Monocular Occlusion Cues Alter the Influence of Terminator Motion in the Barber Pole Phenomenon

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ABSTRACT

The influence of monocular occlusion cues on the perceived direction of motion of barber pole patterns is examined. Unlike previous studies that have emphasized the importance of binocular disparity, we find that monocular cues strongly influence the perceived motion direction and can even override binocular depth cues. The difference in motion bias for occluders with and without disparity cues is relatively small. Additionally, although ‘T-junctions’ aligned with occluders are particularly important, they are not strictly necessary for creating a change in motion perception. Finally, the amount of motion bias differs for several stimulus configuration, suggesting that the extrinsic / intrinsic classification of terminators is not all-or-none.
INTRODUCTION

Determining whether an image boundary is inherent to a surface itself or the product of occlusion by a second surface is critical to understanding the spatial layout of visual scenes (Rubin, 1915, 1958). When two areas, figure and ground, share a common boundary, the figure region is said to “own” the boundary. The figure’s appearance, i.e. its perceived shape, depth, or lightness, is in turn strongly affected by the boundary, while ground is only minimally affected. (Koffka, 1935; Coren, 1969; Nakayama & Shimojo, 1992). Furthermore, there is a tendency to perceive the ground as extending behind the figure. While border ownership is often examined in static displays, it can also play an important role in the perception of moving displays.

The “barber pole” illusion offers a compelling example of the importance of boundary classification. Wallach (1935) showed that under normal conditions the perceived direction of motion of a diagonal grating pattern drifting behind a rectangular aperture depends upon the direction of elongation of the aperture (Wuerger, Shapley & Rubin, 1996). The grating pattern is seen to move along the axis of the longer dimension of the rectangle. The prevailing explanation for this phenomenon suggests that the perceived direction of motion results from the integration of motion signals from the areas where the grating pattern is terminated by the edges of the aperture. Due to the aperture problem, the local velocity signals along the grating are inherently ambiguous. Terminators, however, produce unambiguous motion signals. As a vertically elongated aperture has larger number of terminators with vertical trajectories, vertical motion prevails.

Not all line terminators signal ends of physical objects, however. Wallach (1935) noted that “free-line” endings, those which are not associated with any aperture edge, are
treated differently than line endings at the edge of an aperture (Wuerger et al. 1996). More recently, Shimojo, Silverman & Nakayama (1989) demonstrated that terminator classification plays an important role in the aperture problem. Vertical motion no longer dominates when a vertically elongated barber pole is presented with uncrossed disparities (so the diagonal lines appear to be seen through an aperture). Evidently, intrinsic boundaries (real object boundaries) are treated differently than extrinsic boundaries (those resulting from occlusion). Terminators along extrinsic boundaries are excluded when processing the direction of motion for the barber pole region, as the motion of such terminators may be unrelated to the actual global motion of that region.

Shimojo et al. (1989) suggest that it is not disparity information that is the critical factor, but rather depth information, which can be carried by disparity or other factors including monocular depth cues. However, they argue that the effect of monocular depth cues is weaker than that of disparity cues. Specifically, they demonstrate that directional bias in the barber pole effect is reduced when the pattern is viewed monocularly. For the binocular condition, they suggest monocular occlusion cues, specifically local T-junctions at the end of individual lines of the grating (which signal occlusion), are overridden by zero-disparity binocular cues (which fail to signal occlusion). Shimojo et al. conclude that although disparity is not critical for terminator classification, its effect is significantly stronger than that of monocular depth cues.

There is, however, evidence that monocular segmentation cues can have a pronounced effect on motion processing. Lorenceau and Shiffrar (1992) demonstrated that integration across space is more likely when the salience of terminators is decreased through jagged apertures, low contrast, viewing at large eccentricity, or when terminators are isoluminant
with the background (Shiffrar & Lorenceau 1996). Additionally, binocular depth cues are not always exploited by the motion system. Watamaniuk & McKee (1995) examined subjects’ ability to track dot motion behind occluders. In a two-interval forced-choice procedure, subjects reported which of two stimuli contained a signal trajectory. Unlike monocular occlusion cues, such as the addition of opaque occluders or motion discontinuities, differences in depth were not sufficient to suppress motion noise and allow for signal detectability.

There are three primary purposes to our study. The first is to examine the importance of monocular occlusion cues using experiments within a single paradigm. We measure change in the average perceived motion direction resulting from the addition of occluding patches along either the vertical or horizontal edges of a barber pole pattern (See Figure 1). Experiment 1 measures the influence of occluders at a different disparity than the barber pole patch. Experiment 2 measures the influence of occluders with zero-disparity difference. Our results demonstrate that although the addition of a disparity difference results in a change in the direction of motion perception, the change is almost as strong when only monocular cues indicate occlusion.

The second purpose of our study is to measure the degree to which motion signals from extrinsically classified terminators are discounted. Shimojo et al. (1989) suggest that intrinsic terminators produce strong propagation of velocity signals to the interior of lines, where they exert a biasing effect on local ambiguous signals. On the other hand, they suggest the propagating effect of extrinsic terminators is abolished. Rubin & Hochstein (1993), however, provide evidence that terminators do still retain some influence even when a barber pole is presented with uncrossed disparities. The perceived
direction of lines viewed through an aperture is not perpendicular to the lines, as would be predicted if motion signals from extrinsic terminators were ignored, but deviates in the direction of terminator motion.

We attempt to answer several questions. Is the extrinsic/intrinsic classification an all-or-none attribute? Can one terminator be classified as having stronger extrinsic characteristics than another, and if so how will this differential classification affect motion integration? In our paradigm only half the terminators (vertical or horizontal) are extrinsic, allowing for a comparison with the remaining intrinsic terminators and a measurement of extrinsic terminator influence relative to that of intrinsic terminators.

Our results demonstrate that even terminators with the strongest extrinsic characteristics still have an influence on motion processing. Secondly we demonstrate that terminators can be classified as more or less extrinsic, resulting in a continuum of effects on motion perception. When there is strong evidence for extrinsic terminators,
there is a considerable change in the perception of motion direction. When extrinsic terminators are weakly supported, there is a correspondingly smaller change in the perceived direction of motion.

The third purpose of our study is to determine the relative importance of the different monocular occlusion cues since the monocular conditions that give rise to terminators being classified as extrinsic have not been adequately characterized to date. Although T-junctions have been suggested as the relevant monocular depth cue (Guzman, 1969, Shimojo et al., 1989; Rubin, 1997), we seek to explicitly determine which of the numerous monocular depth cues are important for extrinsic/intrinsic terminator classification and the degree to which each affects motion integration. We attempt to find the minimal stimulus necessary to produce a change in the average perceived direction of motion for a barber pole pattern. The role of contrast relationships between background and occluding patterns, texture, amodal completion, T-junctions and illusory occlusion are all examined.

The principle result of the monocular experiments is that no single monocular occlusion cue is responsible for terminator classification or changing the perceived direction of motion. Rather a multitude of cues participate in the perception of occlusion and their differing strengths result in a continuum of effects on terminator classification and motion perception. Although T-junctions play a prominent role, they are not strictly necessary for occluders to have an influence on motion processing.

**EXPERIMENT 1: Textured Occluders With Depth**

The purpose of the first experiment was to measure how the influence of terminators on the perceived motion of ambiguous line interiors is attenuated when the terminators are
extrinsic. To do so, we created barber pole stimuli in which only one axis of terminators (vertical or horizontal) was extrinsic (See Figure 1). By measuring subjects’ dominant perceived direction of motion, we were able to find the barber pole aspect ratio at which horizontal and vertical motion were in balance, allowing us to calculate the relative attenuation in the influence of the extrinsic terminators with respect to the intrinsic terminators.

**Method**

**Subjects.** Four subjects were employed for this experiment, one of the authors and three others who were naive to the purpose of the experiment. The same subjects participated in all subsequent experiments. All subjects had normal or corrected to normal vision and those other than the author received compensation of $8/hour for their participation in the experiment.

**Simuli.**

The stimuli consisted of translating square-wave gratings oriented at $45^\circ$ viewed through rectangular apertures of different aspect ratios. The light and dark stripes of the grating were 1.6 and 81.2 cd/m$^2$ respectively. The experimental factors were stimulus configuration and aspect ratio of the barber pole. Three stimulus configurations were employed: the barber poles were presented either in isolation, sandwiched between two vertical textured bars, or sandwiched between two horizontal textured bars. For the sandwiched cases, vertical textured bars were placed on the left and right sides of the barber pole and horizontal textured bars placed on the top and bottom of the barber pole (See Figure 1).

The aspect ratio of the barber pole was varied. For the isolated case, thirteen levels were used, with the aspect ratio of the barber pole varying from 2.4:1 to 1:2.4. Only six
levels were used for the occluded conditions, as an increase in the aspect ratio along the occluded dimension would be hidden by the occluder. For the vertical case, the aspect ratio varied from 2.4:1 to 1:1. For the horizontal case, the aspect ratio varied from 1:1 to 1:2.4. (See Legend, Figure 2).

The isolated configuration served as a baseline for the barber pole effect. The vertical and horizontal configurations served to measure the influence of occlusion on the perception of grating motion. As the occluding bars were presented with one orientation (vertical or horizontal), they created extrinsic terminators along one orientation of the barber pole, leaving terminators along the opposite orientation as intrinsic. We expected that the influence of the terminators along the occluded edge would be weakened relative to the non-occluded edge, resulting in an increase in motion perceived in the direction orthogonal to the occluders.

Two grating orientations (45° and -45°) and two directions of motion (left and right) were employed for each stimulus configuration, making four different stimuli per configuration. Stimuli with motion in the vertical direction (up and down) were not necessary, as each upward or downward motion looks identical to one of the horizontal motions. The two veridical directions of motion served to minimize any impact of the motion after effect.

All stimuli were displayed on a Silicon Graphics Reality Engine (model CMN-A011). Observers viewed stimuli through a mirror and prism haploscope, 70cm from the monitor, in a darkened room. The square barber pole (aspect ratio of 1:1) subtended an area of 2° x 2° of arc. The largest barber pole patch (aspect ratio of 2.4:1) subtended an area of 2° x 4.8°. The speed of the grating was 2.5°/sec. The occluders subtended a 2° x 5.2° patch.
They were seen in front of the grating pattern with a disparity of 17 min relative to the grating.

**Procedure**

Each pattern was presented for 300 msec followed by a black screen containing a fixation point. The fixation point served as cue for subjects to respond. Given four keys (one for each of the cardinal directions), subjects were instructed to press the one that corresponded best to their perceived direction of motion for the grating pattern. The key press also initiated the next trial after a small delay. Each subjects completed 6 blocks of 50 trials. All factors were intermixed and presented in random order.

**Results and discussion**

For the isolated configuration trials, Wallach’s barber pole phenomenon was confirmed. There were some individual differences between subjects, some showing an overall bias for vertical motion, others showing an overall bias for horizontal motion. In all cases, however, the greater the horizontal size of the grating patch, the more likely subjects were to report horizontal motion and the greater the vertical size, the more likely subjects were to report vertical motion. For an aspect ratio of 1:1, average subjects’ response was near the point of ambiguity (perceived horizontal motion 50% of the time) (See Figure 2).

A clear bias was found in subjects’ perception of the barber pole direction of motion when textured bars were added to the sides of the barber pole. When vertical textured bars were added to the left and right of the barber pole, subjects were more likely to see horizontal motion (ANOVA: Isolated vertical vs. vertical with occluders: F(1,3) = 198.87, p < 0.0008). A corresponding bias for vertical motion was found for the addition of
FIGURE 2. EXPERIMENT 1: The addition of textured bars with disparity differences. The average percent horizontal motion reported by subjects is plotted against barber pole aspect ratio with solid lines for the *isolated* (•), *vertical* (▲), and *horizontal* (■) configurations. The legend below contains icons depicting the corresponding aspect ratios employed in the experiment. Dotted lines are sigmoid estimations for the response curves. Note that only portions of the sigmoid are visible for the *vertical* and *horizontal* configurations. For the *isolated* configuration 13 different aspect ratios were employed ranging from 2.4:1 to 1:2.4. For the *vertical* and *horizontal* configurations, 6 different aspect ratios were employed. Note that the set of aspect ratios used for the *vertical* and *horizontal* configurations only overlap for the 1:1 case, as an increase in aspect ratio along the occluded sides is invisible. To reduce the number of experimental trials, only the *isolated* configuration employed the 1:2:1 and 1:1:2 aspect ratio.
horizontal textured bars (Isolated horizontal vs. horizontal with occluders: F(1,3) = 70.21, p < 0.0036) (See Figure 2).

Note that the addition of occluding bars did not abolish the influence of terminators along the occluded edge. Rather the influence of extrinsic terminators was merely attenuated with respect to the intrinsic terminators. Elongation of the barber pole aperture still influenced the perceived direction of motion. This enabled us to measure the attenuation of the extrinsic terminators with respect to the intrinsic terminators by comparing the aspect ratio at which a balance is achieved between horizontal on vertical motion.

As a heuristic for determining attenuation, subjects’ average percent horizontal motion was pooled and estimated with a sigmoid function using the simplex search method for function minimization (Nelder & Mead, 1965). The specific sigmoid function used is given by:

$$\frac{100}{1 + e^{-\alpha x + \beta}}$$  \hspace{1cm} (EQ 1)

Where $\alpha$ controls the slope and $\beta$ the position of the sigmoid. Note that only the tail ends of the sigmoid are visible for the occluded configurations (Figure 2, dotted lines). To find a rough estimate of the aspect ratios that result in a balance of horizontal and vertical motion, the points at which the function crossed 50% were calculated. Accordingly, an estimated balance for vertical and horizontal motion for a barber pole with vertical occluders occurred at an aspect ratio of 2.6:1, and a balance for a barber pole with horizontal occluders occurred at an aspect ratio of 1:2.5. Taking any individual subjects’
initial horizontal or vertical bias for the isolated barber pole into account, these aspect
ratios correspond to a 61% and 60% reduction of the influence of terminators along the
occluded sides respectively. (See Appendix: Part I for details.)

**EXPERIMENT 2: Textured Occluders Without Depth**

The first experiment demonstrated that the addition of occluding surfaces, with crossed
disparity along either the horizontal or vertical axis of a barber pole, biases the perception
of barber pole motion in the direction orthogonal to occluder orientation. Presumably this
effect results from the classification of the terminators along the occluded edge as
extrinsic, thereby weakening their contribution to motion disambiguation.

Shimojo & Nakayama (1990) argue for a close interaction between depth and motion
mechanisms, suggesting a role for disparity sensitive-cells in MT. They also note that
monocular depth cues may still influence motion disambiguation, but argue that such cues
may be significantly weaker. However, there is convincing evidence that surface
decomposition occurs rapidly, strongly affecting the early stages of visual processing even
for stimuli without binocular depth cues (Watanabe & Cavanagh, 1993b). Monocular
occlusion cues can change the perception of apparent motion (Ramachandran & Anstis,
1986; Ramachandran, Inada & Kiama, 1986), and when monocular occluders flank an
apparent motion display, they can alter the perception of the entire display (Watanabe &
Cole, 1995). Experiments 2 was designed to examine the importance of disparity
information by comparing Experiment 1 with a case in which the binocular depth cues
suggest there is no disparity difference between the barber poles and the occluders.
Method

The second experiment was conducted under the same conditions as the first, although subjects did not view stimuli through a haploscope. Thus, the textured bars were seen at the same depth of the barber poles. In addition to the same four subjects reported in Experiment 1, two more subjects participated in the second experiment. As subjects in Experiment 2 were not using a haploscope, viewing distance was not strictly enforced, but the stimuli subtended roughly the same angles as in the previous experiment.

The sequence of experiments reported here reflects the order in which the authors felt made for the most clear presentation rather than the order in which subjects participated in the experiments. There was no chance of contamination of the zero-disparity conditions by the binocular condition, as all subjects participated in the zero-disparity conditions before the binocular condition. There remains some possibility that there may have been ordering effects among other experiments. The experiments presented in this paper were conducted over a period of five months. As the results of the initial experiments drove the design of later experiments, it was not possible to fully counter-balance the conditions across experiments.

Results and discussion

Despite the use of zero-disparity, the addition of occluders still produced significant biases for both the vertical (vertical isolated vs. vertical with occluders: $F(1,5) = 71.26, p < 0.011$, Figure 3b) and horizontal (horizontal isolated vs. horizontal with occluders: $F(1,5) = 39.76, p < 0.0032$, Figure 3c) occluders. The bias was reduced in comparison with those seen in Experiment 1, but the reduction was not significant (horizontal occluders, Experiment 1 vs. Experiment 2: $F(1,5) = 4.37, p > 0.1278$, vertical occluders,
Experiment 1 vs. Experiment 2: \( F(1,5) = 7.94, p > 0.0668 \). Approximating subjects’ results with a sigmoid function and reading off the balance points as before, a balance in vertical and horizontal motion was found for an aspect ratio of 2.3:1 for vertical occluders and 1:2.2 for horizontal occluders, corresponding to an attenuation in terminator influence of 57% and 55% respectively.

The changes in the motion biases were relatively small from 61% and 60% for occluders with a disparity difference to 57% and 55% without. The occluders maintain almost all of their ability to influence motion disambiguation despite disparity cues which indicate the barber poles and occluders are at the same depth. This suggests that although disparity is an important cue for determining the relevance of terminators in motion integration, it is not strictly necessary, nor is it even necessarily the strongest such cue in a given display. In this particular case, monocular occlusion cues (indicating occlusion), override disparity cues (indicating the barber pole is in the same depth plane). Compare this with the case of Shimojo et al. (1989) in which disparity cues dominate. When zero-disparity barber pole patterns (without occluders) are employed, the barber pole effect is weakened as binocular cues override monocular cues.

Shimojo et al. (1989) suggest two possible mechanisms by which depth information could influence motion perception. Either other cortical areas that process form cues can influence motion processing areas, or disparity-specific cells within the motion processing areas selectively inhibit end-stopped cells that code terminator motion. The results of Experiment 2 support the idea of influence from other cortical areas. The existence of selectively inhibiting, disparity-specific cells can not be solely responsible, as disparity cues in Experiment 2 do not support occlusion.
FIGURE 3. EXPERIMENT 2: The addition of textured bars without disparity differences. The average percent horizontal motion reported by subjects is plotted against barber pole aspect ratio with solid lines for the isolated (●), vertical (▲), and horizontal (■) configurations. The legend below contains icons depicting the corresponding aspect ratios employed in the experiment. Dotted lines are sigmoid estimations for the response curves. Note that only portions of the sigmoid are visible for the vertical and horizontal configurations.
EXPERIMENT 3A & 3B: Occluder Contrast

Experiment 2 would also seem to suggest that form perception has an early and significant influence on motion disambiguation, as the bias occurs within the first 300 msec of stimulus presentation. Despite the lack of disparity cues, the addition of occluding surfaces influences motion disambiguation. Presumably this occurs as the terminators along the occluded edge appear to be occluded and their influence is therefore attenuated.

Alternatively, the addition of texture near the occluded terminators might somehow have diminished the salience of the nearby terminators. Experiments 3A and 3B were control conditions to ensure that the bias found in Experiment 2 was not due to an interaction between the motion and texture patterns. In particular, we examined the effect for non-textured occluding patches. Additionally, we changed the relative contrast between the occluded and unoccluded sides of the barber poles to ensure that contrast polarity was not a factor.

Method

Simuli. Stimuli sizes and configurations were the same as Experiment 2 and the same set of subjects were employed. However, we used non-textured uniform bars. Experiment 3A, employed a white background and intermediate grey occluders. Experiment 3B, employed an intermediate grey background and white occluders (See Legend, Figure 4).

Results and discussion

No difference was found between the biasing effect of white bars on a grey background and grey bars on a white background (white horizontal vs. grey horizontal: $F(1,4) = 0.13, p > 0.73$; white vertical vs. grey vertical: $F(1,4) = 2.22, p > 0.2$). However,
the effect of the white and grey bars was somewhat weaker than that of the textured bars of the previous experiment. (See Figure 4). This difference was significant for three of the four cases (grey horizontal vs. textured horizontal: F(1,4) = 14.44, p < 0.0191; grey vertical vs. textured vertical: F(1,4) = 5.28, p > 0.0832; white horizontal vs. textured horizontal: F(1,4) = 8.13, p < 0.0464, white vertical vs. textured vertical: F(1,4) = 13.71, p < 0.0208).

As before, the attenuation of terminator influence was estimated by finding the balance point between horizontal and vertical motion. The resulting balance ratios were 2.0:1 and 1:1.7 for white occluders and 2.0:1 & 1:2.1 for grey occluders. The white occluders produced a 48% reduction in the influence of vertical terminators and a 41% reduction for horizontal terminators. Likewise, the grey occluders produced a 49% reduction in the influence of vertical terminators and a 52% reduction for horizontal terminators.

These results support the idea that the bias in the perceived direction of motion in Experiment 2 was not merely result of a change in salience of the terminators along the occluding edge resulting from contrast differences between the terminators and the occluding edge or interference from the texture pattern. As no disparity cues were available to signal occlusion, the results further support the idea that monocular depth cues can have an early and strong influence on motion disambiguation.

The results of Experiments 3a & 3b do, however, indicate that texture played a small role in the previous experiments, as the bias for untextured occluders was slightly less than for textured occluders. This suggests either that the addition of texture created a stronger perception of occlusion, or that the texture itself makes motion signals from terminators along the occluded border somewhat less efficacious.
FIGURE 4. EXPERIMENTS 3A & 3B: The addition of grey bars on a white background, and white bars on a grey background. The average percent horizontal motion reported by subjects for both background types is plotted against barber pole aspect ratio with solid lines for the isolated (●), vertical (▲, ■), and horizontal (◆, ◆) configurations. The legend below contains icons depicting the corresponding aspect ratios employed in the experiment. Dotted lines are sigmoid estimations for the response curves.
EXPERIMENT 4: Amodal Completion or Terminator Classification?

One of the consequences of border assignment is that there is a tendency to see the ground (the object that does not ‘own’ the border) as extending beneath the figure (the object that owns the border) (Rubin, 1915, 1958). The previous experiments indicate that an occluding form can have a major effect on motion disambiguation. However, it remains to be seen whether the border between the occluding form and the barber pole is the only controlling factor. Experiment 4 examines whether the rest of the occluding form plays a role.

The figure-ground relationships suggest that the occluded barber poles are being amodally completed behind the occluders. An occluded barber pole may be seen as a larger unoccluded barber pole that continues behind the occluders (See Figure 5). Experiment 4 was designed to determine if border classification is the only controlling factor. In other words, do the occluding forms need to be wide enough to accommodate an amodal completion of the barber poles? Experiment 4 examined this question by decreasing occluder thickness.

FIGURE 5. A role of amodal completion? The figure on the left could be perceived as a horizontal barber pole extending beneath two vertical occluding patches (depicted in the center) The grey grating symbolizes the invisible, yet amodally competed percept. In some sense, this may be equivalent to the non-occluded barber pole depicted to the right.

Method
The same experimental conditions were used as before, but the occluding bars were significantly thinner, subtending approximately a 0.4° x 4.8° patch. (See Legend, Figure 6.)

**Results and discussion**

The thin occluders produced a large bias (thin vertical vs. isolated vertical: F(1,5) = 42.19, p < 0.0013; thin horizontal vs. isolated horizontal: F(1,5) = 39.72, p < 0.0015). The measured effect was slightly less than that produced by the thick occluders. However, the difference between thick (Experiment 4) and thin (Experiment 2) bars failed to reach significance (thin vertical vs. thick vertical: F(1,5) = 3.75, p > 0.1482; thin horizontal vs. thick horizontal: F(1,5) = 1.79, p > 0.2729). Balance ratios were 2.1:1 and 1:2.2 for vertical and horizontal occluders respectively. Thin vertical occluders produced at 52% reduction in vertical terminators. Thin horizontal occluders produced a 55% reduction in horizontal terminators.

The results of Experiment 4 indicate that classification of the terminators at their border is the major factor influencing motion disambiguation. If indeed amodal completion does occur, there is little need for a wide zone of amodal completion behind the occluders.

**EXPERIMENT 5: Occlusion of One Edge**

The previous experiments demonstrated that the addition of occluding edges can bias the perceived direction of a barber pole pattern. The results are consistent with the idea that the influence of terminator motion is attenuated (but not abolished) when the terminators
appear to have been created extrinsically. A sufficient number of extrinsic terminators can override intrinsic terminators and dominate motion disambiguation.

However, it remains to be seen whether a weakening of terminators is sufficient to explain the change in perception. To explore whether the bias is solely governed by the number of terminators and their classification, Experiment 5 examined barber pole patterns with only one occluded edge. We predicted that occluding only one edge would still attenuate the influence of terminators along that edge, but the extent of the bias was unknown.
If an attenuation of terminator influence is sufficient to account for the bias, the results from Experiment 2 can be used to make a prediction for the aspect ratios required to balance horizontal and vertical motion when an occluder is added to only one side of a barber pole. Experiment 2 found a 57% reduction in the influence of vertical terminators, and a 55% reduction for horizontal terminators for the appropriately added occluders. If only terminator classification is responsible for the bias, we would then expect the same attenuation of terminator influence to occur, but for only half of the terminators. Taking the measured attenuation from Experiment 2 and applying it to half the terminators, we can predict a balance between horizontal and vertical motions at aspect ratios of approximately 1.4:1 and 1:1.38 respectively for barber poles with one side occluded. (See Appendix: Part II for details).

Method

Experimental conditions and stimuli were the same as Experiment 2, but only one side of the barber pole pattern was occluded (See Legend, Figure 7). Results for a horizontal occluder above the barber pole and a horizontal occluder below the barber pole were pooled as were occluders to the left and right of the barber pole for the vertical conditions.

Results and discussion

As expected the occlusion of only one side of the barber pole still results in a bias in the perceived direction of motion (one-side vertical vs. isolated vertical: F(1,4)=18.41, p<0.0127; one-side horizontal vs. isolated horizontal: F(1,4) = 18.52, p < 0.026). However, the bias is significantly weaker than when two sides (Experiment 2) are occluded (two-sides vertical vs. one-side vertical: F(1,4) = 19.19, p < 0.0220; two-sides horizontal vs. one-side horizontal: F(1,4) = 23.02, p < 0.0172) (See Figure 7).
in horizontal and vertical motion was found for an aspect ratio of 1.7:1 and 1:1.8 for vertical and horizontal occluders. These values are larger than the predicted aspect ratios of 1.40:1 (vertical) and 1:1.38 (horizontal). Additionally, the corresponding reduction in terminator influence along the horizontal and vertical occluded sides was 84% and 91% respectively, considerably larger than the values of 49% and 52% calculated in Experiment 2. These values are much higher than would be expected given our previous results. The results suggest that a linear summation of terminator influence based on their classification is not sufficient to account for the perceived biases. Rather, the configuration of the stimulus as a whole influences the perceived direction of motion.

**EXPERIMENT 6: Role of T-junctions**

From the previous experiments, it is clear that the presence of monocular depth cues that support occlusion has a major influence on motion disambiguation. However, whether a single monocular cue is responsible, or the effect can be generated by an array of monocular cues, has yet to be established. Previous research has demonstrated that T-junctions are important cues for occlusion (Cavanagh, 1987; Anderson & Julesz, 1995). Other research has shown that the perception of occlusion depends on the presence of T- or L-junctions even when other occlusion cues are present (Rubin, 1997). T-junctions have frequently been used in computational vision (Guzman, 1969; Grossberg, 1997). The top of the “T” is created by the occluding surface, the stem of the “T” is the occluded contour. The occluding surfaces in all of the previous experiments have created T-junctions between the barber pole pattern and the occluding surface (Figure 8). Experiment 6 was designed to determine if these T-junctions are critical for the introducing the bias.
FIGURE 7. EXPERIMENT 5: The occlusion of one side. The average percent horizontal motion reported by subjects is plotted against barber pole aspect ratio with solid lines for the isolated (○), vertical (▲), and horizontal (■) configurations. The legend below contains icons depicting the corresponding aspect ratios employed in the experiment. Although the icons only depict vertical occluders to the left of the barber pole, trials were run with both left and right vertical occluders and the results folded together. The same is true for the top and bottom horizontal occluders. Dotted lines are sigmoid estimations for the response curves.

Methods
New stimuli were created for Experiment 6 which differed from Experiment 1 in that the occluding bars were given the same length of the barber pole patch. This eliminated T-junctions whose tops are aligned with the occluding patches (See Legend, Figure 9).

Results and discussion

Although T-junctions whose tops are aligned with the occluding surface were eliminated, a bias was still observed (vertical occluders vs. vertical isolated: $F(1,5) = 6.68, p < 0.0472$; horizontal occluders vs. horizontal isolated: $F(1,5) = 16.58, p < 0.0096$). The bias was significantly weaker than found in Experiment 2, where T-junctions were present, (no-T vs. T vertical: $F(1,5) = 29.47, p < 0.0123$; no-T vs. T horizontal: $F(1,5) = 57.85, p < 0.0047$). A balance in horizontal and vertical motion was found at an aspect ratio of 1.5:1 and 1:1.6 for vertical and horizontal occluders respectively. This corresponds to the vertical and horizontal terminators being attenuated by 32% and 38% respectively (See Figure 9).

McDermott, Weiss, & Adelson (1997) recently examined the effect of terminator classification on a different set of motion stimuli than our own. When overlapping vertical and horizontal bars oscillate sinusoidally, $90^\circ$ out of phase, they can be seen moving coherently in a circular path, or separately as two bars sliding over each other. They demonstrated that adding a frame around the edges (create extrinsic terminators at edges
of the two bars) improved coherence, in agreement with our results. They propose that a simple contour-based heuristic is used to segment motion signals. Our results, however, suggest that although T-junctions are a very important cue, they are not critical for the
influence of terminators to be attenuated. A significant motion bias is still observed despite the elimination of T-junctions whose tops are aligned with the occluding surface.

Although local T-junctions between the individual grating bars and the occluding patch are still present in these stimuli, experimental observations suggest their influence is minimal. Shimojo et al. (1989) found that such local T-junctions are overridden by binocular information that suggests the barber pole patch is in the same plane as its surround. It should also be noted that Experiment 3B contained local T-junctions along the non-occluded side of the barber pole (between the grey background and the barber pole). The perception of motion in these stimuli was still one of motion under the occluding patches. This suggests that local T-junctions are not an important factor. Pilot experiments also indicate that the bias in Experiment 6 persists when an intermediate grey-background is used. Such a background creates local T-junctions on both the occluded and non-occluded sides, yet the bias is still for motion to be seen under the occluded side. Together, these observations suggest that it is unlikely that local T-junctions account for the remaining bias found in Experiment 6.

**EXPERIMENT 7: Illusory Occlusion**

The previous experiments demonstrated that the addition of occluding patches to a barber pole pattern alters the perception of motion. Disparity information and T-junctions were not necessary for the occluding patterns to influence motion disambiguation, nor was a specific contrast polarity between the occluders, background and barber poles. This suggests that boundary classification occurs prior to the resolution of motion ambiguity.
As we have previously suggested, these effects might be due to feedback from a higher level or parallel processes which interprets surface segmentation. If this is the case, the presence of a physical luminance change at the edge of a barber pole is not necessary to alter the perceived direction of motion, only the perception of an occluding edge is required. This idea is supported by Wallach (although no objective measurements were made). He noted that one of the perceptions of a moving grating with free-line ends visible is of an illusory surface appearing like a bright stripe under which the grating moves (Wuerger, Shapley & Rubin, 1996). Vallortigara & Bressan (1991) also report that terminators internal to a barber pole or plaid pattern are discounted when they aligned to form subjective occluding bars. Similar results are reported by Gurnsey & von Grünau (1997).

To further examine the role of illusory contours on motion disambiguation and to quantify the phenomenon, we generated occluding surfaces using Kanizsa-like figures. Both the occluded and non-occluded edges of the barber pole had the same luminance profile. However, the occluded edge abutted an illusory contour created by a Kanizsa-like figure (Figure 10). As the previous experiments indicate that it is the perception of an occluding surface rather than a disparity or luminance change that results in a bias of motion disambiguation, we predicted that the Kaniza configuration would also result in a bias in the perception of barber pole patterns.

**Methods**

Six aspect ratios were employed for Experiment 7: 1:4.0, 1:1.32, 1:1.16, 1:1.08, 1:1, 1.08:1, 1.16:1, 1.24:1, 1.32:1, 1.40:1. This smaller range was employed for two reasons. First, we expected the effect of illusory occluders to be significantly weaker than real for
occluders. In informal observations, the authors found an illusory edge to be less salient than a real edge for the experimental configurations. Secondly, the aspect ratio was limited to prevent the illusory figure inducers from getting too far apart. As inducers of a fixed size are moved further apart, the perception of an illusory contour weakens (Watanabe & Oyama, 1988; Shipley & Kellman, 1992).

Results and discussion

A significant bias was found for the illusory occluders configuration (illusory occluders vs. no occluders, vertical: $F(1,6) = 7.75, p < 0.0318$; illusory occluders vs. no occluders, horizontal: $F(1,6) = 0.0138, p < 0.0138$). A balance in horizontal and vertical motion was found for ratios of 1.3:1 and 1.3:1 were found for the horizontal and vertical occluders respectively. The attenuation of vertical and horizontal occluders were both 23%. These results are strongly in support of input from other cortical areas which influences the motion processing areas (See Figure 10).

GENERAL DISCUSSION

There were three primary purposes to our study. The first was to compare the relative importance of disparity and monocular occlusion cues for motion perception. Are monocular occlusion cues significantly weaker than disparity cues? Secondly, we wished to determine the degree to which the influence of extrinsic terminators is discounted. Is it completely abolished? Is the extrinsic/intrinsic classification all-or-none? Finally, we
wanted to determine the relative importance of different monocular depth cues. Do occluder and background contrast make a difference? Are T-junctions necessary?

The first purpose of our experiments, the comparison between disparity and monocular occlusion cues, provides insight into possible neural mechanisms involved the barber pole phenomenon. Recently, a physiological study demonstrated that stereo-based terminator classification affects the responses of cells in area MT (Stoner, Duncan & Albright, 1997). When the depth relationships of a barber pole configuration are such that they bias the

![Diagram of Experiment 7](image-url)
perceived direction of motion in a cell’s preferred direction, the cell elicits its greatest response. There are two possible interpretations for this result. In one interpretation, cells coding terminator motion are suppressed when their terminators have crossed disparities and are seen as in-front. Such an interpretation does not require an analysis of occlusion, but merely the presence of the appropriate disparity cues. For the other interpretation, some manner of form processing is required. It is generally believed that there are separate visual pathways for form and motion (Maunsell & Newsome, 1987). The second interpretation suggests a second system, one that is involved in the analysis of occlusion, feeds into the motion processing areas and influences motion processing. These two possibilities were originally suggested by Shimojo et. al (1989) based on their psychophysical work.

Previous research has demonstrated cases in which disparity information overrides monocular depth cues (Shimojo et al. 1989). Such results are compatible with the first interpretation. Our results, on the other hand, support the latter interpretation, that there is input from a second system, which processes form. Our first major finding is that there is little difference in the influence of occluding patches with and without disparity differences (Experiments 1 and 2). In Experiment 2, monocular occlusion cues (indicating occlusion) override binocular depth cues (indicating no disparity difference). This suggests that the suppression of extrinsic terminators by disparity tuned motion sensitive cells is not a sufficient explanation of how terminators are suppressed.

Although Stoner, Duncan & Albright (1997) found that depth relationships in a barber pole configuration influence the response of MT cells, their result does not necessarily imply an input from the form to the motion pathway, as MT cells are tuned for disparity
(Maunsell & Van Essen, 1983). However, one could test for the influence of form, if the same experiments were performed using the range of stimuli which we have shown to influence motion disambiguation psychophysically.

Our second major finding is that the influence of terminators is not abolished but merely attenuated when terminators are classified as extrinsic. Even the strongest extrinsically classified terminators still retain some of their capacity to bias motion perception. This is particularly noticeable for the larger aspect ratios (See Figure 2). Additionally, the classification appears not to be a strict dichotomy but rather a smooth continuum in which the influence of terminators varies with the strength of occlusion cues (See Figure 11 & Table 1). Terminators with monocular cues that strongly support extrinsic classification exert less of an influence on motion perception than those terminators with weaker support. The perceptual implication of this classification on a given trial is probabilistic. The perceived direction of motion for subjects (with a rare exception) is along a cardinal direction. However, the likelihood of a particular cardinal direction on a given trial depends on the degree to which various terminators can be thought of as extrinsic.

**TABLE 1. Balance Points Between Horizontal and Vertical Motion**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description of Stimuli</th>
<th>Aspect Ratio</th>
<th>Reduction</th>
<th>Aspect Ratio</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Textured Occluders with Depth</td>
<td>1:2.5</td>
<td>60%</td>
<td>2.6:1</td>
<td>61%</td>
</tr>
<tr>
<td>2</td>
<td>Textured Occluders without Depth</td>
<td>1:2.2</td>
<td>55%</td>
<td>2.3:1</td>
<td>57%</td>
</tr>
</tbody>
</table>

1. Note that only the illusory occlusion condition deviates from this smooth continuum. We suggest a possible reason for this is that as the aspect ratio of the barber pole changes, the distance between the barber pole and the illusory contour inducers also changes. In turn the strength of the illusory contour is altered for the different aspect ratios, giving different strengths to the perceived illusory surface.
Our third major finding is that no single monocular cue is responsible for determining the degree to which terminators influence motion disambiguation. In addition to disparity, a multitude of cues exist (texture, T-junctions, etc.) which support the perception of occlusion and attenuate the influence of terminators to varying degrees (See Figure 11 & Table 1). Although past research has emphasized the role of T-junctions, we found that although they are an important cue, they are not strictly necessary.

Many researchers have suggested the existence of separate visual pathways for form and motion (Maunsell & Newsome, 1987), for ‘spatial’ and ‘object’ vision (Mishkin, Ungerleider, & Macko, 1988) or the existence of separate color-opponent and broad-band channels (Schiller & Logothetis, 1990). Livingston & Hubel (1988) argued that motion and shape processing is segregated from the earliest levels in the brain to the highest levels that have been studied. However, the existence of an interaction between form and motion is supported by physiology showing the anatomical pathways in the primate visual system contain cross-connections between the streams (DeYoe & Van Essen, 1988).

Our psychophysical results support such an interaction between streams, demonstrating that form perception has an early and significant influence on the motion pathway, specifically in the disambiguation of motion information. Evidence suggests

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description of Stimuli</th>
<th>Horizontal</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Aspect Ratio</td>
<td>Reduction</td>
</tr>
<tr>
<td>4</td>
<td>Thin Textured Occluders</td>
<td>1:2.2</td>
<td>55%</td>
</tr>
<tr>
<td>3a</td>
<td>Grey Occluders / White Background</td>
<td>1:2.1</td>
<td>52%</td>
</tr>
<tr>
<td>3b</td>
<td>White Occluders / Grey Background</td>
<td>1:1.7</td>
<td>41%</td>
</tr>
<tr>
<td>5</td>
<td>Textured Occluders on One Side</td>
<td>1:1.8</td>
<td>91%</td>
</tr>
<tr>
<td>6</td>
<td>Textured Occluders, no T-Junctions</td>
<td>1:1.6</td>
<td>38%</td>
</tr>
<tr>
<td>7</td>
<td>Illusory Occluding Surface</td>
<td>1:1.3</td>
<td>23%</td>
</tr>
</tbody>
</table>

TABLE 1. Balance Points Between Horizontal and Vertical Motion
that cells in area V2 possess the ability to processes emergent visual forms such as the type of illusory contours in a Kanizsa display (von der Heydt, Peterhans, & Baumgartner, 1984). That Kaniza-like illusory contours can influence motion disambiguation (as shown in Experiment 7), suggests a role for the V2 -> MT connection. Recently, computational models have begun to incorporate such mechanisms (Grossberg, 1991; Francis & Grossberg, 1996).

Other recent psychophysical work also supports a strong interaction between the form and motion systems. In a related study we demonstrated that similarity (or grouping) based on form cues between spatially disparate areas mediates the disambiguation of
motion signals in a barber pole pattern (Lidén, Mingolla & Watanabe, 1997). In particular, contrast similarity rather than contrast magnitude determines the degree to which motion in one spatial area affects another. Croner & Albright (1997) found that form cues such as hue and texture can aid in the discrimination of motion direction, suggesting a strong influence of form cues on motion processing. Watanabe (in press) has demonstrated a reciprocal interaction between form and motion processing, with surface decomposition affecting motion decomposition and vice versa.

Research also supports the idea that occlusion-related processing has an early effect on motion disambiguation. In the realm of apparent motion, Shimojo & Nakayama (1990) found that the addition of an intervening occluding surface in bi-stable apparent motion displays creates a bias for motion in the direction under the occluding surface. He & Nakayama (1994) found that an occluded ‘L’ shape has a bias to move between tokens of the same orientation only when the ‘L’ is seen in front of the occluder. The bias is reduced when the ‘L’ is seen behind. Presumably the ‘L’ is amodally completed behind the occluded patch. Together this work suggests a significant and essential role for information flow between the form and motion streams.

In summary, although previous research has suggested monocular occlusion cues are of less importance than binocular disparity for motion disambiguation in the barber pole phenomenon, we found monocular occlusion cues can profoundly influence motion perception even when zero-disparity is employed. Secondly, our results support the idea that extrinsic/intrinsic classification is not an all-or-none process; rather, a continuum exists in which one terminator can be classified as having stronger extrinsic properties than another. Thirdly, we demonstrated that a variety of occlusion cues, both monocular
and binocular, influence the disambiguation of motion signals. No single cue is responsible. Finally our results support the role of input from the form system to MT for mediating the extrinsic/intrinsic classification rather than a disparity based suppression of cells in MT.
APPENDIX

Part I: Calculating the Attenuation of Terminators

When the perception of horizontal and vertical motion is equally likely, the influence of the horizontal and vertical terminators is presumably equal. If \( x \) is the length of the occluded side, \( y \) is the length of the non-occluded side and \( a \) is the attenuation of terminator influence due to the presence of the occluders, then terminator influence is in balanced when:

\[
a2x = 2y
\]  

(EQ 2)

The length of the non-occluded side, \( y \), was held constant in all experiments. The value of \( x \) can be calculated by finding the 50% level on the sigmoid which best fits the subject data (See Equation 1). The attenuation of the occluded sides is then found by solving for \( a \):

\[
a = \frac{y}{x}
\]  

(EQ 3)

The percent reduction of terminator influence is then given by \((1-a)\).

Part II: Predicting the Attenuation for One Side

When one side of the barber pole is occluded, only one set of terminators along the \( x \)-dimension is attenuated, so a balance between horizontal and vertical motion presumably occurs when:

\[
a x + x = 2y
\]  

(EQ 4)

The attenuation of the occluded terminators is then found by solving for \( a \):
Using the attenuation level calculated for the occlusion of both sides and the fact that length of the unoccluded side, $y$, is held constant in all experiments, one can also make a prediction for the length of the occluded side, $x$, that will result in a balance in the perception of vertical and horizontal motion:

$$a = \frac{2y}{x} - 1$$  \hspace{1cm} (EQ 5)

$$x = \frac{2y}{a + 1}$$  \hspace{1cm} (EQ 6)
REFERENCES


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