Pergamon

0042-6989(94)00299-1

Vision Res. Vol. 35, No. 15, pp. 2137–2146, 1995

0042-6989/95 $9.50 + 0.00

Motion Integration Across Differing Image Features

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Received 13 April 1994; in revised form 21 October 1994

To interpret the projected image of a moving object, the visual system must integrate motion signals across different image regions. Traditionally, researchers have examined this process by focusing on the integration of equally ambiguous motion signals. However, when the motions of complex, multi-featured images are measured through spatially limited receptive fields, the resulting motion measurements have varying degrees of ambiguity. In a series of experiments, we examine how human observers interpret images containing motion signals of differing degrees of ambiguity. Subjects judged the perceived coherence of images consisting of an ambiguously translating grating and an unambiguously translating random dot pattern. Perceived coherence of the dotted grating depended upon the degree of concurrence between the velocities of the grating terminators and dots. Depth relationships also played a critical role in the motion integration process. When terminators were suppressed with occlusion cues, coherence increased. When dots and gratings were presented at different depth planes, coherence decreased. We use these results to outline the conditions under which the visual system uses unambiguous motion signals to interpret object motion.

Aperture problem   Velocity integration   Coherence

INTRODUCTION

The accurate interpretation of moving images is particularly difficult because individual motion measurements are often ambiguous. For example, whenever a translating homogeneous edge is viewed through a relatively small window or aperture, the component of motion parallel to the edge can not be measured. As a result, all motions having the same perpendicular but differing parallel component of translation will appear to be identical. This so called aperture problem has received much attention because all visual systems have spatially limited receptive fields (e.g. Hildreth, 1984). How does the visual system determine object motion from such inherently ambiguous motion measurements?

One approach to this question considers the combination of equally ambiguous motion signals. While the motion measurement of a single translating edge is consistent with infinitely many interpretations, multiple measurements of differently oriented and rigidly connected edges share only a single common motion interpretation. This insight lead to the proposal of an Intersection of Constraints model of motion perception (Adelson & Movshon, 1982; Movshon, Adelson, Gizzi & Newsome, 1985). Subsequent research has emphasized the use of a vector average of the individually ambiguous motion signals (Mingolla, Todd & Norman, 1992; Rubin & Hochstein, 1993; Wilson, Ferrera & Yo, 1992). Both of these models support the proposal that the visual system interprets object motion by combining ambiguous motion signals. This is especially true for plaid patterns in which motion signals are produced by overlapping or nearby contours. On the other hand, observers often have difficulty combining ambiguous motion signals across image space (Adelson & Movshon, 1983; Ramachandran, 1990; Shiffrar & Pavel, 1991; Lorenceau & Shiffrar, 1992). This finding led us to question the extent to which the visual system normally relies upon the combination of ambiguous motion signals during the interpretation of dynamic images.

Complex visual images often contain different features that produce motion signals of differing degrees of ambiguity. For example, while the motion of a translating edge may be ambiguous, the motion of a corner, terminator, or point may be unambiguously measured in two dimensions, as illustrated in Fig. 1. Increasingly, researchers have proposed that the visual system interprets object motion by relying on unambiguous motion signals (Shiffrar & Pavel, 1991; Lorenceau & Shiffrar, 1992; Castet, Lorenceau, Shiffrar & Bonnet, 1993; Derrington, Badcock & Henning, 1993; Lorenceau, Shiffrar, Wells & Castet, 1993). That is, the visual system may overcome the aperture problem by weighting the unambiguous motion signals produced by contour

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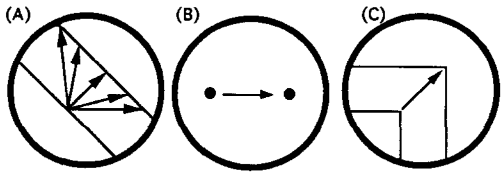

FIGURE 1. (A) The motion of a translating straight line viewed through an aperture is ambiguous. This ambiguity arises from the lack of information parallel to the orientation of the line. However, the two-dimensional motion of some image features can be unambiguously measured within an aperture. These include a small point (B) as well as contour discontinuities such as corners (C) or terminators.

discontinuities more than the ambiguous signals produced by straight contours.

We undertook the current set of studies to determine the extent to which image interpretation is influenced by unambiguous motion signals. We examined the perception of a spotted barber pole stimulus originally designed by Wallach (1935, 1976). In a classic series of experiments, Wallach examined the perception of gratings translating behind rectangular apertures. While the grating motion was ambiguous, observers consistently interpreted the grating to translate in the direction of the longest aperture side when that side produced the greatest number of grating terminators. This suggested to Wallach that observers used terminator motion to disambiguate the grating motion. When translating dots were added to the barber pole stimulus, the perceived direction of grating translation did not change (Wallach, 1935; Rock, 1975). That is, as illustrated in Fig. 2, the stripes of the barber pole continued to appear to translate vertically while the dots translated horizontally.

However, when a single translating dot is added to a grating viewed through a circular aperture, the dot strongly influences the perceived direction of grating translation (Rubin & Hochstein, 1993). Why does the visual system rely on the unambiguous dot motion under some conditions but not others? This question is of interest because it addresses how the visual system resolves the apparently conflicting needs of integrating motion signals from the same object while segmenting motion signals from different objects (Braddick, 1993).

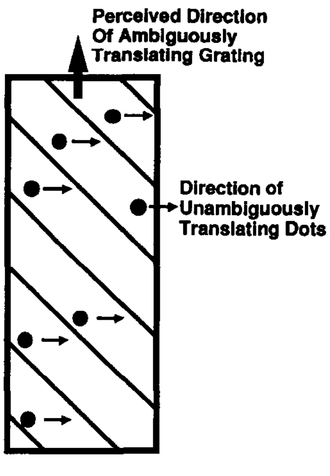

FIGURE 2. Wallach's spotted barber pole display. When viewed in isolation, the stripes of the barber pole appear to translate vertically. When horizontally translating dots are added to the display, they are not used by the visual system to interpret the motion of the stripes. Instead, observers perceive horizontal dot translation and vertical stripe translation.

Wallach's work clearly demonstrates that the visual system uses unambiguous terminator velocities to interpret ambiguous velocities along the length of the same contour. The visual system can also use an unambiguously translating point to disambiguate a non-overlapping, translating line (Rock, 1983; Nakayama & Silverman, 1988). The spotted barber pole stimulus creates a slightly different situation. How does the visual system interpret complex stimuli containing unambiguous yet conflicting motion measurements? The contours, terminators and dots in a spotted barber pole display constitute three different types of image features. When measured through a spatially limited receptor, each of these features produces a motion measurement having a different degree of ambiguity. In two dimensional space, the motion of a translating dot can be unambiguously measured while the motion of a translating homogeneous line can only be ambiguously measured. Line terminators are a particularly interesting image feature since they can be thought of having an intermediate degree of ambiguity depending on whether they are extrinsic or intrinsic to a line. The visual system may assign different weights to the motion signals produced by terminators under different conditions (Shimojo, Silverman & Nakayama, 1989).

How does the visual system interpret moving images containing multiple features having differing degrees of ambiguity? Is the most unambiguous motion signal always used to interpret all of the other more ambiguous signals? Does the visual system weigh each motion signal equally in an IOC or vector averaging analysis? To what extent does the consistency or agreement between velocity estimates from different image features play a role in perceived object motion? The following experiment was conducted to address these questions.

EXPERIMENT 1: A SPOTTED BARBER POLE

To determine how observers interpret multi-featured moving images, we examined stimuli consisting of a translating rectangular wave grating and a pseudo-random dot pattern. Displayed individually, these two components appeared to translate in different directions. The grating, since it was viewed through a vertically oriented aperture, appeared to translate vertically. The random dot pattern translated horizontally. We examined the conditions under which these two components shown together as a "spotted barber pole" appeared to translate coherently. We varied the number of unambiguously translating dots and the relative number of grating terminators translating in the same direction as the dots.

Method

Subjects. Three observers with normal or corrected to normal vision served as subjects in this experiment. Two of the subjects were authors and the third was a naive subject recruited from outside Rutgers University.

Stimuli. Stimuli were presented on a 19 in. RGB Hitachi monitor with a 1266×986 pixel resolution and a 60 Hz refresh rate. The monitor was controlled by a Silicon Graphics 4D/TG30 Personal Iris. Subjects' viewing distance was fixed at 95 cm from the monitor with a chin rest. Subjects used a mouse device to record their responses. This apparatus was used in all experiments.

The stimuli consisted of translating dotted gratings visible through rectangular apertures. As illustrated in Fig. 3, the number of dots and grating terminators varied across trials. The grating was a high contrast, 2.0 c/deg rectangular wave grating oriented 45 deg from vertical. The width of the bright bars subtended 1 min arc of visual angle and the width of the black bars subtended 29 min arc of visual angle. The luminance of the bright bars was 10.25 cd/m^2. The black bars were the same luminance as the black background. We varied the number of visible grating terminators by changing the aspect ratio of the invisible aperture through which the gratings were viewed. Six different rectangular apertures were created from combinations of two possible heights 2.25 or 3.00 deg and three possible widths 0.75, 1.50 and 2.25 deg. When the grating was viewed through each of these six apertures, the resulting numbers of horizontal and vertical grating terminators were 2:8, 2:6, 4:8, 4:6, 6:8 and 6:6, respectively. When these numbers are expressed as the percentage of horizontally translating terminators within each aperture, we have 20, 25, 33, 40, 43 and 50% horizontal terminators. We did not use apertures creating more than 50% horizontal terminators because these would lead to the perception of horizontally translating gratings when viewed in isolation.

The dot patterns were overlaying arrays of pseudorandomly positioned dots with the exception to position randomization being that the dots did not touch the bright bars of the grating. The dots were very short, 0.9×2.7 min arc of visual angle dashes having the same luminance as the bright grating bars. Because we wanted to create a competition between the number of dots and vertical terminators, we selected the number of dots in terms of the number of terminators. The number of dots fell into four categories: no dots (0/2 dot condition), half of the number of vertical grating terminators (1/2 dot condition), the same number of dots as the number of vertical terminators on both aperture sides (2/2 dot condition) and 1.5 times the number of vertical terminators (3/2 dot condition). Thus, in total, there were six possible aperture conditions and four possible dot conditions for a total of 24 stimuli.

Both the dot pattern and the grating translated horizontally with a velocity of 1.4 deg/sec. A wrap around procedure was used to provide continuous motion. To minimize adaptation effects, the direction of horizontal translation was leftward or rightward on alternate trials. On half of the trials, grating orientation was 45 deg from the horizontal and the dots and grating translated horizontally rightward. On the other half of the trials, grating orientation was 135 deg and the dots and grating translated horizontally leftward.

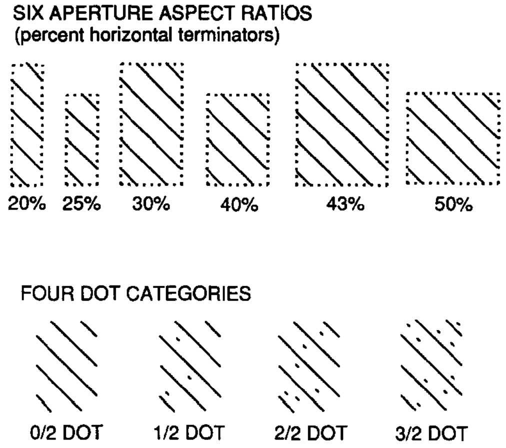

FIGURE 3. The six aperture conditions and four dot conditions used in Experiment 1. The dashed aperture outlines were not visible in the display.

Procedure

Given our use of a control condition in which dots were absent, we could not use a traditional coherence judgment task. Instead, we used a somewhat more conservative measure of perceived coherence. In a two alternative forced choice procedure, subjects reported whether the grating, independent of the dots, appeared to translate horizontally. Since the dots always translated horizontally, coherence only existed when the grating also appeared to translate horizontally. All non-horizontal directions of grating translation, including any oblique and vertical translations, would be inconsistent with a coherent precept. Thus, instead of discriminating between different degrees of perceived coherence, subjects simply judged whether or not the grating appeared to translate horizontally.

Each trial began with the presentation of a fixation point in the center of the monitor. Subjects were instructed to maintain fixation throughout each trial. After 1 sec, the translating barber pole stimulus was presented for 1.6 sec. The stimulus then disappeared and the screen was cleared. In a two alternative forced choice procedure, subjects indicated the perceived direction of the grating's translation by pressing one of two buttons on a mouse device. Subjects pressed one button if the grating appeared to translate strictly along the horizontal and a different button if the grating appeared to translate in any other non-horizontal direction. The next trial began immediately after this button press.

Each subject completed four blocks of 120 trials. Each stimulus was presented five times per block for a total of 20 presentations per stimulus. The order of stimulus presentation was randomized across trials. All subjects completed eight practice trials before beginning the experimental trials.

Results and discussion

The results of this experiment, shown in Fig. 4, are plotted as the probability of perceived horizontal grating translation (i.e. coherence) as a function of the percentage of the grating's terminators that translated horizontally. When the grating was presented in isolation (0/2 condition), subjects rarely perceived the grating to translate horizontally. However, when the horizontally translating dots were added, subjects became significantly more likely to perceive horizontal grating translation under some conditions.

When the grating was seen through the narrow apertures, which limited the number of horizontally translating grating terminators to only 20 or 30% of the total number of grating terminators, subjects rarely perceived the grating to translate horizontally. However, as the percentage of horizontally translating terminators increased, so did the probability of perceived horizontal grating translation. The number of dots within each aperture also influenced the perceived direction of grating translation, although to a lesser extent. Within an aperture, the probability of perceived horizontal grating translation increased with the number of dots. Moreover, as the percentage of horizontally translating terminators increased, so did the disambiguating influence of the random dot patterns. For example, the same number of dots resulted in the perception of horizontal grating translation during roughly half of the trials when 40% of the terminators translated horizontally but nearly all the trials when 50% of the grating terminators translated horizontally. Thus, under some conditions, the unambiguous dot velocities appear to have completely dominated the interpretation of image motion. It appears that the visual system may only use the unambiguous dot velocities when they are in agreement (at least in direction) with a sufficiently large percentage of the terminator velocities.

An interesting aspect of this cross-feature coherence phenomenon is that the change in the perceived direction of grating translation may be associated with a reclassification of the grating's terminators. That is, the perception of vertical grating translation implies that the vertical grating terminators are intrinsic (Shimojo *et al.*, 1989). However, when the dot velocity is used to interpret grating velocity, the vertical terminators must be suppressed or reclassified as extrinsic. This suggests that motion integration may influence terminator classification.

The current results suggest that when determining whether to integrate motion signals across different features, the visual system may consider how many unambiguous motion signals from each feature type share the same direction (i.e. common fate). This conclusion is supported further by informal observations in which we added up to 100 horizontally translating dots to a grating having only 20% horizontally translating terminators. The large increase in dot number did not influence the perceived direction of grating translation as the grating always appeared to translate vertically. This suggests that the percentage of same direction, unambiguous motion signals across features, rather

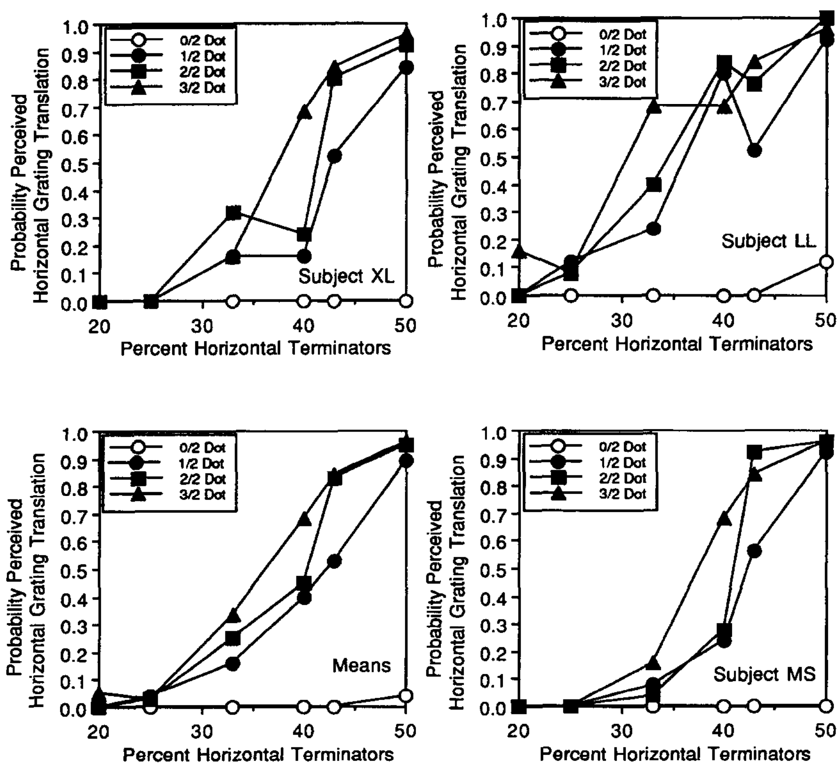

FIGURE 4. Results from Experiment 1. Individual results are shown in addition to the means.

than the total number of same direction signals may determine whether unambiguous motion signals capture or influence the interpretation of ambiguous signals. Secondly, since the dots were more likely to capture the grating as grating length increased, it appears that the number of ambiguous motion signals plays, at most, a minimal role in the cross-feature motion integration process.

Why does the presence of a random dot pattern more strongly influence perceived grating translation when the grating is viewed through wider apertures? One possibility is that greater dot densities increase the probability of the dots capturing the grating. Our results are not consistent with this interpretation since subjects were more likely to perceive horizontal grating translation with smaller dot densities (since dot number was held constant while aperture area increased). A second possible explanation concerns differences in grating length. The perceived direction and speed of a line become increasingly dominated by its terminators as line length decreases (Castet *et al.*, 1993; Lorenceau *et al.*, 1993). If the disambiguating influence of terminators decreases with distance, then the dots might beat out the weakened terminators with increasing grating length. A third possible explanation of these results is that some unambiguous, horizontally translating terminators must be present before the horizontally translating dots can capture the grating. The following experiment addresses the later two hypotheses by increasing grating length while eliminating consistent terminator motion.

EXPERIMENT 2: CONTOUR LENGTH

Is consistent terminator motion needed to perceive coherently translating dotted gratings? Parallelogram shaped apertures, as designed by Wallach (1935), were used to increase contour length while eliminating all horizontally translating terminators. If changes in perceived coherence across apertures resulted from increased grating length, then the results of this experiment should be identical to those of Experiment 1. However, if perceived coherence of the spotted grating resulted from agreement between the dot and terminator velocities, then subjects should never perceive a coherently translating spotted grating in this experiment.

Method

Two observers with normal vision participated in this experiment. Neither subject had participated in Experiment 1. As in the previous experiment, the same translating grating was viewed through invisible apertures. The only difference was that the aperture shape was an upright parallelogram with its top and bottom edges parallel to the grating's orientation. This eliminated all horizontally translating grating terminators while increasing grating length, as illustrated in Fig. 5(A). Again, six aperture and four dot conditions

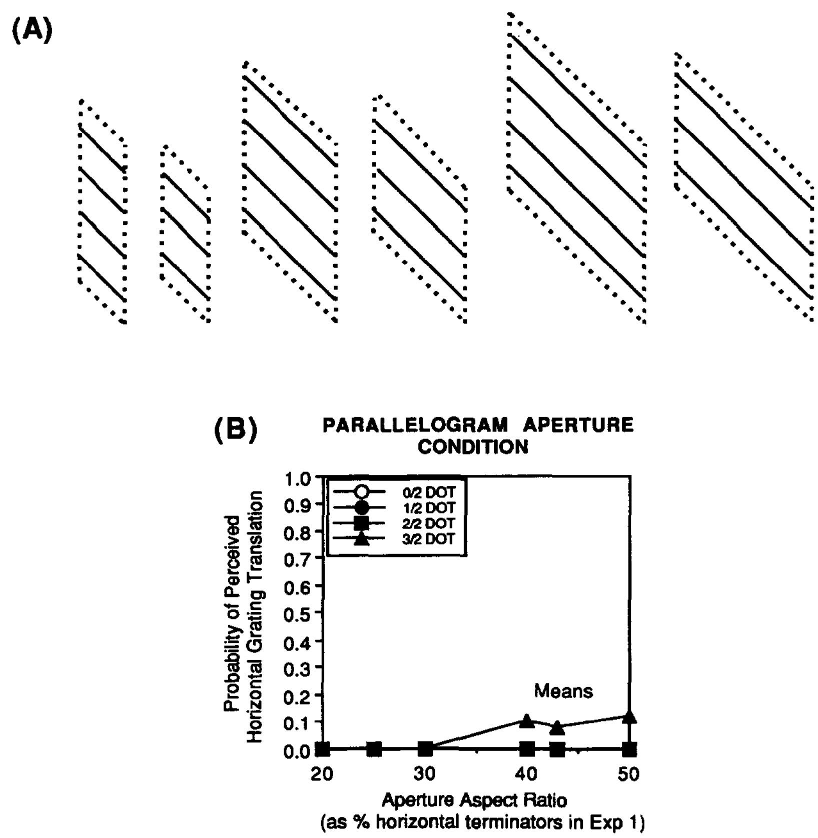

FIGURE 5. (A) Parallelogram apertures used in Experiment 2. The dashed aperture outlines were not visible in the display, (B) the mean results from Experiment 2.

were used. Dot numbers, trial numbers, vertical aperture heights, and horizontal aperture widths were the same as those used in Experiment 1. Finally, the same experimental procedure used in Experiment 1 was employed. Subjects used a mouse device to record whether each grating appeared to translate horizontally.

Results and discussion

The results, shown in Fig. 5(B), indicate that subjects do not perceive horizontal grating translation in the absence of horizontal terminator translation. This lack of perceived dot-grating coherence was observed even though grating length increased across apertures. Thus, changes in the perceived coherence of the spotted barber pole stimulus in Experiment 1 did not result from changes in grating length. Instead, it appears that the probability that the unambiguous dots can capture the grating depends on the directional similarity between some proportion of the grating terminators and the dots. Taken together, these results suggest that the visual system segments motion signals from different image features when unambiguous signals are too inconsistent. Second, while the visual system may overcome the aperture problem by relying on unambiguous motion signals, the conditions under which this occurs are limited. There must be some agreement among the unambiguous velocity estimates before integration occurs.

EXPERIMENT 3: TIME

How does the duration of our spotted barber pole stimuli influence motion integration across features? Recently, several researchers have suggested that the motion mechanisms that analyze local features or discontinuities are relatively slow and only contribute to motion interpretation after some delay (Yo & Wilson, 1992; Derrington, Badcock & Henning, 1993). Since dots and grating terminators can be considered local discontinuities, we examined the perception of the spotted barber pole display at shorter durations.

Methods

The same three subjects from Experiment 1 served as subjects in this experiment. The stimuli and procedure were identical to those of Experiment 1 except that each stimulus was displayed for only 150 msec. Dot and grating velocity remained constant. Again, on each trial, subjects reported whether the grating, viewed through a rectangular aperture and with one of four possible dot patterns, appeared to translate horizontally.

Results and discussion

The results of this experiment, shown in Fig. 6, suggest that duration does influence motion integration across differing image features. While there were large individual differences, each subject reported more horizontal grating translation (dot-grating coherence) at the 150 msec duration than at the 1.6 sec duration used in Experiment 1 (see Fig. 4). Thus, duration may play a critical role in the probability that the dots capture the grating. Since both the dots and the grating terminators are local discontinuities, additional studies are needed to determine whether these discontinuities are analyzed at different rates. Such studies would enable us to determine if the enhanced coherence at short durations resulted from a relatively slower analysis of grating terminators or from the relatively greater distances between the center of each grating and its terminators as compared to the distances between the gratings and dots.

We also examined the robustness of the spotted barber pole effect at increased speeds. During informal observations, we increased the speed of our displays, while holding duration constant at 1.6 msec. The change in dot-grating coherence across aperture aspect ratio appeared to be unaffected by the speed of the display. Thus, while our experiments were conducted at the relatively slow speed of 1.4 deg/sec, the same pattern of results can be expected when speed is increased by an order of magnitude.

In our final experiment, we examined the extent to which terminators determine the perceived coherence of our spotted gratings. Results from the previous experiments suggest that directional conflict between the ambiguous (grating minus terminators) and unambiguous (dot) velocities plays an insignificant role in motion integration. Now we more directly test whether ambiguous contour velocities can inhibit the perceived coherence of the spotted gratings by greatly reducing terminator influence. If terminators alone inhibit the integration of the dot and grating velocities, then suppression of the terminators should significantly increase integration and dot-grating coherence. We also examined whether the disambiguating effects of dots extend across depth planes.

EXPERIMENT 4: DEPTH

Is perceived dot-grating coherence facilitated when the influence of terminators is suppressed? We minimized terminator influence with two types of depth cues. Occlusion cues such as T-junctions are sufficient to cause the visual system to classify the terminators as extrinsic and as a result disregard them in motion interpretations (Shimojo *et al.*, 1989). We therefore created an occlusion cue by simply outlining each of the rectangular apertures from Experiment 1 and each of the parallelogram apertures from Experiment 2. Will the dots be more likely to capture the grating when the grating terminators are extrinsic?

Furthermore, if scene segmentation cues are an important determinant in the interpretation of our dot-grating patterns, then depth cues should be able to inhibit as well as facilitate motion coherence. More specifically, studies across multiple domains have demonstrated that depth based grouping is an early and powerful constraint (Gilchrist, 1977; Kanizsa, 1979). Therefore, we asked whether the disambiguating effects of the dots would extend across different depth planes.

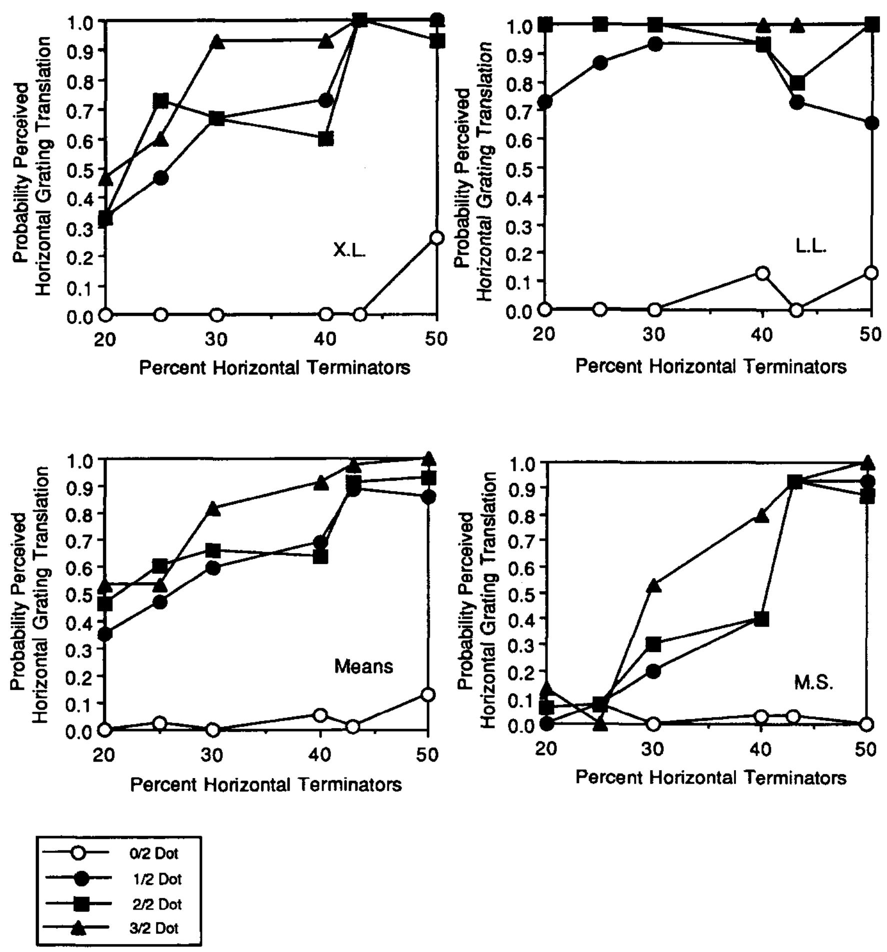

FIGURE 6. The mean and individual observer results from Experiment 3. At short stimulus durations, every subject was more likely to perceive a coherent spotted grating.

Method

Two subjects from Experiment 1 (one naive and one author) served as subjects in the outlined aperture conditions. Two new, naive observers served as subjects in the stereo condition. The stimuli were identical to those used in Experiments 1 and 2 with two critical changes. In the outlined aperture conditions, all of the apertures were outlined with a 5.4 min arc wide stationary border. The luminance of the border was the same as that of the bright grating bars. There were two outlined aperture conditions. Either the aperture was rectangular, as in Experiment 1, or parallelogram shaped, as in Experiment 2. In the stereo condition, the grating was viewed through an invisible rectangular aperture, as in Experiment 1, but this time the dots were presented in front of the grating. This stereoscopic display was created with the CrystalEyes Stereoscopic System produced by Stereographics for use with the Silicon Graphics Iris. With these glasses, 5 min arc of disparity was added between the stereoscopic plane of dots and the plane of the gratings. The experimental procedure was identical to that of Experiment 1. Subjects used a mouse device to record whether the grating appeared to translate horizontally. As before, the same four dot and six aperture aspect ratios were used in each of the three conditions. Each subject completed eight practice trials before beginning the experimental trials. All stimuli were viewed binocularly.

Results and discussion

The results, shown in Fig. 7, indicate once again that scene segmentation cues play a critical role in motion integration. In both outlined aperture conditions, subjects nearly always perceived the grating to translate horizontally. Since the dots always translated horizontally, this suggests that subjects had a strong tendency to perceive a coherently translating spotted grating. It appears that the aperture outlines successfully suppressed the grating terminators. When the grating terminators were extrinsic, the unambiguous dot velocities captured the ambiguous grating motion. This is consistent with previous findings that the integration of motion signals across features can be strongly influenced by depth (Shimojo *et al.*, 1989; Lorenceau & Shiffrar, 1992; Vallortigara & Bressan, 1991; Stoner & Albright, 1993). The results also suggest that while disagreement between unambiguous motion signals results in motion segmentation, disagreement between unambiguous and ambiguous motion signals does not cause segmentation. Instead, the unambiguous motion signals capture the ambiguous signals. The results from the stereo condition, also shown in Fig. 7, indicate that subjects in this condition never perceived the grating to translate horizontally. This suggests that observers do not disambiguate motion with unambiguous velocities available in different depth planes.

When the data from the outlined aperture conditions are compared with those from the invisible apertures used in Experiments 1 and 2, the differences are striking. When gratings were viewed through invisible apertures, the dots only captured a grating when 40% or more of the grating's terminators translated in the same direction as the dots. In contrast, when gratings were viewed through outlined apertures, thereby suppressing terminator motion, the dots almost always captured the grating. For example, in the outlined parallelogram condition, subjects perceived a coherent spotted grating even when all of the grating terminators translated in a different direction from the dots. This finding suggests one reason why dots are unable to capture a grating when viewed through an invisible, narrow aperture. The visual system may be unable to fully suppress the conflicting terminator velocities. When the number of conflicting terminators is relatively large, their residual effects may be combined to cause segmentation.

GENERAL DISCUSSION

The interpretation of object motion is difficult because local velocity measurements are often ambiguous. One way the visual system may overcome this difficulty is by relying on the unambiguous motion signals available in an image. Contours having a high degree of curvature, such as corners, intrinsic terminators, and dots, produce unambiguous velocity measurements. The visual system may determine object motion by heavily weighting motion measurements from contour discontinuities. The purpose of this set of experiments was to determine how such a process might occur. We investigated how observers interpret multi-featured images containing motion signals of varying degrees of ambiguity. Our stimuli consisted of spotted gratings viewed through a single aperture of different shapes. Subjects became increasingly likely to interpret the grating as translating horizontally with the dots as the percentage of intrinsic terminator velocities having the same direction and same depth increased. These results suggest that if locally unambiguous velocities differ, then those velocities are segmented and assigned to different objects. Locally ambiguous signals are captured by nearby unambiguous velocities. This finding has important implications for motion experiments using plaid stimuli. If the nodes created at the grating intersections in a plaid stimulus are treated as contour discontinuities that provide unambiguous motion signals, then the nodes themselves may play a pivotal role in the interpretation of the plaid's motion.

The proposal that the visual system relies on some motion signals more than others is not new. For

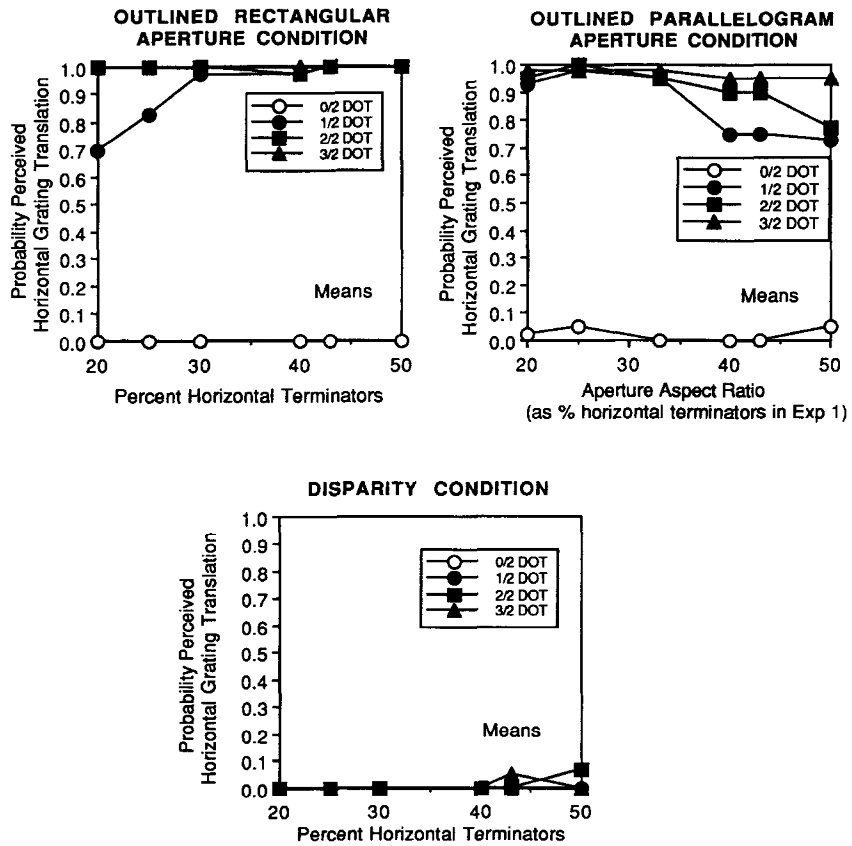

FIGURE 7. The mean results of the outlined rectangular aperture, outlined parallelogram aperture and stereo conditions of Experiment 4.

example, when interpreting the motion of a translating bar, the visual system often uses the velocity of the bar's terminators to interpret the motion of the entire bar (Wallach, 1935). At sufficiently long durations and high contrasts, terminator velocity completely dominates the interpretation of a bar's motion (Castet *et al.*, 1993; Lorenceau *et al.*, 1993). Similarly, we have demonstrated that when integrating motion signals across disconnected but nearby image features, under some conditions the visual system appears to rely on some motion signals to the near exclusion of others.

The results of these studies may shed some light on how the visual system satisfies the apparently conflicting requirements of motion integration and segmentation (Braddick, 1993; Stoner & Albright, 1993). Debates regarding whether the visual system uses an IOC or a vector average motion analysis sometime assume that every velocity estimate within a receptive field enters equally into the integration process. Such an assumption does not take into consideration the possibility that images of multiple objects may fall within the same receptive field. Our results suggest that some percentage of unambiguous velocity estimates from different features must be consistent before observers interpret multi-featured images coherently. It may be that a clustering of common motion directions, or common fate, implies that the signals come from the same object and therefore should be grouped together. Conflicting unambiguous velocity measurements may indicate that more than one object is present in the visual field and that therefore, motion integration should be consistent with the presence of multiple objects. Indeed, using random dot stimuli, Newsome and Pare (1988) found that coherent dot motion could be detected when as few as 5% of the dots in their display translated in the same direction. Distance also appears to play a critical role in determining whether moving random dot patterns are interpreted coherently (Nawrot & Sekuler, 1990). The present results suggest that the critical role of velocity similarity extends to motion integration across differing image features. Locally unambiguous velocity estimates could be identified by specific discontinuity detectors such as end stopped cells (Hubel & Wiesel, 1968; Versavel, Orban & Lagae, 1990), dot-responsive cells (Saito, Tanaka, Fukada & Oyamada, 1988) and contour cells (von der Heydt & Peterhans, 1989; Peterhans & von der Heydt, 1989). This approach has been successfully implemented in a computational model of area MT (Nowland & Sejnowski, 1994) in which motion integration depends explicitly on the ambiguity of local velocity estimates.

In summary, studies of motion integration have traditionally used either random dot or grating stimuli. In an attempt to understand how the visual system analyzes more complex, multiple feature visual images, we examined the perception of dynamic dotted gratings. We asked how the visual system interprets images containing multiple ambiguous and unambiguous velocity estimates. Our subjects were more likely to interpret a grating's direction of translation in terms of unambiguous, non-overlapping dot velocities when more of the grating's intrinsic terminators translated in the same direction as the dots. This cross-feature coherence was enhanced when occlusion cues were used to minimize the disambiguating influence of the grating terminators. These results suggest that while the visual system may rely on unambiguous velocities, there must be sufficient directional similarity across unambiguous velocity estimates before motion integration proceeds across different image features.

REFERENCES

Adelson, E. & Movshon, J. A. (1982). Phenomenal coherence of moving visual patterns. *Nature*, *300*, 523–525.

Adelson, E. & Movshon, J. A. (1983). The perception of coherent motion in two-dimensional patterns. *Proceedings of the ACM Siggraph Interdisciplinary Workshop on Motion: Representation and Perception*, Toronto, 11–16.

Braddick, O. (1993). Segmentation versus integration in visual motion processing. *Trends in Neuroscience*, *16*, 263–268.

Castet, E., Lorenceau, J., Shiffrar, M. & Bonnet, C. (1993). Perceived speed of moving lines depends on orientation, length, speed and luminance. *Vision Research*, *33*, 1921–1936.

Derrington, A. M., Badcock, D. R. & Henning (1993). Discriminating the direction of second-order motion at short stimulus durations. *Vision Research*, *33*, 1785–1794.

Gilchrist, A. (1977). Perceived lightness depends on perceived spatial arrangement. *Science*, *195*, 185–187.

von der Heydt, R. & Peterhans, E. (1989). Mechanisms of contour perception in monkey visual cortex. I. Lines of pattern discontinuity. *Journal of Neuroscience*, *9*, 1731–1748.

Hildreth, E. (1984). *The measurement of visual motion*. Cambridge, Mass.: MIT Press.

Hubel, D. & Wiesel, T. (1968). Receptive fields and functional architecture of the monkey striate cortex. *Journal of Physiology*, *195*, 215–243.

Kanizsa, G. (1979). *Organization in vision. Essays on Gestalt psychology*. New York: Praeger.

Lorenceau, J. & Shiffrar, M. (1992). The role of terminators in motion integration across contours. *Vision Research*, *32*, 263–273.

Lorenceau, J., Shiffrar, M., Wells, N. & Castet, E. (1993). Different motion sensitive units are involved in recovering the direction of moving lines. *Vision Research*, *33*, 1207–1218.

Mingolla, E., Todd, J. & Norman, J. F. (1992). The perception of globally coherent motion. *Vision Research*, *32*, 1015–1031.

Movshon, J., Adelson, E., Gizzi, M. & Newsome, W. (1985). The analysis of moving visual patterns. In Chagas, C., Gattass, R. & Gross, C. (Eds), *Pattern recognition mechanisms* (pp. 117–151). New York: Springer.

Nakayama, K. & Silverman, G. (1988). The aperture problem—II. Spatial integration of velocity information along contours. *Vision Research*, *28*, 747–753.

Nawrot, M. & Sekuler, R. (1990). Assimilation and contrast in motion perception: explorations in cooperativity. *Vision Research*, *30*, 1439–1451.

Newsome, W. & Pare, E. (1988). A selective impairment of motion processing following lesions of the middle temporal visual area (MT). *Journal of Neuroscience*, *8*, 2201–2211.

Nowland, S. & Sejnowski, T. (1995). A selection model for motion processing in area MT of primates. *Journal of Neuroscience*. In press.

Peterhans, E. & von der Heydt, R. (1989). Mechanisms of contour perception in monkey visual cortex. II. Contours bridging gaps. *Journal of Neuroscience*, *9*, 1749–1763.

Ramachandran, V. S. (1990). Visual perception in people and machines. In Blake, A. & Troscianko, T. (Eds), *AI and the eye*. London: Wiley.

Rock, I. (1975). *An introduction to perception* (pp. 231-234). New York: Macmillan.

Rock, I. (1983). *The logic of perception* (pp. 119–120). Cambridge, Mass.: MIT Press.

Rubin, N. & Hochstein, S. (1993). Isolating the effect of one-dimensional motion signals on the perceived direction of two-dimensional objects. *Vision Research*, *33*, 1385–1396.

Saito, H., Tanaka, K., Fukada, Y. & Oyamada, H. (1988). Analysis of discontinuity in visual contours in area 19 of the cat. *Journal of Neuroscience*, *8*, 1131–1143.

Shiffrar, M. & Pavel, M. (1991). Percepts of rigid motion within and across apertures. *Journal of Experimental Psychology: Human Perception and Performance*, *17*, 749–761.

Shimojo, S., Silverman, G. & Nakayama, K. (1989). Occlusion and the solution to the aperture problem for motion. *Vision Research*, *29*, 619–626.

Stoner, G. & Albright, T. (1993). Image segmentation cues in motion processing: Implications for modularity in vision. *Journal of Cognitive Neuroscience*, *5*, 129–149.

Vallortigara, G. & Bressan, P. (1991). Occlusion and the perception of coherent motion. *Vision Research*, *31*, 1967–1978.

Versavel, M., Orban, G. & Lagae, L. (1990). Responses of visual cortical neurons to curved stimuli and chevrons. *Vision Research*, *30*, 235–248.

Wallach, H. (1935). Uber visuell wahrgenommene Bewegungsrichtung. *Psychologische Forschung*, *20*, 325–380.

Wallach, H. (1976). On perceived identity: I. The direction of motion of straight lines. In Wallach, H. (Ed.), *On perception* (pp. 201–216). New York: Quadrangle, The New York Times Book Co.

Wilson, H., Ferrera, V. & Yo, C. (1992). A psychophysically motivated model for two-dimensional motion perception. *Visual Neuroscience*, *9*, 79–97.

Yo, C. & Wilson, H. (1992). Perceived direction of moving two-dimensional patterns depends on duration, contrast and eccentricity. *Vision Research*, *32*, 135–147.

Acknowledgements—This research was supported by NSF grant INT-9216895 and NIH grant EY09931.