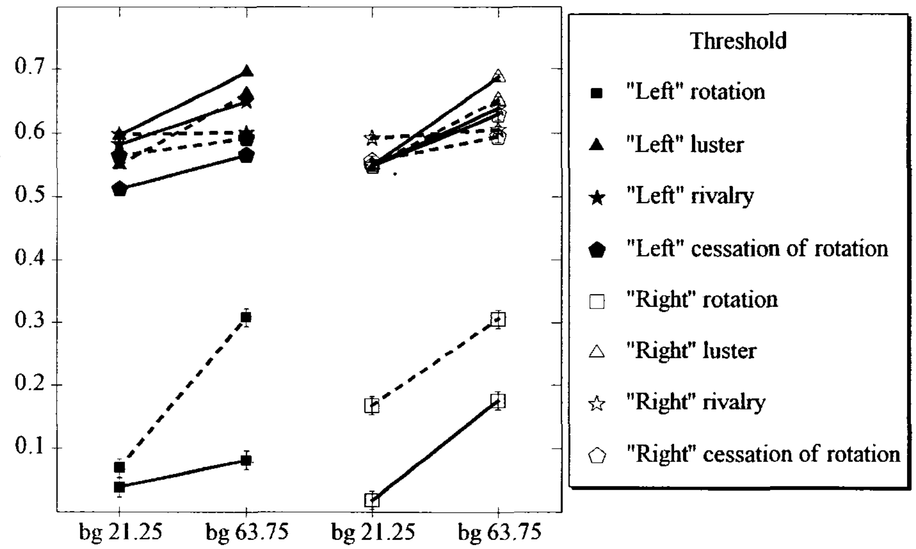

Figure 45. Experiment III thresholds for WWS. Modulation values are plotted for the occurrence of rotation, luster, rivalry, and cessation of rotation, as noted in the legend. Filled symbols are for the left "eye" condition and empty symbols for right "eye." Solid lines are for the adaptation condition of 21.25 cd/m^2 and dashed lines for 63.75 cd/m^2. "bg" refers to the "background" condition, also 21.25 cd/m^2 or 63.75 cd/m^2. See text.

rivalry ($F_{2,20} = 10.3585$, MSRES = 0.0007227, $p = 0.0008176$, $\rho_I = 0.7573$), which is not surprising given the various differences seen between participants in Experiment I-II.

The impact of background luminance is far more compelling, and can be seen by comparing Figure 40-42 to any other plot. In considering the "average luminance" condition in Experiment II (see Figure 34-36), the current data gathered from using "average luminance" images are dramatically different. In any of the adaptation and background combinations, rotation is actually perceived, and binocular luster and binocular rivalry are perceived less frequently than before. Further, the change follows the point of monocular equality to the background, such that thresholds in the current "average luminance" data look more like the "light luminance bars" thresholds from Experiment II. However, they are not identical to the "light luminance bars" thresholds, as the slight shift of the point of monocular equality to the background is followed by a slight shift in thresholds.

The effects of this shift in the background luminance are not symmetrical as luminance is raised and lowered. In fact, there are significant effects of background luminance when considering binocular luster ($F_{1,17} = 104.9730$, MSRES = 0.0005184, p = $1.0836*10^{-8}$, $\omega^2 = 0.8125$), binocular rivalry ($F_{1,20} = 60.4172$, MSRES = 0.0007227, p = $1.8137*10^{-7}$, $\omega^2 = 0.7123$), and the cessation of perceived rotation ($F_{1,22} = 75.8152$, MSRES = 0.001703, p = $1.4066*10^{-8}$, $\omega^2 = 0.757122$). As the background luminance is lowered, lower modulation values are necessary before luster and rivalry are perceived and rotation ceases. As the background luminance is raised, higher modulation values are necessary. With these higher modulation values necessary to see the cessation of rotation, one can also note a "divot" in the perceived rotation data at the point of monocular equality to the background, which is similar to "divots" in the Experiment II data. This result is likely due to one monocular image not being visible, resulting in dominance by the other monocular image.

This asymmetry in the impact of background luminance may be related to informal observations about the appearance of the stimuli. When the background luminance is low, most of the plain bars are more luminant than the background, and fused images may tend to appear bright. When the background luminance is high, most of the plain bars are less luminant than the background, and fused images may tend to appear dark. Criteria for judging that, say, luster is present may become confused when the bars themselves appear dark. In fact, JJD noted that the "glowing" parts of previous grating images had always been the brighter bars. The idea that the perception of the bars as light or dark is important is underscored by WWS's data in the "2-6" and "6-6" conditions, where he rarely sees rotation. This result replicates his reports in Experiment II (p. 62), where perceived rotation in dark bars seemed present only for some sessions.

Discussion

The nonsignificant effect of adaptation luminance on the three perceptual phenomena is as predicted, along with the fact that moving the background luminance relative to the images moves the thresholds for perception. The statistically significant asymmetry in the effects of raising versus lowering the background luminance is not as predicted. This result disagrees with Anstis's (2000) research concerning subjective ratings of luster that were symmetrical. However, that research used dichoptic luminance modulation of 0.16 or 0.17, and in the current research modulation of 0.50 was needed before the images dichoptically straddled the background. Perhaps, as suggested in the results section (p. 77), the experience of these bars as "dark" versus "bright" in certain circumstances impacted the results, and using stimuli closer to those of Anstis might bring the current results in line.

Establishing the importance of the relation between the stimuli and the background is the final goal of the current experiments. Now all three experiments can be considered in relation to each other, along with possibilities for the nature of the perceptual mechanisms involved.

CHAPTER VI

GENERAL DISCUSSION

My experiments demonstrate several principles that add to the understanding of perceived rotation (the Venetian blind effect), binocular luster, and binocular rivalry. The results support, expand, and possibly explain past observations in the study of these three perceptual phenomena, and provide new insight in how to characterize the stimuli that give rise to them. It is also possible now to perform several passes at describing the underlying mechanism or mechanisms that give rise to perceived rotation, luster, and rivalry, from which future research could naturally follow.

Together, the experiments demonstrate that using average luminance and contrast to define a stimulus for measuring any of these three perceptual phenomena overlooks important factors, despite Legge and Kersten's (1983) argument that contrast is generally a useful measure. In Experiment I (see Figure 27-29), it was certainly possible to measure the thresholds for perception based in dichoptic luminance modulation or dichoptic contrast modulation, but Experiment II-III (see Figure 34-36 and 40-42) show that the individual light bars and their relation to the background is driving the perception of luster and rivalry. Specifically, for reasons that are not determined here, the visual system seems to take into account only the luminance of the light bars in a grating, and having those bars dichoptically straddle the background luminance is necessary for luster and rivalry to be perceived (extending work by Anstis, 2000; Fry & Bartley, 1933; Wolfe & Franzel, 1988).

When isolating the light bars and dark bars, as Legge and Kersten (1983) had done, rotation is also seen to relate to dichoptic straddling of the background. The pattern differs in that perceived rotation doesn't *occur* when the straddling occurs, but rather it *ceases*. That is, there seems to be a certain magnitude of disparity above zero at which perceived rotation begins, and another past the point of monocular equality to the background at which it ends. This pattern is not in strict opposition to that of luster and rivalry, though, because when participants are presented with an intact square-wave grating, it is only at the highest disparity levels that perceived rotation ceases. In fact, all three perceptual phenomena can occur concurrently with grating stimuli. As noted in the literature summary and rationale for current research (p. 40), perceptual phenomena that arise in similar circumstances and/or that co-vary may arise from similar underlying mechanisms. In this light, rotation is clearly different from luster and rivalry.

As mentioned briefly in the discussion to Experiment II (p. 65), this result could be explained by treating the dark bars in an intact grating as though they were a special sort of "local background." The results of Experiment III, showing that adaptation has few if any reliable effects on these perceptions, bears on the issue. It is possible that, given that the visual system is unperturbed by abrupt changes in luminance and simply responds to the relation between images and their background, the "local background" composed of dark bars literally counts as the background when judging perceived rotation. As the light bars, by definition, never cross the dark bars in luminance, there would be little reason for perceived rotation to cease. In this sense, it may be logical to state that the occurrence of rotation is "opposite" the occurrence of luster and rivalry around a midpoint at the background luminance, given that the definition of "background" is sufficiently loose.

However, other interpretations are possible. In Experiment II-III, the point of monocular equality to the background (or some other modulation value near it, following changes in the background luminance as in Experiment III) often marks a transition between rotation and rivalry. This result is consistent with the view that dichoptically straddling the background causes rivalry, and rivalry itself prevents the perception of other phenomena. That is, luster may be perceived during rivalry as first mentioned by Dove (1851), but the alternation of perception between monocular images means that all other binocular phenomena are lost.

This argument is flawed because the *perception* of rivalry does not preclude the uptake of binocular *information* (as discussed in the subsection on the relation between stimuli and the background, p. 28, and the section on binocular rivalry, p. 34, 36, in the introduction). In fact, the very existence of rivalry demonstrates that binocular information is entering the visual system, as the visual system must be receiving input from both eyes in order to experience a conflict. If not, then rivalry would end in the lasting dominance of one image, likely the stronger image. This result would go against the important role Levelt (1965b, chapter 5) observed is given to the weaker image, and other phenomena such as the ability of a changing suppressed image to command attention (see, e.g., Blake, 2005).

Other issues in the perception of rotation, luster, and rivalry pertain to the nature of the stimuli. The perception of rotation of an individual bar is fundamentally related to the presence of edges. As discussed in the section on perceived rotation in the introduction (p. 9), the attempt by Fiorentini and Maffei (1971) to eliminate edge-based explanations for perceived rotation as a function of contrast disparity was not convincing, as Filley (1998), Filley and Stine (1998), and Stine and Filley (1998) argued that an edge was present as an artifact in their setup. In comparison, though binocular rivalry can occur in images with strong edges, the example from Desaguliers (1716) and Helmholtz (1873, 1910/1925) of color rivalry (discussed in the section on binocular rivalry in the introduction, p. 35) shows that edges aren't necessary.

The role of edges in luster is less certain. Ludwig et al. (2007) argued that luster is visible in dichoptic circle images that have a fusible monoptic border, but that otherwise-identical images without a border result in a perception of rivalry. An example of images with a border is Figure 22 (discussed in the section on binocular rivalry in the introduction, p. 34), where the white circles have a thin black rim. However, a thin and distinct border is not the only form of "edge" possible, as the solid black circles in Figure 22 have edges without such borders. Further, the initial discussion of Figure 21-23 was in the context of Howard's (1995) sieve effect, where the size of the image influences the perception of luster and rivalry. Therefore, though edges and borders do not have a fully clear impact, they provide further evidence that rotation is its own phenomenon in visual perception while luster and rivalry are linked.

For another approach to relating these three perceptual phenomena, I refer to Hetley (2005). As was discussed in the introduction (p. 3), I studied the relationship between the Venetian blind effect and brightness (and between the Venetian blind effect and perceived contrast). I determined that the perceptions of rotation and of brightness involve fundamentally different uses of the "input" luminance disparity information, which would be consistent with separate mechanisms in the visual system for perceived rotation and for brightness. Perhaps the current research does indeed touch on two underlying mechanisms, but they are the same two discussed in my master's thesis. After all, all figures of data from my current research show some levels of disparity where perceived rotation occurs, but where nothing else occurs *that was measured.* It is possible that with images of low luminance disparity, or, more likely, images that do not dichoptically straddle the background, there are separate mechanisms that are handling perceived rotation and brightness; then, at or near the point of monocular equality to the background, these separate mechanisms switch over to two other perceptions.

There are multiple possibilities for how this changeover could occur. One possibility is that, after the initial rotation versus brightness pairing, the rotation mechanism could switch to handling rivalry and the brightness mechanism could switch to handling luster. This result would be consistent with Howard's (1995) proposal that binocular luster is the result of brightness summation during mosaic dominance, and consistent with the above suggestion of rotation and rivalry being in conflict. However, it is likely that the experience of brightness does not "stop" as soon as luster takes over, given the informal mention in the discussion of Experiment III (p. 77) of different lustrous plain bars seeming bright or dark.

A second possibility is that, after the initial rotation versus brightness pairing, the brightness mechanism could remain functioning for all or nearly all values of disparity, and the rotation mechanism could switch to handling both rivalry and luster simultaneously. The connection between luster and rivalry has been discussed repeatedly, whether in terms of luster occurring during moments of transition (e.g., Dove,

1851) or occurring when rivalry is halted (e.g., Helmholtz, 1873, 1910/1925), but faith in this proposed division depends on the reliable co-varying of both luster and rivalry.

Such a possibility is thrown into question given that participants show somewhat different luster and rivalry patterns, with one large discrepancy appearing in participant JJD's data in the "average luminance" condition in Experiment II (see Figure 34). However, as discussed in that results section (p. 62), there was a shift in the criteria being used for stating the perceptions were present, which means there is uncertainty in the thresholds. There is also the question of fluorence (Evans, 1959), which, as discussed in its subsection in the introduction (p. 29), is a perceived glow when images are close to the background luminance. Informal observations suggest that there was a qualitatively different "glow" in some limited cases near the background luminance in the "average luminance" condition in Experiment II, meaning there is further uncertainty in the thresholds.

For both of the above possibilities, there remains the question of why rotation, luster, and rivalry would be perceived simultaneously both in my master's thesis (Hetley, 2005) and in Experiment I. A third possibility is akin to that presented in the discussions in Experiment I-II (p. 53, 65), namely that luster and rivalry are handled by their own mechanism and perceived rotation is handled by its own. In this view, that perceived rotation has been demonstrated to be paired with brightness (Hetley, 2005) is merely incidental, and so this third possibility allows for three mechanisms instead of two, where brightness is handled by its own mechanism that was not studied here. Of course, more mechanisms mean a less parsimonious explanation.

Given that a shift in criteria is less of a theoretical concern than a practical concern that can be corrected in future work, I place a certain amount of faith in the second possibility listed here. Given that the third possibility suffers from mainly the same concerns, I likewise would support it. Further experimentation, of course, is necessary to tease apart these different possibilities.

Further experimentation could take the form of another study like Experiment I, but where the "light bars" and "dark bars" were both directly manipulated. In this proposed "fourth" experimental setup, a manipulation where the "dark bars" were raised above the luminance of what had been the "light bars" would test whether the explanation of a "local background" for the pattern shown in perceived rotation made sense. Measuring not just the detection of each effect, but subjective ratings of the magnitude of each effect as in Anstis (2000), would reveal whether changing this "local background" also affected luster and rivalry. If rotation on one hand and luster and rivalry on the other were shown to more directly oppose each other through these manipulations, then this discovery would be just as fundamental as the discovery that looking at the light bars and dark bars mattered in the first place. This result would support any possibility for underlying mechanisms that placed rotation in opposition to luster and/or rivalry.

Measurement of brightness in the fused images is also necessary. Brightness matching experiments could be performed with the grating stimuli where the "light bars" and "dark bars" were being manipulated together. It is already known that, for instance, simple luminance decrements against a background are more detectable than luminance increments (e.g., Legge & Kersten, 1983), and here one could determine the pattern followed by individual bars that were both against a background and within a grating.

Patterns detected this way could support or refute any of the possibilities suggested above.

It should be noted that direction of perceived rotation was not measured in my current experiments, and neither was the distinction between stable luster (e.g., Helmholtz, 1873, 1910/1925) and transient luster (e.g., Dove, 1851). The latter distinction is more interesting in this context, as informal observations suggested each type of luster had its own threshold. A simple experiment, perhaps using the setup from one of my three experiments or this new fourth setup, could be conducted to measure the thresholds for perceiving one or the other type of luster. These new thresholds could occur at meaningful points in relation to any of the perceptual phenomena discussed so far, leading to new possibilities for underlying mechanisms.

Lastly, edges and borders are important to consider. A fifth experimental setup could involve replacing all square-wave gratings or bars with sinewave. If multi-axis rotation were replaced with single-axis as in Fiorentini and Maffei (1971; see p. 9), but binocular luster and rivalry were unaffected, then that would support the unique place of rotation. A sixth experimental setup could involve taking all square-wave images presented so far and manipulating the presence or absence of thin borders, as discussed with the research of Ludwig et al. (2007; see p. 82). It could be predicted that luster would occur more regularly with the presence of thin borders while rivalry would occur less. If there were little effect of a border on perceived rotation, then, again, rotation would be shown to be in opposition to luster and rivalry.

In summary, the phenomena of perceived rotation or the Venetian blind effect, binocular luster, and binocular rivalry have rarely been studied together. As discussed in the introduction, there are many different explanations for each, and not all explanations adequately predict the phenomena. Now, at least, it is easier to properly describe the circumstances in which the perceptual phenomena arise. Consideration of individual dichoptic parts of an image in relation to the background, often specifically the more luminant dichoptic parts of an image, allows for prediction of the occurrence of binocular luster and binocular rivalry and the cessation of perceived rotation. Possible explanations for these patterns of occurrence and cessation involve various underlying visual mechanisms, but further experimentation is necessary to support or refute each one.

REFERENCES

Agresti, A., & Caffo, B. (2000). Simple and effective confidence intervals for proportions and differences of proportions result from adding two successes and two failures. *The American Statistician, 54*, 280-288.

Agresti, A., & Coull, B. A. (1998). Approximate is better than "exact" for interval estimation of binomial proportions. *The American Statistician, 52*, 119-126.

Alais, D., & Blake, R. (Eds.). (2005). *Binocular rivalry*. Cambridge, MA: MIT Press.

Ames, A., Jr., Ogle, K. N., & Gliddon, G. H. (1932). Corresponding retinal points, the horopter and size and shape of ocular images. *Journal of the Optical Society of America, 22*, 575-631.

Andrews, T. J., Sengpiel, F., & Blakemore, C. (2005). From contour to object-face rivalry: Multiple neural mechanisms resolve perceptual ambiguity. In D. Alais & R. Blake (Eds.), *Binocular rivalry* (pp. 187-211). Cambridge, MA: MIT Press.

Anstis, S. M. (2000). Monocular lustre from flicker. *Vision Research, 40*, 2551–2556.

Backus, B. T., Banks, M. S., van Ee, R., & Crowell, J. A. (1999). Horizontal and vertical disparity, eye position, and stereoscopic slant perception. *Vision Research, 39*, 1143-1170.

Birnkrant, R. S., Wolfe, J. M., Kunar, M. A., & Sng, M. (2004). Is shininess a basic feature in visual search? *Journal of Vision, 4* (8), 678a, http://journalofvision.org/4/8/678/ (Abstract Only).

Blake, R. (2005). Landmarks in the history of binocular rivalry. In D. Alais & R. Blake (Eds.), *Binocular rivalry* (pp. 1-27). Cambridge, MA: MIT Press.

Blake, R., & Cormack, R. H. (1979). Does contrast disparity alone generate stereopsis? *Vision Research, 19*, 913-915.

Blakemore, C. (1970). A new kind of stereoscopic vision. *Vision Research, 10*, 1181-1199.

Boynton, R. M. (1966). Vision. In J. B. Sidowski (Ed.), *Experimental methods and instumentation in psychology* (pp. 273-330). New York, NY: McGraw-Hill.

Cibis, P. A. & Haber, H. (1951). Anisopia and perception of space. *Journal of the Optical Society of America, 41*, 676-683.

Desaguliers, J. T. (1716). A plain and easy experiment to confirm Sir Isaac Newton's doctrine of the different refrangibility of the rays of light. *Philosophical Transactions of the Royal Society of London, 29*, 448-452.

Dove, H. W. (1851). Ueber die ursachen des glanzes und der irradiation, abgeleitet aus chromatischen versuchen mit dem stereoskop. *Annalen der Physik und Chemie, 83*, 169-183.

Evans, R. M. (1959). Fluorescence and gray content of surface colors. *Journal of the Optical Society of America, 49*, 1049-1059.

Filley, E. T. (1998). *An investigation of the Venetian blind effect.* Unpublished master's thesis, University of New Hampshire, Durham.

Filley, E. T., & Stine, W. W. (1998). Characterizing the "Venetian blind" effect. *Perception, 27 Supplement*, 99. (Abstract Only).

Fiorentini, A., & Maffei, L. (1971). Binocular depth perception without geometrical cues. *Vision Research, 11*, 1299-1305.

Fox, R. (2005). Foreword. In D. Alais & R. Blake (Eds.), *Binocular rivalry* (pp. vii-xv). Cambridge, MA: MIT Press.

Fry, G. A., & Bartley, S. H. (1933). The brilliance of an object seen binocularly. *American Journal of Ophthalmology, 16*, 687-693.

Gottesman, J., Rubin, G. S., & Legge, G. E. (1981). A power law for perceived contrast in human vision. *Vision Research, 21*, 791-799.

Von Helmholtz, H. (1873). Chapter 6: The recent progress of the theory of vision (B. A. Pye-Smith, Trans.). In E. Atkinson (Ed. and Trans.), *Popular lectures on scientific subjects* (pp. 197-316). London: Longmans, Green, and Co.

Von Helmholtz, H. (1910/1925). Chapter 32: Rivalry between the visual globes. In J. P. C. Southall (Ed.), *Helmholtz's treatise on physiological optics* (Trans. from 3rd ed., Vol. III, pp. 493-528). Menasha, WI: Optical Society of America.

Hering, E. (1879-1883/1942). *Spatial sense and movements of the eye* (C. A. Radde, Trans.). Baltimore, MD: American Academy of Optometry.

Hering, E. (1920/1964). *Outlines of a theory of the light sense* (L. M. Hurvich & D. Jameson, Trans.). Cambridge, MD: Harvard.

Hetley, R. S. (2005). *Repartitioning luminance disparity information into brightness and perceived rotation*. Unpublished master's thesis, University of New Hampshire, Durham.

Holm, S. (1979). A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics, 6*, 65-70.

Howard, I. P. (1995). Depth from binocular rivalry without spatial disparity. *Perception, 24*, 67-74.

Howard, I. P. (2005). Binocular rivalry and the perception of depth. In D. Alais & R. Blake (Eds.), *Binocular rivalry* (pp. 169-186). Cambridge, MA: MIT Press.

Howard, I. P., & Rogers, B. J. (1995). *Binocular vision and stereopsis*. New York, NY: Oxford University Press.

Julesz, B., & Tyler, C. W. (1976). Neurontropy: An Entropy-like measure of neural correlation in binocular fusion and rivalry. *Biological Cybernetics, 23*, 25-32.

Kirk, R. E. (1995). *Experimental design: Procedures for the behavioral sciences* (3rd ed.). Pacific Grove, CA: Brooks/Cole.

Lack, L. C. (1978). *Selective attention in the control of binocular rivalry*. The Hague, the Netherlands: Moulton.

Land, E. H. (1983). Recent advances in retinex theory and some implications for cortical computations: Color vision and the natural image. *Proceedings of the National Academy of Sciences of the United States of America, 80*, 5163-5169.

Legge, G. E., & Kersten, D. (1983). Light and dark bars; Contrast discrimination. *Vision Research, 23*, 473-483.

Levelt, W. J. M. (1965a). Binocular brightness averaging and contour information. *British Journal of Psychology, 56*, 1-13.

Levelt, W. J. M. (1965b). *On binocular rivalry*. Soesterberg, the Netherlands: Institute for Perception.

Ludwig, I., Pieper, W., & Lachnit, H. (2007). Temporal integration of monocular images separated in time: Stereopsis, stereoacuity, and binocular luster. *Perception & Psychophysics, 69*, 92-102.

Macknik, S. L., & Martinez-Conde, S. (2004). Dichoptic visual masking reveals that early binocular neurons exhibit weak interocular suppression: Implications for binocular vision and visual awareness. *Journal of Cognitive Neuroscience, 16*, 1049-1059.

McCamy, C. S. (1998). Observation and measurement of the appearance of metallic materials: Part II: Micro appearance. *Color Research and Application, 23*, 362-373.

Michelson, A. A. (1927). *Studies in optics*. Chicago, IL: University of Chicago Press, Ltd.

Münster, C. (1941). Ueber den einfluß von helligkeitsunterschieden in beiden augen auf die stereoskipische wahrnehmung. *Zeitschrift für Sinnesphysiologie, 69*, 245-260.

Necker, L. A. (1832). Observations on some remarkable phenomena seen in Switzerland; and an optical phenomenon which occurs on viewing a figure of a crystal or geometrical solid. *London and Edinburgh Philosophical Magazine and Journal of Science, 1*, 329-337.

Ogle, K. N. (1952). A criticism of the use of the word "anisopia." *Journal of the Optical Society of America, 42*, 142.

Ogle, K. N. (1962). The optical space sense. In H. Davson (Ed.), *The eye: Vol. 4* (pp. 271-320). New York, NY: Academic Press.

Panum, P. L. (1858). *Physiologische untersuchungen über das sehen mit zwei augen*. Kiel, Germany: Schwerssche Buchhandlung.

Sclar, G., Maunsell, J. H. R., & Lennie, P. (1990). Coding of image contrast in central visual pathways of the macaque monkey. *Vision Research, 30*, 1-10.

Šidák, Z. (1967). Rectangular confidence regions for the means of multivariate normal distributions. *Journal of the American Statistical Association, 62*, 626-633.

Stine, W. W., & Filley, E. T. (1998). Modeling the "Venetian blind" effect. *Perception, 27 Supplement*, 106. (Abstract Only).

Stine, W. W., & Hetley, R. S. (2006). A model of perceived bar rotation, the Venetian blind effect, in square-wave gratings as a function of contrast disparity. *Perception, 35 Supplement*, 10. (Abstract Only).

Treisman, A., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology, 12*, 97-136.

Tyler, C. W. (2004). Binocular vision. In W. Tasman & E. A. Jaeger (Eds.), *Duane's foundations of clinical ophthalmology: Vol. 2* (chap. 24). Philadelphia, PA: J. B. Lippincott.

Wade, N. J. (2005). Ambiguities and rivalries in the history of binocular vision. In D. Alais & R. Blake (Eds.), *Binocular rivalry* (pp. 29-46). Cambridge, MA: MIT Press.

Wheatstone, C. (1838). Contributions to the physiology of vision--Part the first: On some remarkable, and hitherto unobserved, phenomena of binocular vision. *Philosophical Transactions of the Royal Society of London, 128*, 371-394.

Williams, D. R., Brainard, D. H., McMahon, M. J., & Navarro, R. (1994). Double-pass and interferometric measures of the optical quality of the eye. *Journal of the Optical Society of America (A), 11*, 3123-3135.

Wilson, E. B. (1927). Probable inference, the law of succession, and statistical inference. *Journal of the American Statistical Association, 22*, 209-212.

Wolfe, J. M., & Franzel, S. L. (1988). Binocularity and visual search. *Perception & Psychophysics, 44*, 81-93.

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26-Sep-2007

Hetley, Richard S
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Durham, NH 03824

IRB #: 4074
Study: The Venetian blind effect, binocular luster, and binocular rivalry
Approval Date: 24-Sep-2007

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