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Identifying contours from occlusion events

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Surface contours specified by occlusion events that varied in density, velocity, and type of motion (rotation or translation) were examined in four experiments. As a fourth experimental factor, there were both figure-motion trials (the occluding surface moved over a stationary background) and background-motion trials (the background moved behind a stationary surface) in each experiment. Displays contained line patterns and rotary motion (Experiment 1), line patterns and translatory motion (Experiment 2), textured surfaces and rotary motion (Experiment 3), and textured surfaces and translatory motion (Experiment 4). Results indicate that contour identifications are more accurate with translation than with rotation, and that background-motion trials are generally easier than figure-motion trials. Although density in all experiments affected identifications in both background- and figure-motion trials, velocity did so in Experiment 4 only. In Experiments 1, 2, and 3, velocity affected identifications in background-motion trials but not in figure-motion trials. In Experiments 3 and 4, the rate of accretion and deletion of texture was a poor predictor of identification accuracy. These results are not consistent with previous accounts of contour perception from occlusion events, and may reflect an involvement of ocular pursuit as a mechanism for registering contour information.

Occlusion events are surface projective transformations caused by the co-occurrence of occlusion and motion. Consider two opaque surfaces. We use the term *occlusion* when one of the surfaces hides part of the other from view. Occlusion *events* occur when motion is added to this state of affairs, either because the viewpoint moves or because the surfaces move. Thus, occlusion events may be characterized as motion transformations in which occluded surfaces are progressively revealed or hidden (Gibson, 1979, pp. 78-79).

Vision scientists have long known that occlusion events can signal to viewers the presence of occluding surfaces and contours. In a phenomenon known as the screen effect (Sampaio, 1943), the transformations of a disk translating horizontally are sufficient to induce a phenomenal occluding surface (the "screen" under which the disk gradually disappears). Appropriate transformations of solid-color, untextured surfaces can induce figures outside the luminance domain, or kinetic illusory figures (Kellman & Cohen, 1984; Kellman & Loukides, 1987; Petry & Meyer, 1987). A different type of transformation, accretion and deletion of texture, has been investigated as a determiner of surface order in depth and of the two-dimensional contour of the occluding surface (Andersen & Braunstein, 1983; Gibson, Kaplan, Reynolds, & Wheeler, 1969; Gibson & Kaushall, 1973; Kaplan, 1969; Yonas, Craton, & Thompson, 1987). Thus, classic and recent demonstrations concur in suggesting that occlusion events can be a powerful source of information about surface contour.

Despite the abundance of such demonstrations, there has been surprisingly little speculation concerning the basis of contour perception from occlusion events. According to one hypothesis, the relevant variable may be the rate of accretion and deletion, that is, the number of texture elements being covered and revealed per unit of time (Kaplan, 1969). However, it has recently been shown that accretion and deletion is not necessary for determining the depth order of surfaces from relative motions of texture (Yonas et al., 1987), and that displays with identical rates of accretion and deletion are *not* equally informative about surface contours (Andersen & Cortese, 1989). Moreover, an account of occlusion events based solely on accretion and deletion cannot explain occlusion phenomena involving solid-color surfaces, such as the screen effect (Sampaio, 1943).

According to a more comprehensive account, contours are extracted from occlusion events by processes that relate discontinuities in space or time, or both (Kellman & Loukides, 1987), spatial discontinuities being loci where contour functions are not differentiable, and temporal discontinuities being projective transformations that violate projective identity. Consider, however, an illusory square over four black disks. With regard to perceived contours, moving the square or moving the disks should be irrele-

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vant because if relative motion is identical, then the two kinds of manipulation produce identical projective transformations. But if the disks are rotated behind the stationary figure, viewers report a square; if the square rotates over the stationary disks, viewers report a shrinking and expanding figure (Meyer & Dougherty, 1987). Similarly, if a line pattern is rotated behind a stationary illusory triangle, a triangle is seen; if the triangle is rotated over stationary lines, viewers see a deforming blob (Bruno, 1989). What causes the asymmetry is still unclear, although some speculations have been offered (Bruno & Gerbino, in press; Shiffrar & Pavel, 1990). Taken together, these findings make existing speculations about occlusion events unsatisfactory, or at least problematic.

One of the reasons for the lack of theorizing on occlusion events may well be the scarcity of parametric data. In the only study presently available, Andersen and Cortese (1989) varied texture density and velocity, and asked observers to discriminate between four occluding contours: a star, a diamond, a square, and a circle. Density and velocity proved to be excellent predictors of identification rates, but accretion and deletion did not (Andersen & Cortese, 1989). Taking this result as a starting point, we performed a series of experiments to compare the effects of textured versus untextured (line pattern) displays, of figure versus background as motion carriers, and of translation versus rotation as motion types.

The purpose of the first of these comparisons was to assess the role of the background pattern. Andersen and Cortese (1989) looked at textured surfaces, but observers can retrieve contour information from other kinds of display as well, as shown by the many demonstrations cited above. The comparison between textured and untextured patterns is decisive regarding the role of accretion and deletion, and provides data that could be useful for identifying the motion processes involved. In particular, finding that the same parameters are relevant in the two conditions would probably indicate that the mechanisms involved do not operate on individual texture elements, but treat global texture transformations as essentially analogous to global transformations of solid forms.

The second comparison investigated the type of motion. Andersen and Cortese (1989) translated textures behind stationary figures. However, moving a background behind a stationary figure can be very different from moving a figure over a stationary background (Bruno, 1989; Meyer & Dougherty, 1987). Because of the theoretical relevance of this asymmetry, it is important to determine whether the same factors determine contour identifications in the two cases.

Finally, a third important issue concerns the role of eye movements as a source of information for motion perception. Essentially all demonstrations of occlusion events have concentrated on translatory motions, a condition in which the eyes can easily track a moving figure. Such tracking might constitute a way to obtain information about observer-relative displacements (Wallach, 1982). Alternatively, eye movements could serve as a cue to the motion of a figure that is not fully specified in the luminance domain, as seems to be the case in anorthoscopic perception (Rock, Halper, DiVita, & Wheeler, 1987). These kinematic components could have a role in assessing relative motions and surface depth order (Yonas et al., 1987), or in solving motion ambiguities associated with occlusion (Shiffrar & Pavel, 1990). Given that eye torsions around the sagittal plane cannot exceed a few degrees (Hallet, 1986), tracking of rotating targets is necessarily more difficult and limited in range than tracking of translating targets. Thus, to assess the role of tracking, we compared performance in translation displays with performance in rotation displays.

EXPERIMENT 1

The purpose of Experiment 1 was to assess contour identifications from occlusion events involving untextured patterns and rotary motion. We computed motion sequences simulating line patterns occluded by either a rectilinear-edge or a sinusoidal-edge figure that had the same color as the background. We chose line patterns, instead of solid-color forms, so that the only cues as to the shape of the occluder would be those provided by the occlusive transformations of the lines. Observers viewed each sequence once and had to decide whether the occluding figure had a rectilinear or a slightly sinusoidal edge. We examined three variables: line density, velocity of rotation, and rotation condition (whether the figure rotated over stationary lines or the lines rotated behind the stationary figure). Given previous reports of asymmetries between figure rotation and background rotation in illusory figure displays (Bruno, 1989; Meyer & Dougherty, 1987), we expected background rotation to produce more accurate identifications of the occluding contours.

Method

Observers. Four observers participated—the authors and 2 volunteers who were graduate students of the University of Padua and were naive as to the purpose of the study. All had normal or corrected-to-normal vision.

Displays. The displays simulated radial patterns of black lines occluded by either a regular square with rectilinear edges or a square-like figure that had sinusoidally curved edges. Both figures had the same area and were drawn in the same color as the background, which was white (Figure 1). The occluding figures were 3.5 cm in both dimensions. Curved edges consisted of a complete cycle of a sinusoid with an amplitude approximately equal to 3 mm. The circle defined by the outside line endings was 8 cm in diameter. Each motion sequence was presented for 10 sec.

Apparatus. Displays were computed and shown on a Mac IIx computer equipped with an Apple High-Resolution RGB monitor. This monitor has a refresh rate of 35 kHz horizontally and 66.7 Hz vertically, and a resolution of 640 × 480 pixels. As a reminder for the observers, a drawing of the two kinds of occluding figures was pasted on the wall behind the monitor.

Design and Procedure. Five displays, which contained 4, 6, 8, 10, and 12 equally spaced lines, were examined. When set in motion, these displays caused 1, 1.5, 2, 2.5, or 3 line terminators to be present, on the average, on each side of the occluding figure. Rotation rates were .25 and .75 rev/sec, with both of which rotary motion is smooth and easily perceived. In the area relating to occlusion and disocclusion, linear velocities resulting from these rotation rates were, on the average, 8.3 and 25.5 cm/sec. Motion sequences were computed in order to simulate either occlusion of stationary lines behind a rotating figure (figure-rotation condition) or occlusion of rotating lines behind a stationary figure (background-rotation condition). When the figure was stationary, its orientation was chosen at random before the beginning of the trial. The combination of 5 densities, 2 velocities, 2 types of occluding figure, and 2 rotation conditions yielded 40 different motion sequences. These were completely randomized and presented in sequence in one experimental block. Each observer saw 10 blocks, for a total of 400 presentations.

The observers sat at a distance of approximately 50 cm from the monitor. Before beginning the actual experiment, they were instructed regarding the difference between the two kinds of occluding contour and given a few practice trials. After each 10-sec experimental presentation, they were prompted for the response, which they registered by pressing either the "s" (for straight) or "c" (for curved) keys on the computer keyboard. Each response started the

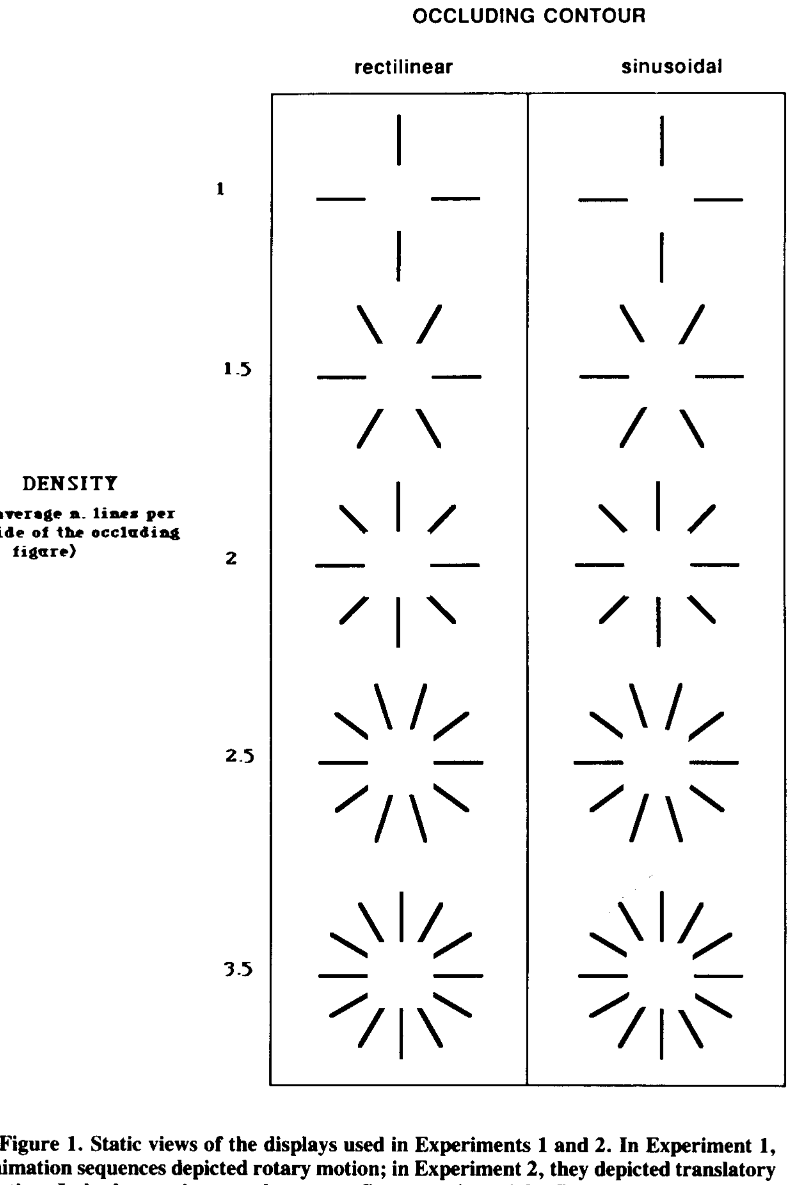

Figure 1. Static views of the displays used in Experiments 1 and 2. In Experiment 1, animation sequences depicted rotary motion; in Experiment 2, they depicted translatory motion. In both experiments, there were figure-motion trials (figures rotated or translated over stationary backgrounds) and background-motion trials (backgrounds rotated or translated behind stationary figures). Slightly thicker diagonal lines are caused by the software used to laser-print the picture. On the computer screen, these lines were as thick as the others, but jagged due to aliasing. However, aliasing was barely noticeable at a distance of 1 m.

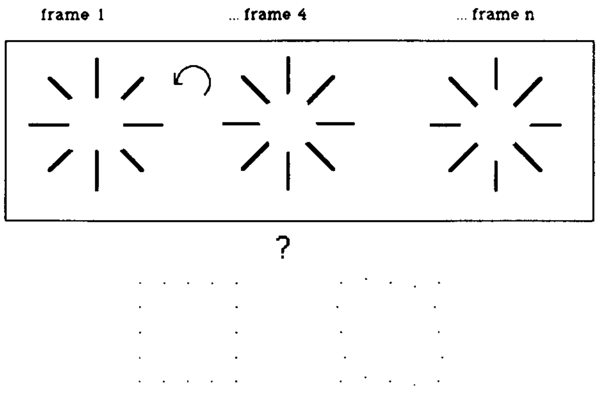

Figure 2. General procedure. Observers were shown a 10-sec motion sequence that simulated a rectilinear- or sinusoidal-contour figure occluding a line pattern (Experiments 1 and 2) or a random texture (Experiments 3 and 4). After viewing the sequence, the observers had to decide which figure had been presented. The example illustrates three frames from a figure-motion trial in Experiment 1.

computations for the following trial. There was a 15-sec interval between presentations. A beep was used to signal the next trial. (See also Figure 2.)

Results and Discussion

Each observer contributed 20 scores, each of which corresponded to the percentage of correct identifications in one cell, with rectilinear and sinusoidal edges collapsed. Here and in the following experiments, we decided, for two reasons, not to consider the comparison between types of occluder: We wanted to avoid many-way interactions, which are hard to interpret, and we felt that the comparison of occluders was not relevant to the issue under investigation. This may not be the case with all types of occluding figures. It has been speculated, for instance, that figure orientation affects the availability of a useful motion component (Andersen & Cortese, 1989). In that event, a comparison of different types of figures might be informative regarding the role of such a component. Within our two types of figure, however, orientation changes were essentially equivalent, and overall orientations relative to the background were completely randomized. Thus, a comparison between our two types of figure would probably not be informative.

Furthermore, although a bias for the response "sinusoidal" was apparent in some of the conditions, closer inspection of the individual data showed that a systematic bias occurred only for some figure-rotation displays. This is consistent with previous reports indicating that figure rotation can easily produce an illusion of nonrigidity (Bruno, 1989), and suggests that preferences for the "sinusoidal" response were not genuine individual biases but a direct consequence of the phenomenon under study. Because the rotating figure could be seen as deforming, its edge was seen more easily as curved, or sinusoidal. For instance, the observers reported that displays with four lines looked like a pulsating figure, those with six lines, somewhat like an amoeba deforming cyclically, and so on. It is difficult to determine, at present, whether such nonrigid contours should be kept distinguished from merely incomplete, but rigid, contours perceivable in most background-motion displays. Bruno and Gerbino (in press) investigated the determinants of the illusion of nonrigidity. According to their analysis, nonrigid contours result from lack of adequate kinematic information about the occluding edge, and therefore should be regarded as qualitatively different from incomplete contours, where adequate information is present but weak. Suppose that a velocity of .75 rev/sec is necessary for the optimal background-motion identification of a contour with two lines per side of the occluding figure. At lower velocities, background-motion identification will still be possible, but observers will be more likely to commit errors because the relevant information is less salient. In corresponding figure-motion displays, on the other hand, observers will commit errors for a different reason, namely, because there is *no* kinematic information to specify the edge. A specific prediction deriving from this analysis is that figure-motion identifications should be no better than identifications in static stimuli. Preliminary results support this prediction for the displays used in Experiment 1.[1] However, the present experiments were not specifically designed to test the above proposal; they were designed to assess only the ability to identify contours from occlusion events. Therefore, in the remainder of this paper the distinction between the two possible sources of mistaken identifications will not be addressed.

Data were analyzed in two steps. First, results from each observer were intercorrelated to check for observer consistency. Correlations were high between the authors [$r(18) = .69$, $p < .005$] and between each author and each naive observer [$.45 < r(18) < .69$, all ps $< .05$ or better]. The correlation between the two naive observers was less satisfactory [$r(18) = .38$, $.05 < p < .1$]. The average correlation between all observers was .573 ($p < .005$). Next, the percentages were entered in a $5 \times 2 \times 2$ analysis of variance (ANOVA) (density $\times$ velocity $\times$ type of rotation) with repeated measures on all factors. Percentages of correct identifications, averaged across observers, are graphed in Figure 3. Observers were more accurate in the background-rotation condition (on the average, 74.1% correct responses) than in the figure-rotation condition (62.4% correct responses). This difference approximated significance [$F(1,3) = 9.3$, $p = .056$]. Observer accuracy improved with line density (on the average, 53.8%, 62.8%, 66.3%, 76.9%, and 81.6% correct responses for 4, 6, 8, 10, and 12 lines, respectively). This effect of line density was also significant [$F(4,12) = 15$, $p < .001$]. Finally, accuracy improved with velocity in the background-rotation condition (79.8% correct responses at .75 rev/sec vs. 68.5% at .25 rev/sec), but not in the figure-rotation condition (61.8% correct responses at .75 rev/sec vs. 63% at .25 rev/sec). This asymmetry yielded a significant rotation condition $\times$ ve-

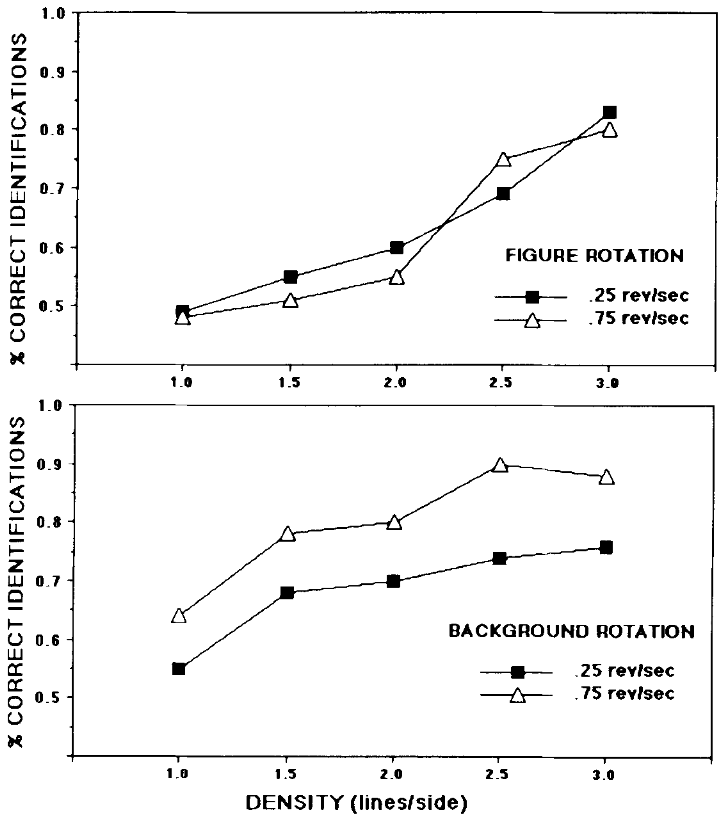

Figure 3. Effects of density, velocity, and motion type in Experiment 1 (line patterns, rotary motion). Observers were generally more accurate in background-motion trials. Density affected identification rates in both the figure-motion and the background-motion trials, whereas velocity affected identification only in background-motion trials.

locity interaction [$F(1,3) = 12, p = .04$]. The overall effect of velocity, the remaining two-way interactions, and the three-way interaction were not significant [velocity, $F(1,3) = 3$, $p = .178$; rotation condition × density, $F(4,12) = 2.4$, $p = .106$; density × velocity, $F(4,12) < 1$; rotation condition × density × velocity, $F(4,12) < 1$].

These results suggest that the illusion of nonrigidity observed when stimulus displays simulate continuous occlusion by a rotating figure (Bruno, 1989; Bruno & Gerbino, in press; Meyer & Dougherty, 1987) has a functional counterpart in the ability to use these motion displays to extract contour information. The effect manifests itself in two ways: by producing overall greater accuracy in the background-rotation displays than in the figure-rotation displays, and by producing greater accuracy with faster rotating backgrounds but not with faster rotating figures. It is as if contour information in the figure-rotation condition was a function only of the spatial parameter, density, whereas information in the background-rotation condition was a function of both density and the temporal parameter, velocity. Two implications of the present finding are already worth mentioning. First, discontinuity theory (Kellman & Loukides, 1987) cannot account for the greater accuracy in the background-rotation condition, because spatial and temporal discontinuities, however defined, must be identical in the two types of rotation. Second, previous findings of density and velocity effects in discrete occlusion displays (Andersen & Cortese, 1989) do generalize to continuous occlusion. However, an important, and so far neglected, difference exists between occlusion by a rotating figure over a stationary background and occlusion by a stationary figure over a rotating background. Should this difference generalize to translation and textured displays, it would force us to conclude that previous accounts of occlusion events are at least incomplete and probably need reconsideration.

EXPERIMENT 2

The purpose of Experiment 2 was to determine whether the results obtained with untextured displays and rotary motion generalize to horizontal translatory motion. There are several reasons why translation and rotation might behave differently. When a figure rotates, each point on the figure moves at a different linear velocity, depending on the distance of that point from the center of rotation. When a figure translates, on the other hand, each point on the figure moves with the same linear velocity. Thus, in translation displays all points share a "common motion" component which is lacking in rotation, and may be important for the extraction of contour information. Moreover, because the eye cannot rotate around the sagittal axis, rotation makes full tracking of the figure impossible. If ocular movements play some role in occlusion events, then results obtained from translatory displays might differ from those obtained from rotary displays. We used the same displays and the same task as in Experiment 1. However, figure or background this time translated back and forth horizontally instead of rotating.

Method

Observers. Four observers participated—the authors and 2 Cornell University undergraduates who participated in the experiment as a requirement for a summer perception course and who were naive regarding the purpose of the study. All had normal or corrected-to-normal vision.

Displays, Apparatus, Design, and Procedure. The displays were the same as those used in Experiment 1, and they were displayed on the same apparatus. However, for the part of the experiment that was run at Cornell, a Macintosh Plus computer was used instead of a Mac II. Hardware differences were compensated for by adjusting the parameters of the animation. Again, five displays, containing 4, 6, 8, 10, and 12 equally spaced lines, were examined. Translation velocities were .66 and 3.5 cm/sec, with both of which motion is smooth and easily perceived. The extent of translation was approximately equal to one-sixth of the total length of the display, or 1.33 cm.

As in Experiment 1, motion sequences were computed in order to simulate either occlusion of stationary lines behind a translating figure (figure-translation condition) or occlusion of translating lines behind a stationary figure (background-translation condition). Figure orientation was chosen at random before the beginning of the trial. The combination of 5 densities, 2 velocities, 2 types of occluding figure, and 2 translation conditions yielded 40 different motion sequences, which were completely randomized and presented in sequence in one experimental block. Each observer saw 10 blocks, totaling 400 presentations.

The procedure was similar to that of Experiment 1. Between presentations, there was an interval of 15 sec when the Mac II was used and an interval of about 45 sec when the Mac Plus was used.

Results and Discussion

The analysis was similar to that of Experiment 1. Individual percentages of correct responses were first collapsed across occluding figures. Next, percentages were intercorrelated to check for consistency among observers. Finally, a 5×2×2 ANOVA (density × velocity × type of translation) was performed.

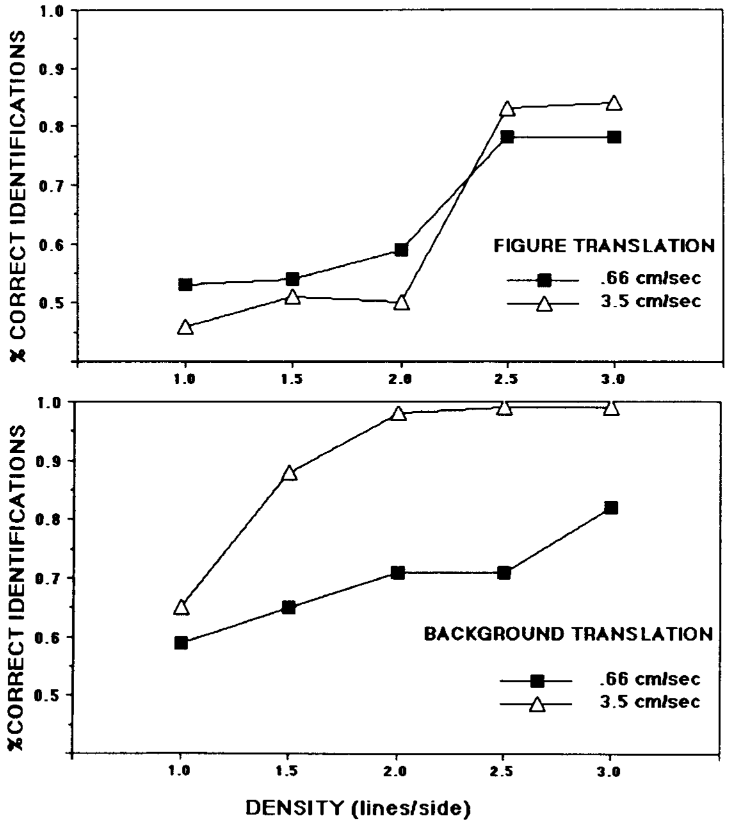

Figure 4. The results of Experiment 2 (line patterns, translatory motion) were identical to those of Experiment 1. Observers were generally more accurate in background-motion trials. Density affected identification rates in both the figure-motion and the background-motion trials, whereas velocity affected identification only in background-motion trials.

Interobserver correlations were extremely high in these conditions, yielding an average correlation of .76 ($p < .005$). The correlation between the authors was practically perfect [$r(18) = .92$, $p < .0001$]. However, all other correlations were also quite high [$.64 < r(18) < .76$, all ps $< .005$]. These correlations suggest that differences in hardware had essentially no influence on the task, and that the task was easier, or at least less noisy, than the similar task that employed rotation. This was also confirmed by the results of the ANOVA, which yielded effects that were similar to, but more clear-cut than those obtained in Experiment 1 (see Figure 4). As in Experiment 1, the observers were more accurate in the background-translation condition than in the figure-translation condition (on the average, 80.6% correct responses vs. 63.4%). This difference yielded a significant effect of translation condition [$F(1,3) = 160.5$, $p = .001$]. Also as in Experiment 1, accuracy increased with line density (on the average, 53.6%, 64.4%, 69.4%, 85%, and 85.6% correct responses for 4, 6, 8, 10, and 12 lines, respectively), yielding a significant effect of density [$F(4,12) = 19$, $p < .001$]. And, also mirroring Experiment 1, velocity improved accuracy in the background-translation condition (on the average, 89.5% correct responses at 3.5 cm/sec vs. 71.8% at .66 cm/sec) but not in the figure-translation condition (62.8% correct responses at 3.5 cm/sec vs. 64% at .66 cm/sec). This yielded a significant translation condition × velocity interaction [$F(1,3) = 23.3$, $p = .017$]. The effects of velocity, the density × velocity interaction, and the three-way interaction were not significant [velocity, $F(1,3) = 4.91$, $p = .113$; density × velocity, $F(4,12) = 1.56$, $p = .248$; translation condition × density × velocity, $F(4,12) = 2.22$, $p = .128$]. In short, the only difference from the previous experiment was a significant translation condition × density interaction [$F(4,12) = 6.18$, $p = .006$].

These results parallel and reinforce those of Experiment 1. Density and velocity are the major determiners of identifications, as found by Andersen and Cortese (1989) with textured displays. Supporting the hypothesis that tracking can help in extracting contour information, a qualitative comparison between the first two experiments indicates less variability (as demonstrated by interobserver correlations) and greater accuracy (overall, 72% vs. 68% correct identifications) with translation displays than with rotation displays. However, the advantage of background-motion displays observed with rotary motion appears to be present also with translatory displays. This result speaks against an involvement of tracking, for it suggests that even if observers can track the figure, they are still less accurate than they would be if the figure were stationary. It could be, however, that figures moving over line patterns are particularly difficult to track. A test of this possibility is offered by the next two experiments, where we replicated Experiments 1 and 2, substituting random textures for line patterns.

EXPERIMENT 3

Experiment 3 replicated Experiment 1. The same three variables were controlled: density, velocity, and type of motion (the figure rotated over a stationary background or the background rotated behind the stationary figure). However, instead of a line pattern, a random-dot texture was placed in the background. There are at least two reasons why textures and lines might behave differently. First, as discussed before, because each individual texture element is occluded in an essentially instantaneous fashion, textured and untextured patterns can yield similar results only if the contour-extracting mechanism operates at a level that is higher than that of the individual elements. Second, kinetic occlusion of a random texture produces accretion and deletion. If accretion and deletion of texture is critical to the identification of contours from occlusion events, then the rate of accretion and deletion should predict performance in this experiment. It is also possible that extra information provided by accretion and deletion could cancel the advantage of background rotation observed in Experiment 1.

Method

Observers. Five observers participated—the authors and three graduate students at the University of Padua, who were volunteers, had not participated in the previous experiments, and were naive regarding the purpose of the study. All observers had normal or corrected-to-normal vision.

Displays. The displays simulated circular, textured surfaces occluded by either a regular square with rectilinear edges or a square-like figure that had sinusoidally curved edges. Dots were 2 pixels both horizontally and vertically and were plotted in black. As before, figures had the same area and were plotted using the same color as the background, which was white (see Figure 5). Because no texture was plotted on the figures, the displays contained static information concerning figure position. Occluding figures were 3.5 cm both horizontally and vertically. The circle defined by the textured area was 8 cm in diameter. Each motion sequence was presented for 10 sec.

Apparatus. The apparatus was the same as that used in Experiment 1.

Design and Procedure. Three displays with densities equal to 2.5, 7.6, and 12.6 dots/cm² were examined. Rotation velocities were equal to those of Experiment 1, .25 and .75 rev/sec. Also analogous to Experiment 1, motion sequences were computed to simulate either occlusion of a stationary texture behind a rotating figure (figure-rotation condition) or occlusion of a rotating texture behind a stationary figure (background-rotation condition). When the figure was stationary, its orientation was chosen at random before the beginning of the trial. The combination of 3 densities, 2 velocities, 2 types of occluding figure, and 2 types of translation yielded 24 different motion sequences, which were completely randomized and presented in sequence in one experimental block. Each observer saw 10 blocks, totaling 240 presentations. The observers sat at a distance of approximately 1 m from the monitor. Before beginning the actual experiment, they were instructed regarding the difference between the two kinds of occluding contour and given a few practice trials. There was a 20-sec interval between trials.

Results and Discussion

Each participant contributed a data set with 12 values, corresponding to the 12 percentages of correct identifi-

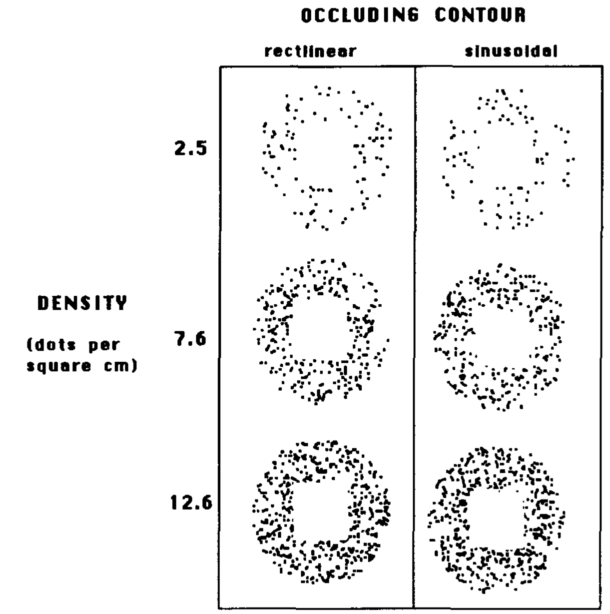

Figure 5. Static views of the displays used for Experiments 3 and 4. In Experiment 3, animation sequences depicted rotary motion; in Experiment 4, they depicted translatory motion. As in Experiments 1 and 2, there were both figure-motion trials (figures rotated or translated over stationary backgrounds) and background-motion trials (backgrounds rotated or translated behind stationary figures).

cations of rectilinear and sinusoidal edges collapsed. As in Experiments 1 and 2, we first correlated individual data sets and then performed a three-way ANOVA. Suggesting that the task was now less straightforward, correlations were lower than in the previous experiment, yielding an average correlation equal to .474 ($p < .05$). Not all individual correlations were reliable [$.126 < r(10) < .59$]. Results from the 3×2×2 (density × velocity × rotation condition) ANOVA, however, closely mirrored those of Experiment 1 (see Figure 6). The observers were more accurate in the background-rotation condition than in the figure-rotation condition (on the average, 66.2% correct responses vs. 58.2%), yielding a significant effect of type of rotation [$F(1,4) = 12.34, p = .025$]. Observer accuracy increased with dot density (on the average, 53.3%, 60.8%, and 72.5% correct responses for 2.5, 7.6, and 12.6 dots/cm^2, respectively), yielding a significant effect of density [$F(2,8) = 10.78, p = .005$]. Finally, observer accuracy increased with velocity in the background-rotation condition (72.3% correct responses at .75 rev/sec vs. 60% at .25 rev/sec) but not in the figure-rotation condition (55.65% correct responses at .75 rev/sec vs. 60.7% at .25 rev/sec). As in Experiment 1, the overall effect of velocity, the remaining two-way interactions, and the three-way interaction were not significant [velocity, $F(1,4) < 1$; type of rotation × density, $F(2,8) = 2.18, p = .398$; density × velocity, $F(2,8) < 1$; type of rotation × density × velocity, $F(2,8) < 1$].

To evaluate the importance of the rate of accretion and deletion as a determiner of contour identifications, we also conducted a regression analysis. To determine accretion and deletion rates, we employed a modification of the formula for accretion and deletion with translatory motion (see Andersen & Cortese, 1989):

$$a/d \text{ rate} = dvh, \tag{1}$$

where d is texture density, v is a linear velocity associated with the event, and h is the height of the rectangular area being covered and revealed by a figure translating horizontally. In order to apply the formula to rotary motion, we reasoned as follows: Consider one of our rectilinear-edge figures (squares) rotating over a textured background. (Because sinusoidal edges are symmetrical about their midpoint, the analysis is equivalent for the other type of occluding figure.) As the square rotates around its center, accretion and deletion occurs where the disk is bounded by the inscribed (radius $= r$) and the circumscribed (radius $= R$) circumferences. Given that the linear velocity of rotating points is a function of eccentricity, we can consider the amount of accretion and deletion within the disk as essentially equivalent to the amount of accretion and deletion within a rectangular area with height $h = R - r$, length = circumference with radius $= r + [(R-r)/2]$, and at linear velocity v = linear velocity of point on circumference with radius $= r + [(R-r)/2]$. By this calculation, texture elements in our displays were accreted and deleted at the rates of 15.6, 47.3, 78.4 dots/sec when rotating at .25 rev/sec, and 47.8, 145.3, 241 dots/sec at .75 rev/sec.

We assessed both the absolute effect of accretion and deletion, as measured by simple linear regression, and the effect of accretion and deletion while controlling for the effects of density and velocity, as measured by multiple regression. If accretion and deletion rate is a major determiner of contour identification, then its simple regression slope or at least its multiple regression slope should be different from zero. Simple regression, however, indicated that accretion and deletion was a very poor predictor of contour identifications ($R = .037$), accounting for only .15% of the variability and yielding a slope that was hopelessly indistinguishable from zero [$F(1,58) = .082, p = .7761$]. The joint effect of accretion and deletion, velocity, and density proved to be a better predictor ($R = .573$), and accounted for 32.8% of the variability. However t tests on regression slopes indicated that only density had a slope that was significantly different from zero [$b = .024$; $t(59) = 5.19, p = .0001, \beta = .598$]. The unimportance of accretion and deletion as a predictor of identifications fits well with the qualitative difference between figure and background rotation. Because accretion and deletion of individual dots is exactly identical in the two types of rotation, accretion and deletion clearly cannot account for the qualitative difference. Thus, our results with rotary displays are wholly consistent with those of Andersen and Cortese (1989), who found that

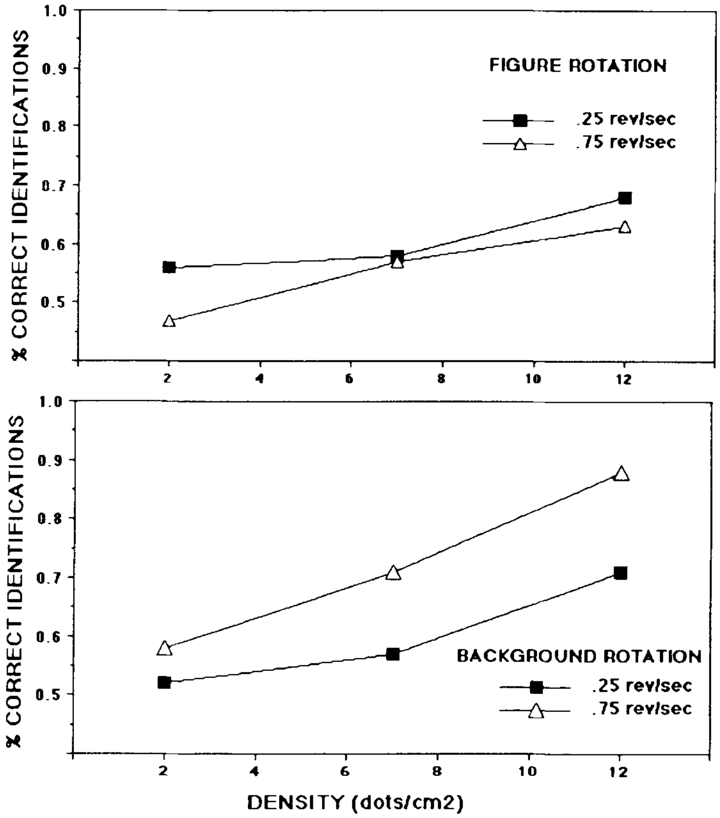

Figure 6. Effects of density, velocity, and motion type in Experiment 3 (textured pattern, rotary motion). Again, density always affected identification rates, but velocity did so only in background-motion trials.

accretion and deletion in translatory displays did not account for contour identifications.

The pattern of these results was essentially equivalent to that of Experiment 1. With rotary motion, contour identifications was a function of two parameters: density of occluded elements and velocity of the event. Velocity, however, was effective only when the background dots rotated. When the dots were stationary and the figure rotated over them, only density counted. Thus, the asymmetry observed in Experiments 1 and 2 generalizes to textured surfaces and rotation. We still needed to know whether these results would generalize to textured surfaces in translatory motion.

EXPERIMENT 4

Experiment 4 replicated Experiment 2. However, instead of a line pattern, a random-dot texture was placed in the background. As in the previous experiments, three variables were controlled: density, velocity, and type of motion (whether the occluding figure translated over a stationary background or the background translated behind a stationary figure). Since the latter translation condition was used by Andersen and Cortese (1989), who also varied density and velocity, the experiment was in part also a replication of their work. Given the previous experiments and Andersen and Cortese's results, we expected density and velocity to determine percentages of identification. Andersen and Cortese did not, however, investigate occlusion of a stationary texture by a moving figure. On the basis of the previous results, it seemed possible that this translation condition would yield different results.

Method

Observers. Five observers participated: one of the authors, M.B., a graduate student at the University of Padua, and three Cornell University undergraduates. The graduate student was a volunteer, whereas the undergraduates participated in fulfillment of a requirement for a summer perception course. All three students were naive as to the purpose of the study. All observers had normal or corrected-to-normal vision.

Displays. The displays were identical to those employed in Experiment 3. However, occlusion events were produced by translatory occlusion events rather than rotary motion. As in the previous experiments, motion sequences lasted 10 sec.

Apparatus. The apparatuses were the same as those used in Experiment 2. A Mac II was used in Padua, and a Mac Plus was used at Cornell.

Design and Procedure. The three displays were the same as those used in Experiment 3, whose densities were equal to 2.5, 7.6, and 12.6 dots/cm². Translation velocities were the same as those used in Experiment 2 at .66 and 3.5 rev/sec. Also analogous to Experiment 2, motion sequences were computed in order to simulate either occlusion of stationary texture behind a translating figure (figure-translation condition) or occlusion of a translating texture behind a stationary figure (background-translation condition). Figure orientation was chosen at random before the beginning of each trial. The combination of 3 densities, 2 velocities, 2 types of occluding figure, and 2 types of translation yielded 24 different motion sequences, which were completely randomized and presented in sequence in one experimental block. Each observer saw 10 blocks, totaling 240 presentations. The observers sat a distance of approximately 1 m from the monitor. Before beginning the actual experiment, they were instructed regarding the difference between the two kinds of occluding contour and given a few practice trials. There was a 20-sec interval between trials.

Results and Discussion

As in Experiment 3, each participant contributed 12 scores, corresponding to the percentage of correct identifications in each cell after collapsing across edge type. To assess observer consistency, first the individual data sets were correlated. Some correlations were low ($.32 < r < .75$), confirming that the task was noisier with textured displays. The average interobserver correlation was .58 ($p < .05$). Next, the data were subjected to a three-way 3×2×2 ANOVA (density × velocity × translation condition), which yielded only two significant effects: the overall effect of density [$F(2,8) = 38.771$, $p < .001$] and the overall effect of velocity [$F(1,4) = 34.6$, $p = .004$] (see Figure 7). Thus, as in all previous experiments, observer accuracy increased with density (53%, 72.75%, and 80% correct identifications at 2.5, 7.6, and 12.6 dots/cm^2, respectively). However, contrary to the previous experiments, velocity affected identifications both in the background-translation condition (75.65% correct identifications at 3.5 cm/sec vs. 61.3% at .66 cm/sec) and in the figure-translation condition (76.65% correct identifications at 3.5 cm/sec vs. 61.3% at .66 cm/sec). Consequently, the translation condition × velocity interaction was no longer significant [$F(1,4) < 1$], and the advantage of translating the background disappeared, yielding almost identical identification rates in the two translation conditions (68.5% for background translation vs. 68.6% for figure translation). The remaining two-way interactions and the three-way interaction were also not significant [translation type × density, $F(2,8) < 1$; density × velocity, $F(2,8) = 1.55, p = .27$; translation type × density × velocity, $F(2,8) = 1.8$, $p = .226$].

The effect of accretion and deletion was assessed as in Experiment 3. For each of our displays, we computed accretion and deletion rates using Equation 1, and used

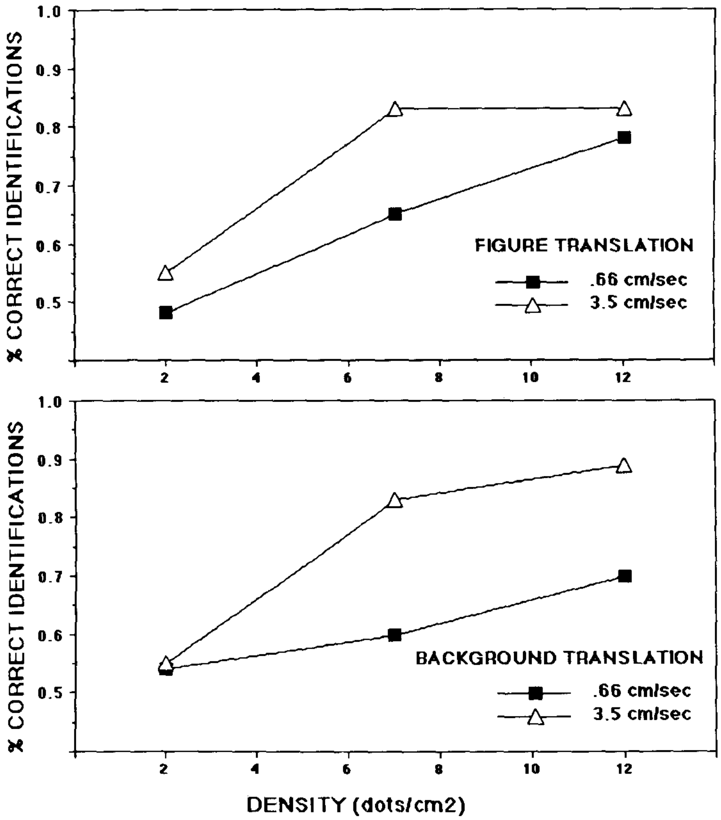

Figure 7. Results from Experiment 4 (textured pattern, translatory motion). In contrast to the previous experiments, velocity, in Experiment 4, affected identification rates in both background-motion and figure-motion trials.

these rates as predictors of contour identifications either alone (simple regression) or in conjunction with density and velocity (multiple regression). On the basis of Andersen and Cortese's (1989) results and on those of our Experiment 3, we expected accretion and deletion to be a negligible determiner of identifications. Computed rates of accretion and deletion were 7, 21.3, 35.3 dots/sec at .66 cm/sec and 37.2, 113, and 187.4 dots/sec at 3.5 cm/sec. Supporting our expectations, simple regression yielded a poor fit (R = .105), which explained only 1.1% of the variability and corresponded to a slope indistinguishable from zero [$F(1,58) = .644, p = .4255$]. Multiple regression yielded a better fit (R = .726), which explained 52.6% of the variance. While controlling for the effects of density and velocity, the slope of accretion and deletion was different from zero [$b = .0007$; $t(59) = 2.43, p = .018$]. However, β coefficients indicated that the effect of accretion and deletion was small relative to that of density (β density = .677, β accretion and deletion = .242) and less important than the effect of velocity (β velocity = .276).

These results confirm that the determinants of contour identification from translatory occlusion events involving textures are density and velocity, as previously found by Andersen and Cortese (1989). However, these results also go one step further, indicating that the asymmetry between figure motion and background motion observed with three kinds of occlusion events (rotary motion with untextured displays, translatory motion with untextured displays, and rotary motion with textured displays) might not apply to translatory motion with textured displays. At least in the study reported here, with translatory motion and textured displays contours could be identified equally well in the two motion conditions.

GENERAL DISCUSSION

The present results indicate that observers use density and velocity information to identify contours from occlusion events. Not all occlusion events, however, are equally effective in providing information useful for identification. At a qualitative level, our results indicate that translatory motion is somewhat more useful than rotation; that the presence of texture in the display is not necessary for accurate identifications; and that a puzzling, and so far neglected, asymmetry exists between background motion trials, where the background moves behind a stationary figure, and figure-motion trials, where the figure moves over a stationary background. At a quantitative level, our results suggest that identifications are a function of two parameters: density of background elements, or patterns, and velocity associated with the event. This finding extends the previous results of Andersen and Cortese (1989), who performed a similar study but examined only textured displays, translatory motion, and background-motion trials.

The results of the present study suggest that very different pictures can emerge in the data if figure-motion trials are used instead of background-motion trials. Especially with rotary events, displays that yield 70% to 80% correct identifications with background motion can drop to chance with figure motion. This puzzling asymmetry is particularly troublesome for two notions that have been connected with the human ability to use occlusion events: the notion of discontinuity (Kellman & Loukides, 1987) and that of accretion and deletion of texture (Kaplan, 1969). According to discontinuity theory, figural contours and illusory figures are extracted from occlusion events by a process that interpolates, or "connects," across discontinuities in either the space or the time domain. Although interpolation does not contrast in principle with facilitations due to increased densities and velocities, it predicts that whenever discontinuities to be interpolated across are identical, the extraction of contours should be equally easy. Our results provide plenty of evidence that this is not the case. First, contour identifications based on the very same line densities vary contingent on the type of motion, translation or rotation, with translation yielding the better identification rates despite the fact that linear velocities were many times higher in the rotary displays. Second, although temporal and spatial discontinuities are identical in the two cases, identifications are more accurate with moving backgrounds than with moving figures. According to the accretion and deletion hypothesis, the more accurate identifications result from the higher rates of accretion and deletion. At least in our studies, however, the conditions that yielded the best identifications resulted from displays that contained changing line patterns rather than from displays that contained accretion and deletion. Moreover, displays with identical rates of accretion and deletion yielded more accurate identifications if the background moved, although only with rotary motion. Finally, regression analyses have indicated that accretion and deletion rate is a poor predictor of identifications with both rotary and translatory displays.

The most interesting finding to emerge from our investigation concerns the role of velocity in signaling contour. It would seem that increasing velocity should imply higher identification rates, but this effect depends critically on the type of motion and on the type of display. When displays contain lines, with both rotation (Experiment 1) and translation (Experiment 2), increasing velocity yields higher identification rates in background-motion trials but not in figure-motion trials. When displays contain texture and rotations (Experiment 3), again velocity is effective in background-motion trials but not in figure-motion trials. But when displays contain texture and translations (Experiment 4), velocity becomes effective in both background-motion *and* figure-motion trials. The latter finding suggests that the background-motion advantage observed in Experiments 1–3 is not just a position constancy effect. Rather, it seems that the figure-motion displays of Experiment 4 offer viewers richer information than do the corresponding displays in Experiments 1–3. We suspect that this surplus of information lies not in the displays per se, but in the opportunity provided for viewers to track the translating figure. This possibility was greatest in the displays of Experiment 4, where the motion was translatory and the position of the figure and its vertices were best signaled by texture elements. A comparison of the texture displays (Figure 5) with the line-pattern displays (Figure 1) should convince the reader of this point. Given that the position information is likely to be crucial for successful tracking, if tracking were involved one would expect the background advantage to disappear when position information was made available. Also supporting this interpretation, recent evidence suggests that visibility of vertices is particularly important for solving motion ambiguities associated with occlusion (Meyer & Dougherty, 1990; Shiffrar & Pavel, 1990).

The idea that eye movements and tracking might be involved in the extraction of contour from occlusion events is not new. It stems from work on a phenomenon related to occlusion, anorthoscopic perception. In anorthoscopic conditions, observers attempt to retrieve the shape of a contour displayed over time through a narrow aperture. Eye movements serve two functions in these viewing conditions. First, they can keep the image of the moving figure stationary with respect to the eye, thereby causing the image of the figure to be painted on the retina over time (Anstis & Atkinson, 1967). Second, they can serve as a cue to the motion of the contour, helping to perceive it veridically (Rock et al., 1987).

Both functions are likely to be involved in our displays as well. If a figure is stationary, as in our background motion trials, and the eye fixates it, then the background moving behind it will trace an outline of the occluding figure on the retina. Provided that the outline is traced out quickly, observers may be able to obtain enough information to identify the occluding contour. In support of this interpretation, background-rotation identifications were better than figure-rotation identifications in our study, presumably because the latter condition lacks the prerequisite of a stable retinal projection of the figure. Also supporting this interpretation, we found better background-motion identifications at higher velocities, that is, when the hypothetical retinal picture was outlined more quickly. Analogously, if the figure moves, as in our figure translation trials, and assuming that the eye can track accurately, then again the retinal projection of the figure will be stationary whereas the background will be retinally displaced, causing an outline of the figure to be painted on the retina. It is doubtful, however, that, in these conditions, the pursuit system would be able to match velocities and changes of direction with a precision sufficient to produce retinal painting (Hallet, 1986). It seems more likely, therefore, that tracking in figure-motion trials serves a different function, that of providing information about figure movement. The figure-movement component, in conjunction with the configural change component provided by the transformation of the occluded background, can be used to extract local motion along the occluding edge, which specifies local contour direction (Bruno & Gerbino, in press). Further experiments are presently in progress on these issues and will be the subject of a future report.

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NOTE

1. Reported in Bruno, N., *Occlusion events and the Perception of Surfaces*, poster presented at the 5th International Conference on Event Perception and Action, Miami University, Oxford, Ohio, June 1989.

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