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Optical tearing in spatiotemporal boundary formation: When do local element motions produce boundaries, form, and global motion?

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Abstract—Perception of continuous boundaries, shape, and global motion can be produced by transformations in local elements separated in both space and time, a process here called spatiotemporal boundary formation (SBF). Prior research has shown that a broad class of element transformations gives rise to SBF. The present work used the transformation of local element displacement to explore the initiating conditions for SBF. Three experiments assessed SBF using a 10-alternative, forced-choice, shape identification task. Experiment 1a showed that large element displacements, but not small ones, produced high accuracy in shape identification. Experiment 1b tested the detectability of the small and large element displacements in an unrelated task, indicating that the results of Experiment 1a were not due to poor detectability for small displacements. Experiment 2 found no variation in SBF performance with changes in viewing distance. Experiment 3 provided evidence that initiating SBF depends on a ratio of element displacement to element separation. These results support an interpretation of SBF as a process geared to detection of object boundaries from spatiotemporal change. Initiating SBF requires transformations in local elements that are classified as spatiotemporal discontinuities (STDs). Small element displacements in a display of a given density do not register as STDs because they are classified as local deformations in an intact, implicit surface connecting visible elements. Complementarity is suggested between element changes which preserve continuity with their neighbors (optic flow) and those comprising spatiotemporal discontinuities (optic tearing). Classification of element transformations as optic flow or tearing may determine whether they provide information about surface form (e.g., through structure-from-motion) or about object boundaries, through SBF.

INTRODUCTION

A basic question in visual perception is how separate objects and surfaces in the world are determined from information in the optic array. The starting point for processes that segment the array and form units must be the locating of significant edges. Although these sometimes depend on straightforward spatial discontinuities in luminance, the general problem of segmentation has turned out to be much more complex. Segmentation can be based on disparity differences in the absence of any other information (Julesz, 1971). It can also be based on certain classes of texture differences between regions (Julesz, 1975). In the latter domain, the work of Bela Julesz has been fundamental in both defining the problem and developing a systematic understanding

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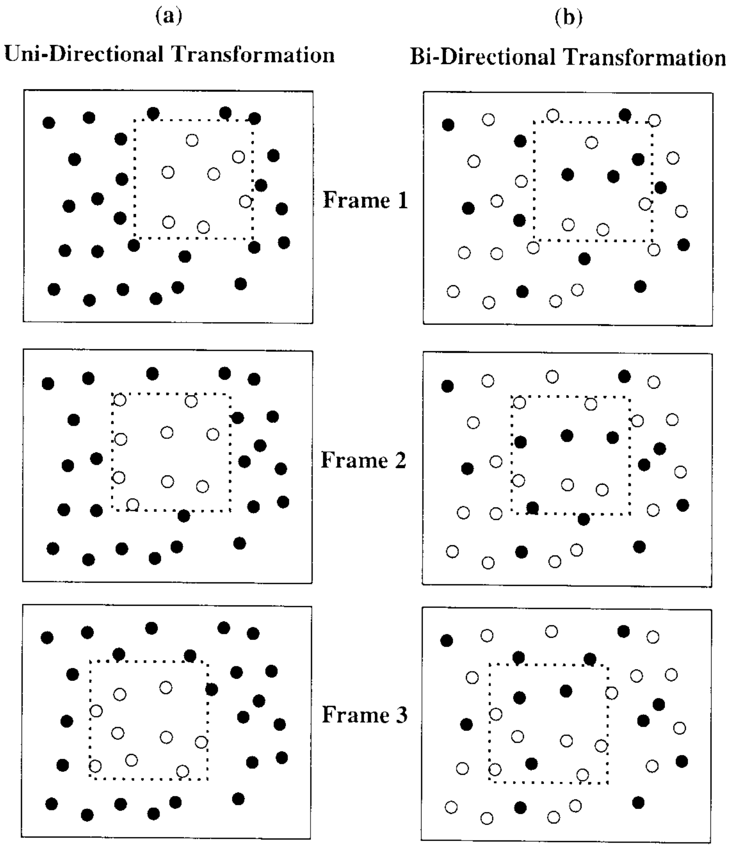

Figure 1. Two types of element transformations. (a) A three-frame sequence of a square region moving over an array of texture elements. Elements within the region change from black to white. Invisible elements, the white elements on a white background, are illustrated with outline circles. This sequence illustrates the unidirectional transformation condition; (b) A sequence illustrating the bidirectional transformation condition. (See text for details.) From Shipley and Kellman (in press).

of the stimulus variables underlying effortless (preattentive) segmentation using texture (Julesz, 1981).

Little of the rigor and precision of Julesz' work on segmentation has yet been applied to the less well understood issue of boundary perception from textural changes over time. Gibson *et al.* (1969) first noted that edges may be defined by temporal changes in texture. When one surface moves relative to a more distant surface, the accretion and deletion of texture on the distant surface defines the boundaries of the nearer surface. An example is shown in Fig. 1a. In that example, boundary information is given by texture changes over time as well as by luminance differences in texture elements inside and outside the boundary. If the moving surface has texture identical to the background, continuous boundaries can be perceived from the accretion and deletion alone (Gibson *et al.*, 1969; Andersen and Cortese, 1989; Stappers, 1989).

Until recently, the information that specified a moving figure was identified with the specific case of accretion and deletion of texture elements, that is, the case where individual texture elements appear at the trailing edge of a surface or disappear at the leading edge. Recently we have argued that accretion and deletion is only one case of a broad class of transformations of texture elements that gives rise to perception of continuous boundaries and shape. This generalization can be introduced with respect to Fig. 1a. The accretion/deletion of elements in Fig. 1a may be conceptualized as a color change of each element that falls within the moving surface. Figure 1a shows a unidirectional color change in which each element goes from black to white upon entering the moving region. This description seems odd physically, because the normal cause of textural disturbance is occlusion, and the background elements do not normally 'enter' the occluding region (except with semi-transparent occluders). In terms of perceptual process, however, the visual system for various reasons may rely on changes occurring in particular visual directions rather than continuous tracking of particular physical elements (Shipley and Kellman, in press).

By conceptualizing Fig. 1a as a case of unidirectional color change, we can easily understand the bidirectional color change illustrated in Fig. 1b. Here, the background and moving region contain randomly arrayed elements of two colors. Whenever an element enters or leaves the moving region, its color value switches to the other value. Such a display has no static spatial differences in luminance, contrast, texture, etc.; moreover, the display does not correspond to any plausible effects of occlusion. Nevertheless, observers perceive continuous boundaries and shape of the moving figure in such displays (Shipley and Kellman, 1991, in press). We refer to the process by which spatially and temporally separated changes in texture elements lead to perception of boundaries as *spatiotemporal boundary formation* or SBF.

The class of transformations producing SBF includes changes in texture element color, orientation, shape and even location. Although perceived surface properties may vary for different transformation types (e.g., changes in color may cause the moving region to appear as a semi-transparent surface), phenomenally continuous, clear edges are produced by all of these transformations. Each transformation may be described as a discontinuous change in some feature over time. We have suggested that such *spatiotemporal discontinuities* (STDs) may serve as the starting point for boundary formation processes occurring from temporally extended information (Kellman and Shipley, 1991; Shipley, 1991; Shipley and Kellman, in press). In the series of experiments presented here, we develop the hypothesis that changes that are classified as continuous (changes that are not STDs) will not produce boundary formation; instead they may appear as changes within a surface. To investigate this hypothesis, we utilize an interesting element transformation previously shown to produce SBF: change in element location, or displacement. In SBF displays based on element displacement, perceived global movement is manifest only by local position changes of elements at the leading and trailing edges. Here the terms *local* and *global* refer to the individual texture elements and the emergent figure defined by the pattern of changes of these individual elements, respectively. An interesting property of these displays is that the direction and velocity of local element motions are not related to the global motion of the moving figure; yet, when a number of elements undergo changes with the appropriate arrangement in space and time, continuous boundaries, overall shape, and global motion of the region are clearly seen (Shipley and Kellman, 1991, in press).

EXPERIMENT 1a

If discontinuous changes in elements are necessary for SBF then large, abrupt, changes in location should result in a moving bounded figure, while small location changes, that might be seen as continuous, may not produce a moving bounded figure. This rationale requires further elaboration. Strictly speaking, when a stationary element abruptly moves, by either a small or large amount, its velocity as a function of time is discontinuous at some instant. To distinguish between changes that are mathematically discontinuous but below threshold and changes that are perceptually discontinuous we will use the term *registered spatiotemporal discontinuities* (RSTD) to refer to the latter changes. The prediction that small displacements may not register as STDs depends on some auxiliary assumptions. One assumption is that arrays of closely spaced texture elements are perceived as connected surfaces (Julesz, 1971). Given that individual elements are taken to be textural markings on a surface, there must be some constraints on how much they can move separately while still preserving connectivity. Non-rigid surfaces can stretch or wrinkle, but at some degree of displacement, they must tear. These considerations of implicit surface formation lead to the prediction that SBF might arise from large displacements, but not small, although perceptible, element motions. It should be stressed that this prediction is not easy to derive on other grounds. In fact there are grounds for the opposite prediction. Studies of SBF implicate a process that uses spatiotemporal relationships to specify precise boundaries and shape (Shipley and Kellman, 1991, in press). For such a process, local motions inconsistent with the global motion might be disruptive, with larger element displacements adding more noise.

In Experiment 1a we tested shape identification accuracy in displays with large and small element displacements. Although the pattern of small displacements may define a moving shape, the boundaries of the shape may not be available perceptually, if the SBF process is not triggered. In that case, shape identification accuracy should be low. We investigated the effect of variations in displacement using a set of displays with a range of spatial density of texture elements.

Method

Subjects. Ten University of Georgia undergraduates served as subjects in 20–30 min individual testing sessions. Subjects participated as partial fulfillment of the requirements of their introductory psychology course.

Apparatus. All stimuli were designed and presented using a Macintosh II computer with an E-Machines TX16, 25 cm high by 33 cm wide, RGB monitor. The screen resolution was 34.25 dots per cm (808 vertical by 1024 horizontal pixels).

Subjects were positioned 150 cm from the monitor. The room was dark except for the illumination provided by the monitor, and a small shielded light (4 W) that illuminated the keyboard so subjects could enter their responses.

Stimuli. The stimuli used for all experiments were similar to the SBF displays developed by Shipley and Kellman (1991, in press). Each display consisted of an array of small elements and a moving shape. All of the elements were white (94.6 cd/m^2) circles on a black (0 cd/m^2) background. The diameter of each element was 0.18 cm (4.12 arcmin visual angle). The moving shape was one of ten

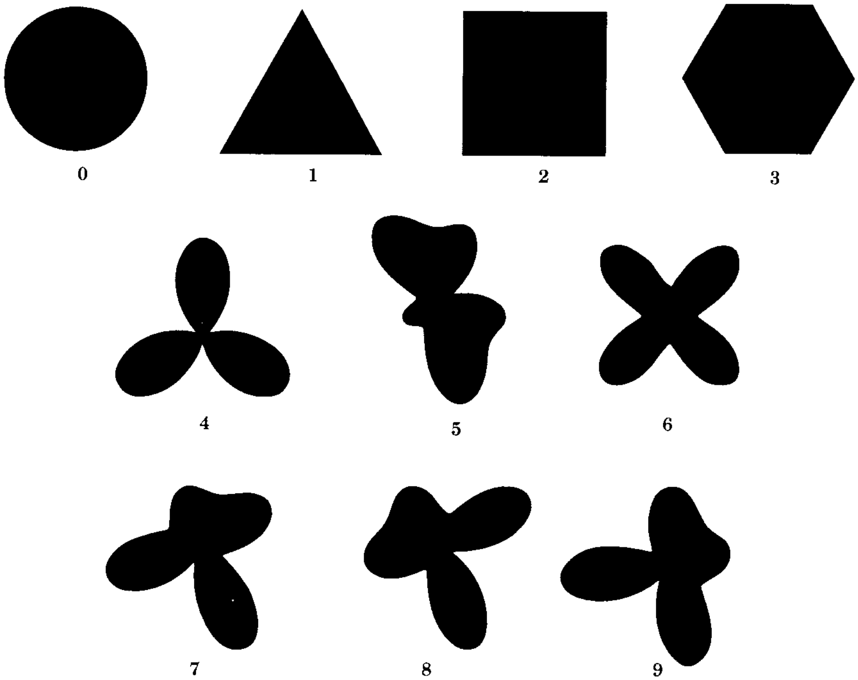

Figure 2. The ten pseudosurfaces used in the 10-alternative forced-choice procedure. From Shipley and Kellman (in press).

possible shapes (see Fig. 2). We referred to these as *pseudosurfaces* to emphasize the fact that these regions are mathematical entities which are not defined in any physical domain. The pseudosurfaces were roughly 30 times the size of the individual elements (e.g., the diameter of the circle was 5.6 cm (2.1 arcdeg)). All of the pseudosurfaces employed in these experiments were circularly monotonic, meaning that any given radian would cross the boundary of the pseudosurface once and only once.

Experiment 1a employed four arrays with 50, 100, 200, or 400 elements. The percent of the field occupied by elements ranged from 0.3% to 2.8%. Elements were distributed pseudorandomly over a 14.6 by 14.6 cm field (visual angle of 5.58 arcdeg). Large areas without elements were avoided by constraining the distribution of elements. The 14.6 cm square field was divided into 100 equal sized subregions and an equal number of elements was placed at random locations within each subregion. When the number of elements was less than 100, a correspondingly smaller number of equal sized subregions was used.

The pseudosurface traveled a circular path with a radius of 3.65 cm (1.39 arcdeg visual angle). The orientation of the pseudosurface did not change as it moved over the array. A circular path was used because all edges of the pseudosurface are perpendicular to the direction of motion along some portion of such a path. This guaranteed that element transformations would occur with equal frequency along the entire boundary of the pseudosurface. A circular path also allowed continuous presentation of the pseudosurface.

Displays were generated by sequentially positioning the pseudosurface at 60 equally spaced points along the circular path (the distance between each point was 0.38 cm or 8.7 arcmin). These 60 frames were used to animate a display. In each frame, any element that was inside the pseudosurface would be positioned above its original position. The initial displacement occurred when the element first fell within the boundaries of the pseudosurface. An element would return to its original position when it was no longer inside the pseudosurface. In all of these experiments an element was defined as inside the pseudosurface if the center of the element was within the pseudosurface. The average number of elements that changed from one frame to the next was: 0.64, 1.35, 2.64, and 5.44 for the 50, 100, 200, and 400 element arrays respectively. In each display one of two suprathreshold displacements was used. In half the displays, elements were displaced 0.06 cm (1.42 arcmin), and in the other half, 0.6 cm (14.2 arcmin). Each display was animated by showing the 60 frames in sequence with each of the frames lasting 33 ms. The inter-frame interval was zero, and the entire cycle lasted 2 s. The cycle was repeated, up to 20 times without a break, so the pseudosurface would appear to circle continuously for 40 s.

In all experiments, display transformations were unidirectional (Shipley and Kellman, in press). In a unidirectional transformation, elements change in exactly the same way along any small section of an edge (Fig. 1a). For the transformation of element displacement, elements were displaced upward along the leading edge of the pseudosurface; they returned to their original locations at the trailing edge.

The two displacement distances crossed with four element densities and 10 pseudosurfaces resulted in 80 displays. Each subject was given a chance to identify the shape of the moving pseudosurface in each of the 80 displays. On each trial the display could last up to 40 s (20 revolutions of the pseudosurface). If the subject indicated that he or she was ready to identify the shape the display would stop at that point.

Procedure. Subjects were presented with the 10-alternative, forced-choice task as follows. They were seated in front of the monitor and given the following instructions:

"This program will display a motion sequence in which you may see a moving figure. Your task is to determine which figure is being presented from this set of ten possible figures (*the subject was given a sheet similar to Fig. 2*). The figure will move around the center of the computer screen. As it circles the screen it will remain upright, so, for example, the top of the triangle will always point upward. You should try to make your decision as quickly as possible. When you think you know which figure is being presented click the mouse button. The display will stop and you will be prompted for the number of the figure corresponding to your choice. The computer will display each sequence for up to 40 s. After 40 s the display will stop, and you will be prompted for your best guess as to which figure was present."

Subjects were then shown a single example of the animation sequence, a triangle circling over 400 elements with large displacements. Subjects were then shown all 80 displays in random order.

Results

Mean accuracy for each display type in Experiment 1a is shown in Fig. 3. With the

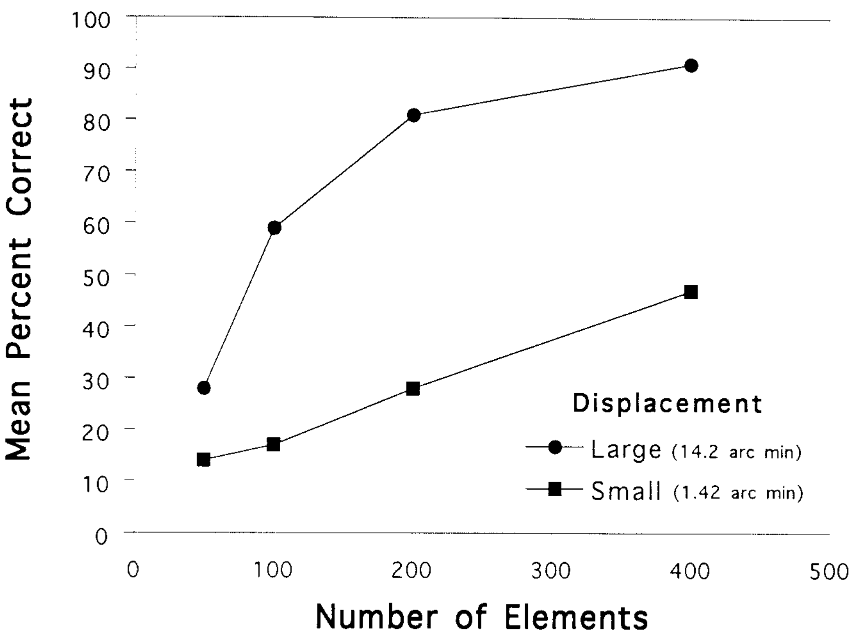

Figure 3. Mean identification accuracy for shapes defined by large (14.2 arcmin) and small (1.42 arcmin) displacements plotted as a function of number of texture elements.

large displacement displays, subjects accurately identified the pseudosurfaces on 64% of trials (chance responding should produce 10% accuracy). However, subjects had a considerably harder time in the small-displacement condition. They correctly identified the shape of the pseudosurface on fewer than 27% of the trials. In fact, for small displacements, accuracy in the 50 element condition was not above chance ($t = 1.17$, $\mathrm{df} = 9$, n.s.), and the accuracy for the 100 element condition was only marginally significant, ($t = 1.77$, $\mathrm{df} = 9$, $p < 0.1$).

To confirm these observations, subjects' accuracy data were subjected to a two-way ANOVA with repeated measures, with size of displacement (large or small) and number of elements as factors. There was a substantial effect of displacement size, $F(1,9) = 102.22$, $p < 0.0001$. There was also a reliable effect of number of elements; accuracy increased as the number of elements in the display increased, $F(3,27) = 69.94$, $p < 0.0001$. The interaction between type of transformation and number of elements was also reliable, $F(3,27) = 16.33$, $p < 0.0001$.

Planned comparisons showed a reliable effect of displacement size at each level of element density (all $F\mathrm{s}(1,27) \geq 11.26$, $\mathrm{p} < 0.003$). There were also significant increases in accuracy with each increase in element density. However, the pattern of increases differed for the two displacement conditions. In the large-displacement condition the largest increases occurred between 50 and 200, whereas, in the small-displacement condition the effect of element density is most clearly seen between 100 and 400 elements. The leveling off in the two conditions may reflect ceiling and floor effects respectively.

Discussion

The extent of element displacement substantially affected SBF, as measured by shape identification accuracy. This is consistent with the hypothesis that SBF is triggered by registered spatiotemporal discontinuities (RSTDs) in local elements, and that small displacements are not consistently registered as STDs. The phenomenal appearance of displacement in low density displays is consistent with this account; small changes look like nonrigid surface deformations, as if something were moving underneath a piece of fabric. Large changes were seen as the boundary of a separate surface moving over a background surface. However, this was only true at low densities. As texture density increased, perception of separate moving surfaces in the small displacement displays became more likely. Furthermore, shape accuracy increased as density increased. If small displacements do not enter into the boundary formation process, why was there an effect of element density in these displays?

There are three classes of explanation for the density effect in small displacement displays. The first explanation is that small displacements are simply less effective than large displacements in defining an edge. They do not differ in any qualitative way; both types of displacements can define the boundaries of a shape. The effect of density would then not be anomalous. Edge clarity for small and large displacements would simply be an increasing function of the density of element changes along an edge. A second explanation retains the idea that the two displacements differ qualitatively. A displacement may qualify as a RSTD or not, and displacements that do not will not affect boundary formation. Whether or not a displacement constitutes a RSTD may depend not on the absolute distance moved, but on the displacement extent relative to the spacing between the moving element and the neighboring texture elements. Perhaps as the ratio of displacement to local element distances increases there is some threshold where a displacement becomes discontinuous. At higher densities, where the ratio of small displacements to average spacing was larger, the small displacements might register as STDs. This hypothesis is consistent with the phenomenology. In the small displacement/low density displays, where shape accuracy was near chance, nonrigid deformations were seen. This suggests that at low densities the small displacement was seen as a continuous change in a unitary surface. At higher densities, where accuracy was well above chance, the small displacement was adequate to 'tear' the surface, thus becoming a RSTD and participating in the process of SBF. We call this explanation the 'optical tearing hypothesis' (cf. Shaw *et al.*, 1974). Optic tearing occurs whenever element changes are incompatible with a smooth connection between adjacent elements. This idea is not meant to be merely a statement of the phenomenology. The idea is that stimulus variables can be discovered that trigger region segmentation, much as is the case in the luminance or texture domains. The remaining experiments not only support the optic tearing hypothesis but begin to identify the important stimulus relationships.

While the results of Experiment 1a may be consistent with the optical tearing hypothesis, there is a third, much more mundane explanation. Small displacements may simply be less detectable than large ones. We tried to avoid this problem by selecting changes that were within the detectable range (Shaffer and Wallach, 1966). Phenomenally the small displacements were readily apparent, suggesting that detectability of the small location change was not the problem. Nevertheless, Experiment 1b served as a control to rule out the possibility that the results of Experiment 1a reflected a difference in the detectability of the two displacements.

EXPERIMENT 1b

To test the detectability hypothesis, we used a task that did not involve SBF or shape identification. Subjects were instructed to count the number of moving points within an array of stationary elements. This task required accurate detection of the moving points without requiring the displacements be used to define the boundaries of a figure.

Method

Subjects. Ten University of Georgia undergraduates served as subjects in 10–20 min individual testing sessions. Subjects participated as part of the requirements for their introductory psychology course.

Apparatus. The apparatus and viewing distance were the same as the ones used in Experiment 1a.

Stimuli. Each of the displays used in Experiment 1b consisted of 25 elements (the size, shape, color, and background matched those used in Experiment 1a). In each of the displays 0, 1, 2, 3, 4, or 5 elements were displaced. In half of these displays the large displacement (0.6 cm) was used, for the other half, the small displacement (0.06 cm). To vary the density of the elements, the size of the element array was varied. Four rectangular regions (14.6 × 7.3 cm, 7.3 × 7.3 cm, 7.3 × 3.6 cm, and 3.6 × 3.6 cm) were used (these corresponded to element densities of 0.23, 0.47, 0.94, and 1.88 elements per cm^2 respectively). These rectangles were chosen to equate the density of the 25 elements used in Experiment 1b with the element densities of the 50, 100, 200, and 400 element arrays used in Experiment 1a.

To animate these displays, a two-frame sequence was created where elements were displaced in one of the frames. When the two frames were cycled, the elements would appear to move and then return to their original position at the beginning of the next cycle. In Experiment 1a, the average time interval between when an element was displaced upwards and then returned to its original position was 300 ms, and these jumps occurred every 2 s as the pseudosurface circled the screen. So, to animate the sequences used in Experiment 1b, the first frame was shown for 2000 ms, the second was shown for 300 ms. Each trial could last up to 40 s as in Experiment 1a. If the subjects indicated that he or she was ready to identify the number of moving elements, the display would stop at that point.

The two displacement distances crossed with four element densities, and six number-of-elements-moved resulted in 48 displays. Each subject was given a chance to identify the number of moving elements in each of the 48 displays.

Procedure. Subjects were presented with the 6-alternative-forced-choice task as follows. They were seated in front of the monitor and given the following instructions:

"This program will display a motion sequence in which you may see a number of moving elements. Your task is to determine how many are moving. There may not be any elements moving or there may be as many as five moving. You should try to make your decision as quickly as possible. When you think you know how many are moving click the mouse button once. The display will then be replaced by a request for that number. The computer will display each sequence for up to 40 s. After 40 s the display will stop and you will be prompted for your best guess as to how many were moving."

Subjects were then shown the 48 displays in random order.

Results

Subjects' mean accuracy in Experiment 1b was 99% and 98% for the large and small displacements respectively. Clearly, subjects could detect both the large and small displacements without difficulty. Subjects made so few errors (a total of five errors were made in 480 trials) that further analysis using ANOVA was not appropriate.

Discussion

We found no difference in detectability between the two levels of displacement. Detectability does not explain poor shape identification in displays with small displacements. That effect appears to be more specific to shape perception based on SBF. Following Experiments 2 and 3 we will return to consider which of the other two classes of explanation, qualitative versus quantitative differences in displacements, is best supported by the data.

EXPERIMENT 2

Under the optical tearing hypothesis, the effect of element displacement is determined relative to adjacent texture. If the ratio of displacement extent to average element separation is the governing factor, then the effects of element changes in initiating SBF would be scale invariant. The property of being at least roughly scale invariant is shared by a number of important perceptual processes, including: apparent motion perception (Burt and Sperling, 1981), grouping (Gillam, 1981), illusory figure perception (Shipley and Kellman, 1992), and binocular fusion (Burt and Julesz, 1980). The observations of Burt and Julesz are particularly relevant here. Given two binocular points with different disparities, Burt and Julesz found that fusion depended on how large the disparity difference was relative to the distance between the two points. At a particular point, roughly when disparity and lateral distance are equal, a break occurs and one of the points appears diplopic.

On the optical tearing hypothesis, the situation is analogous in SBF. A dot moving a small distance relative to its separation from neighboring points maintains its phenomenal identity and may be seen as a local movement within a surface. When a displacement becomes too large, the element may lose its identity (e.g., the element in the original position is seen to disappear and a new element appears in the displaced position). This perceptual event may result in 'optic tearing'. If optic tearing is a necessary condition for SBF, and if tearing depends on a ratio of displacement and separation extents, there are two implications. The first, tested in Experiment 2, is that SBF should be scale invariant, it should not change if we change angular displacement distance without changing the relative spacing of surrounding elements. In Experiment 3 we test the second implication, that the effect of displacement should change if the relative spacing of surrounding elements is changed.

Scale invariance was tested in Experiment 2 by varying viewing distance. Subjects were shown displays with a range of displacements at two viewing distances.

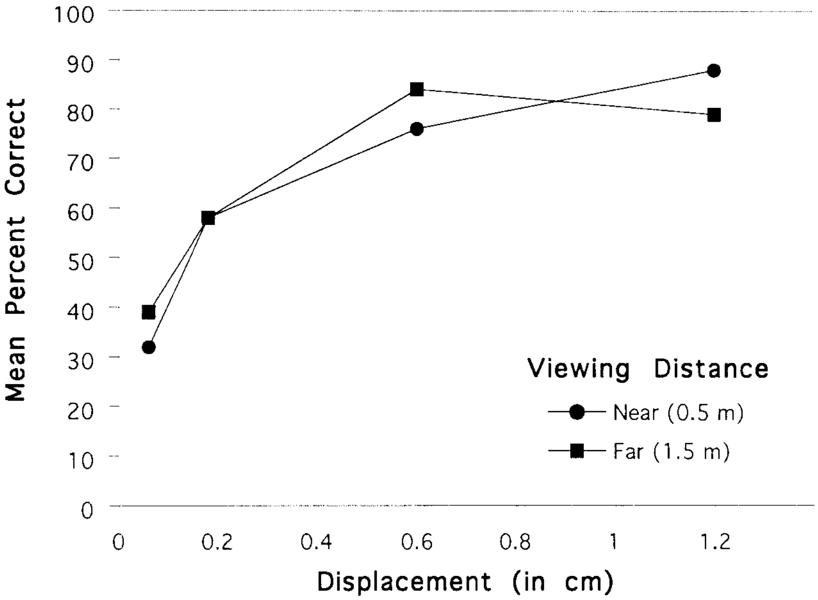

Figure 4. Mean shape identification accuracy for two different viewing distances plotted as a function of the physical distance of the displacements that defined the boundary of the pseudosurface.

Method

Subjects. Ten University of Georgia undergraduates served as subjects in 20–30 min individual testing sessions. Subjects participated as part of the requirements for their introductory psychology course.

Apparatus and procedure. The apparatus and procedure used for Experiment 2 were the same as the ones described in Experiment 1a with the following exceptions. Subjects viewed displays from two distances, 1.5 and 0.5 m. All subjects viewed all displays from both viewing distances. Half of the subjects were initially seated at the nearer distance and shown each display in random order and then seated at the farther distance and shown the entire set of displays a second time using a different random order. The other half of the subjects were initially seated at the farther distance and then moved to the nearer.

Stimuli. The displays used in Experiment 2 were the same as those used in Experiment 1a, with the following exceptions. All displays had 200 elements. In each display one of four displacements was used, 0.06, 0.18, 0.6, 1.2 cm (4.26, 12.8, 42.6, 85.2 arcmin and 1.42, 4.26, 14.2, 28.4 arcmin for viewing distances of 0.5 and 1.5 m, respectively). Elements were displaced in the same manner as in Experiment 1a. As the pseudosurface passed over the element array it changed the location of each element that fell within it.

Two viewing distances (near or far) crossed with four distance displacements and ten pseudosurfaces resulted in 80 displays. Each subject was given a chance to identify the shape of the moving pseudosurface in each of the 80 displays. As in Experiment 1a each display could last up to 40 s unless the subjects indicated that they were ready to identify the shape, in which case the display would stop at that point.

Results

Subjects' mean accuracy for each display type in Experiment 2 is shown in Fig. 4. While there was a clear effect of displacement distance, there was no effect of viewing distance.

To confirm these observations, subjects' accuracy was subjected to a two-way ANOVA with repeated measures, with viewing distance and size of displacement as factors. There was no significant effect of viewing distance, $F < 1$. There was a substantial effect of size of displacement, $F(3,27) = 45.74$, $p < 0.0001$. The interaction between viewing distance and size of displacement was not significant, $F(3,27) = 1.52$, n.s.

Planned comparisons showed a significant increase in the effect of displacement distance up to 0.6 cm, $Fs(1,27) \geq 22.37$, $p < 0.0001$. There was no significant increase from 0.6 to 1.2 cm, $F < 1$. There was also no effect of viewing distance at any level of displacement, $Fs(1,27) \leq 2.00$, n.s.

Discussion

The clear lack of effect of viewing distance at any level of displacement is consistent with the effects of displacement being scale invariant. Displacement extent (at the retina) does not determine whether SBF occurs; the effect of displacement appears to be a relative one.

The fact that shape identification accuracy did not change with viewing distance also suggests that the integration and interpolation mechanisms responsible for SBF are scale invariant. We have found that for visual interpolation in stationary illusory figures, the clarity of the illusory edge appears to vary as a ratio of the interpolated to total (interpolated plus defined) edge (Shipley and Kellman, 1992). Perhaps the same sort of ratio can be applied to spatiotemporal interpolation. Here the clarity of the defined boundary may vary as a function of the interpolated to total edge. The defined portion of the edge might be the amount of contour defined within 150 ms, as previous work suggests that SBF is limited to integration within a 150 ms window (Shipley and Kellman, 1991, 1993, in press).

These results also provide additional evidence against the possibility that small and large displacements differ in detectability. If detectability were an issue, subjects should have been more accurate when sitting near the monitor, since the angular velocity was larger in that condition. However, angular velocity did not predict accuracy.

EXPERIMENT 3

In Experiment 3 we consider the hypothesis that the usefulness of a given element displacement in SBF depends on the relative distances among texture elements. In Experiment 1a, we observed an increase in accuracy as the spatial density of texture elements increased. However, this increase may simply have been the result of additional boundary location information in the higher density displays. To separate the effect of relative element distance from increasing density-of-element changes, displays were designed with additional elements that did not change. If element density increases accuracy simply by making more information available, then inert elements should not contribute in any way to shape recognition. In fact, they might interfere with SBF. On the optical tearing hypothesis, in contrast, adding elements would change the effect of a given element displacement, by decreasing the average distance to neighboring elements.

Method

Subjects. Ten University of Georgia undergraduates served as subjects in 20–30 min individual testing sessions. Subjects participated as part of the requirements for their introductory psychology course.

Apparatus and procedure. The apparatus and procedure used for Experiment 3 were the same as the ones described in Experiment 1a.

Stimuli. The displays used in Experiment 3 were the same as those used in Experiment 1a, with the following exceptions. Only two levels of element density, 100 and 400 elements, were used. In half of the displays an additional 300 elements were added. These *static* elements were distributed over the 14.6 by 14.6 cm field using the same distribution constraint employed in Experiment 1a. These additional elements resembled the other elements in all ways except they were not displaced when they fell within the pseudosurface. As the pseudosurface passed over the element array, it changed only the location of the 100 or 400 changeable (active) elements. As in Experiment 1a, two displacements were used. In half of the displays, elements were displaced a large distance (0.6 cm, 14.2 arcmin) and in half a small distance (0.06 cm, 1.42 arcmin).

Presence/absence of static elements crossed with two distance displacements, two element densities, and ten pseudosurfaces resulted in 80 displays. Each subject was tested with all 80 displays. As in Experiment 1a, each display persisted until the subjects indicated that he or she was ready to identify the shape, up to a maximum of 40 s.

Results

Mean accuracy for each display type in Experiment 3 is shown in Fig. 5. Overall, the static elements did not interfere with performance. In fact they facilitated it slightly. In the displays with no static elements, we replicated the basic findings of Experiment 1a. Subjects were more accurate with large displacements (82%) than small displacements (33%). A similar pattern appeared for displays with 300 static elements, where mean accuracy was 79% and 45% for large and small displacements respectively. Note that the beneficial effect of the added static elements appeared only in the small displacement condition.

To confirm these observations, subjects' accuracy was subjected to a three-way ANOVA with repeated measures, with presence/absence of static elements, size of displacement (large or small), and number of elements (100 or 400) as factors. There was a reliable effect of the presence of static elements, $F(1,9) = 7.94$, $p < 0.02$. There was a substantial effect of distance moved, $F(1,9) = 128.62$, $p < 0.0001$. There was also a reliable effect of number of elements; accuracy was higher for displays with more elements, $F(1,9) = 73.72$, $p < 0.0001$. The interaction between static elements

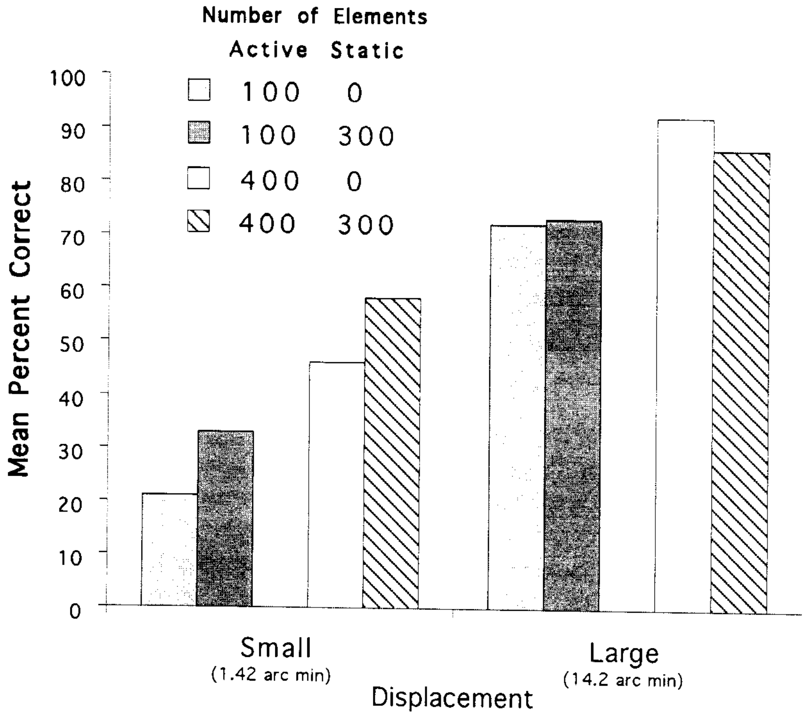

Figure 5. Mean shape identification accuracy for small (1.42 arcmin) and large (14.2 arcmin) displacements in displays with: 100 or 400 active texture elements, with and without an additional 300 static elements. (See text for details.)

and size of displacement was significant, $F(1,9) = 6.26$, $p < 0.03$. The interaction between size of displacement and number of elements was also significant, $F(1,9) = 5.40$, $p < 0.05$. No other interactions reached significance ($F\mathrm{s} < 1$).

Planned comparisons showed a reliable effect of static elements at both levels of element density within the small displacement condition, $F\mathrm{s}(1,9) \geq 11.75$, $p < 0.01$. There was no reliable effect with large displacements; if anything there was a slight tendency for the unchanging points to interfere in the high element density, $F\mathrm{s}(1,9) \leq 2.93$, n.s.

Discussion

The results of Experiment 3 indicate that the effect of displacement on SBF depends on the proximity of surrounding texture elements. The results support the ideas of implicit surface formation and optical tearing as requirements for SBF. Whether an element motion functions to initiate the boundary formation process is governed by a relation between extent of its displacement and the distance of nearby surface elements.

Experiment 3 also allows us to address the question of whether the effect of size of displacement is a quantitative or qualitative one. The hypothesis that the difference between small and large displacements is qualitative rather than quantitative is supported by the effect of extra elements only manifesting itself in displays with small displacements. If the large displacements already register as STDs, then adding additional elements should not improve SBF. The data indicate no enhancement of shape identification in the large displacement condition from the addition of static elements.

GENERAL DISCUSSION

These experiments advance our understanding of the perceptual process by which the boundaries of moving surfaces may be defined by changes over time. Earlier work indicated that a wide range of changes appear to be sufficient to define a boundary (Shipley and Kellman, 1991, in press). The present work suggests some constraints on the element changes that can initiate SBF. Not all detectable changes are sufficient to initiate SBF.

SBF: A robust process for locating object boundaries

As we have argued elsewhere (Shipley and Kellman, in press), SBF may represent an elegant solution to an important problem: segregating the visible world into objects. Although simpler processes might handle some cases of object segregation, SBF represents a much more robust process. Specifically, it is robust in the face of four challenges for object perception: motion, occlusion, surface similarity, and sparse boundary information. A homogeneous, dark gray region moving in front of a white background could be detected as a bounded object from any momentary optical projection; its boundaries, motion in space, and depth relations to other surfaces might be computed using processes less complex than SBF. However, a surface moving in front of a background similar in color, with sparse textural markings, might not be detected. A more general process for segregating moving regions might include the following: (1) A means of detecting local projective changes caused by moving occluding edges. (2) A means of relating local changes so that complete boundaries may be reconstructed from spatially and temporally sparse information. (3) A means of integrating boundary information into global shape and tracking the global motion of the shape.

These are exactly the characteristics of SBF. How these functions are accomplished, especially those in steps 2 and 3, are not yet clear. What is clear is the existence of a process that determines global boundaries, shape and motion from local element transformations sparsely arrayed in space and time.

Optic flow and optic tearing

If such a process exists as a robust means of detecting moving objects, it must avoid a basic problem. Not all local changes in luminance, color, texture, stereoscopic disparity, position, or motion result from motion and occlusion. Changes may occur within a non-rigid surface, for example. Moreover, changes in a given visual direction occur whenever there is a relative motion between objects and observers. Such changes come from both object boundaries as well as elements internal to a surface. The latter information, when produced by the observer's motion, is referred to as optic flow. Optic flow can specify both how the observer is moving within an environment and the shapes of the surfaces within that environment (e.g., Warren and Wertheim, 1990). Many analyses of the recovery of observer motion and surface shape require continuity over time of texture elements and may suffer when texture elements disappear.

These observations suggest that the changes in the optic array contain two complementary components, *optic flow*[1] and *optic tearing*. Perturbations of local elements must be classified in terms of whether they are continuous with nearby elements, as when interior points of a surface move rigidly, or discontinuous, as at surface boundaries. Continuity allows the use of element changes as optic flow, whereas the initiating conditions for finding boundaries are loci of spatiotemporal discontinuity, so-called optic tearing. The boundary formation system might ignore changes occurring within a surface, whereas the system that uses optic flow might ignore changes occurring at edges.

Categorizing optic changes as optic flow or optic tearing can exploit differences in the spatiotemporal patterns characteristic of each. For example, changes that occur within a surface will tend to vary smoothly across adjacent elements in a two-dimensional neighborhood. In contrast, changes at surface boundaries are abrupt, except along a relatively smooth, one-dimensional path.

The present results illustrate this hypothesis that optical changes are classified in terms of continuity, which determines whether they are processed as optic flow or as boundary information. Element displacements served as inputs to SBF only under certain conditions. At certain densities, large displacements initiated SBF but small displacements did so weakly or not at all, despite the fact that both displacements were clearly detectable. A small, ineffective displacement could be made more effective by the addition of static elements, increasing the density of surface elements. Shape identification from SBF was found to depend on displacement extent relative to element density, whereas it appeared relatively insensitive to changes in viewing distance.

All of these findings support the same general interpretation. Whether a particular element displacement initiates spatiotemporal boundary formation depends on whether it is classified as a spatiotemporal discontinuity, which in turn depends on exceeding some ratio of displacement relative to element separation. Dependence on such a ratio is consistent with two ecological constraints about surfaces. First, surfaces are relatively smooth, that is, adjacent points tend to be closer in depth than two randomly selected points. As a result, when an observer moves, the velocities of points on the same surface will tend to be more similar than for points on different surfaces. Secondly, a certain amount of stretching or bending would be consistent with maintaining a connected surface, if that surface has a certain amount of elasticity. At some increased extent of displacement, the implied elasticity would exceed that characteristic of naturally occurring surfaces, and the displacement is classified as a surface discontinuity (optic tear). It would be interesting to compare the elasticity and depth gradients implied by our results with those of naturally occurring non-rigid surfaces. An intriguing possibility is that the process sorting surface element displacements into optic flows or optic tears reflects implicit ecological constraints about the sorts of surfaces that exist in the world.

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NOTE

1. Our use here of the term optic flow is more restrictive than usual, since it applies only to relatively smooth regions of the flow. However, the proposed distinction between optic flow and optic tearing highlights a functional difference in the way optical changes are processed. This distinction is implicit in some mathematical analyses of optic flow (e.g., Koenderink, 1986), where certain variables are definable only within piecewise smooth flow regions.