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The dynamic specification of surfaces and boundaries

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Abstract. Sequential changes in small separated texture elements can produce perception of a moving form with continuous boundaries. This process of spatiotemporal boundary formation may exist to provide a robust means of detecting moving objects that occlude more distant textured surfaces. Whereas most research on spatiotemporal boundary formation has been focused on boundary and shape perception, two experiments are reported here on the perception of surface qualities in spatiotemporal boundary formation. In experiment 1 a free-report procedure was used to investigate whether surface perception can be determined by dynamic information alone, apart from static spatial differences. Results showed that dynamic information was sufficient to determine the appearance of a surface. This dynamic information may play an important role in other aspects of perception. In experiment 2, it was shown that dynamically specifying an extended, opaque surface facilitated edge perception. Implications for the relation of boundary and surface perception and for theories of perceptual transparency are discussed.

1 Introduction

The surfaces in static scenes often differ from their background along a number of physical dimensions including luminance, spectral distribution, and texture. The spatial pattern of change across the edges of a surface can specify the shape of a surface as well as its phenomenal appearance (Cornsweet 1970; Craik 1966; Gerbino et al 1990; Metelli 1974; O'Brian 1958; Wallach 1948; Yarbus 1967). Surfaces do not, however, always differ from their background, eg when similar objects are clustered together. In such situations, if one textured object moves relative to the others it becomes visible immediately. For example, a camouflaged animal is nearly invisible when it is in front of the appropriate background. As soon as such an animal moves it is readily visible. In these cases the shape of the object is specified by two sources of information—the common motion of its parts and the pattern of dynamic occlusion of the more distant surface. Early work on the latter source of edge information was focused on the accretion and deletion of texture elements as the basis for shape information in dynamic occlusion displays (eg Gibson et al 1969; Michotte et al 1964). Recently we have shown that accretion and deletion are not necessary for edges to be seen in dynamic displays; rather, they are members of a broader class of events in which local element changes across space and time give rise to object segmentation and perception of boundaries, form, and motion in the absence of static edge information (Shipley and Kellman 1993, 1994, 1997). We refer to this general boundary-formation process as 'spatiotemporal boundary formation'. Spatiotemporal boundary formation is robust in that it can recover edges in minimal dynamic displays (theoretically as few as three changes are sufficient). Because it is robust, it may serve as an important basis for the perception of edges in natural scenes. While a number of researchers

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have found, implicitly, that surfaces are also apparent in some dynamic displays, there are no systematic studies of the information that can specify a surface dynamically or how the perception of surfaces and edges interact. Here we briefly review previous work on edge and surface perception in dynamic scenes and consider whether local element changes are sufficient to define an extended, opaque surface, and how the presence of a dynamically defined extended surface influences boundary formation.

Patterns of element appearance and disappearance along the edge of a moving form can precisely define the boundaries of that form (Andersen and Cortese 1989; Bruno and Bertamini 1990; Bruno and Gerbino 1991; Gibson et al 1969; Hine 1987; Kaplan 1969; Shipley and Kellman 1993, 1994; Stappers 1989). For example, we showed subjects a set of displays where one of ten virtual figures moved over a static array of white elements on a black background (Shipley and Kellman 1994; see figure 1). These figures were only visible to the subject through their effect on the texture elements: whenever an element was within the moving figure the element changed to black. Thus, the elements were only visible outside of the moving figure. Since the elements all changed in the same manner, along a local edge segment, we (Shipley and Kellman 1994) referred to such displays as 'unidirectional'. These displays produced sharp, well-defined boundaries, as indicated by subjects' performance on a ten-alternative forced-choice shape-identification task.

The class of element changes, or transformations, that can define boundaries over time extends well beyond appearance and disappearance, and includes changes in color, orientation, shape, and location (Shipley and Kellman 1993, 1994). We noted that for each of these cases, the transition from one state to another is discontinuous—the transformations are abrupt. We found that when a transformation was perceived as continuous, the spatiotemporal pattern did not produce a sharp edge and was seen

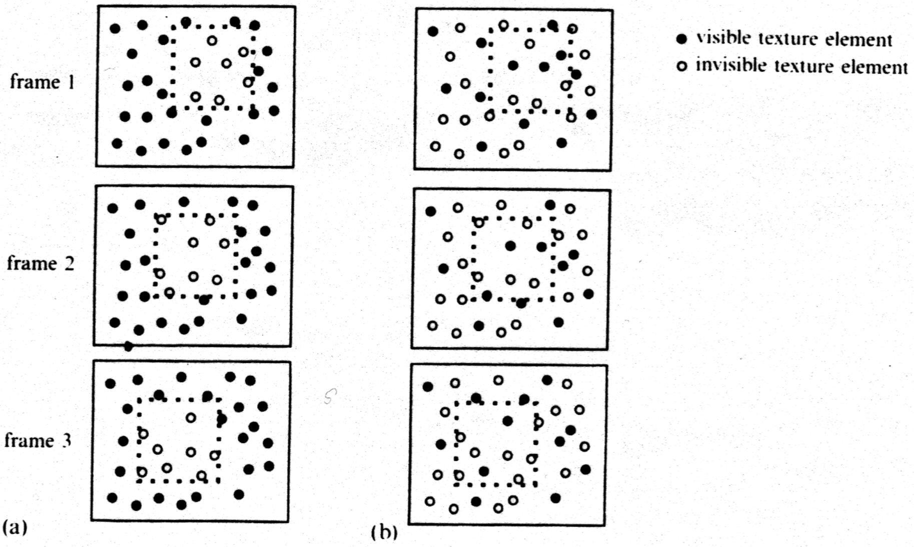

Figure 1. Two patterns of spatiotemporal change which define a moving form. (a) In unidirectional displays the texture elements progressively disappear and reappear as the square region moves. In such displays, texture elements are only visible while outside the moving form. (b) In bidirectional displays, half of the elements are only visible while outside the form. The remaining elements are only visible while inside the moving form. So, elements in these displays appear and disappear along the same edge. For the purposes of illustration, the colors here are the reverse of the actual experimental displays, where white elements appeared against a black background. This figure is similar to figure 2 from Shipley and Kellman (1994).

as the nonrigid deformation of a surface. We concluded that any type of transformation that produces spatiotemporal discontinuities can support dynamic edge perception.

Unidirectional spatiotemporal-boundary-formation displays have two qualitatively different sources of information for boundaries. Besides dynamic information given by local element changes, static characteristics such as space-averaged luminance and texture density differ inside and outside of the moving region. Using displays that simulated one random-dot surface moving over another, Gibson et al (1969) and Kaplan (1969) demonstrated that edges could be seen in displays that did not have these static sources of shape information. However, these displays had several sources of dynamic shape information, specifically common motion of texture elements on different surfaces, and accretion and deletion of elements along the trailing and leading edges respectively. To test whether local element transformations alone are sufficient to produce spatiotemporal boundary formation, we created *bidirectional* displays (Shipley and Kellman 1994: see figure 1). In bidirectional displays, elements in the arrays have one of two values, eg the array contains equal numbers of randomly distributed white and black elements. Transformations upon entering or leaving the moving figure are then in two directions (hence the term bidirectional), eg white elements turn to black and vice versa. Bidirectional displays provide no static shape information because there are no global differences in luminance, texture, hue, etc. The finding that the spatiotemporal-boundary-formation process works with bidirectional displays indicates that the spatiotemporal pattern of local element changes is sufficient for boundary or shape perception (Shipley and Kellman 1994).

While much of the work on dynamic scene perception has been focused on boundary formation, our perceptual experiences of objects involve more than just shape. Object surfaces have a number of important perceptual properties, such as opacity, lightness, color, and texture (Katz 1935). In addition to demonstrating dynamic edge perception, Gibson et al (1969) and Kaplan (1969) demonstrated, at least implicitly, that changes over time are sufficient to define an extended surface. The displays employed in these studies contained several potential sources of dynamic surface information (eg relative motion, and accretion and deletion). Consequently, it is unknown what sources of information can initiate dynamic surface perception. Additionally, since these studies only mention surface qualities tangentially, it is also unclear from them exactly which surface qualities can be defined over time.

In several studies the perception of surfaces in dynamic scenes has been explicitly investigated (Cicerone et al 1995: Shipley and Kellman 1993, 1994). These studies were focused on interactions between static sources of surface information and element color changes in the perception of surface color and transparency. In no study has the perception of surfaces defined purely by dynamic information been systematically examined, and thus it remains unknown how surfaces are defined over time. The experiments reported here directly address the potential role of local element transformations in defining an extended, opaque surface.

Both Cicerone et al (1995) and we (Shipley and Kellman 1993, 1994) provide some basic insights into the dynamic specification of surface color and transparency. In these investigations of spatiotemporal boundary formation, we noted (Shipley and Kellman 1994) that subjects spontaneously reported differences in surface appearance for various display types. For example, in unidirectional displays with a black background and a white-to-blue color transformation (ie elements turned blue upon entering the moving region and returned to white upon leaving) subjects reported that the moving figure appeared to have a transparent blue surface. In these displays, the blue of the texture elements was seen to extend throughout the moving region. The transparency was similar to that reported in neon-color-spreading displays: however, no neon-like brightness effects were noted. For unidirectional displays where elements were transformed from white to black on a black background (ie they disappeared) subjects reported seeing an opaque black surface. For bidirectional displays, both white-to-blue and white-to-black transformations appeared to have an edge but no surface (eg a moving circular region looked like a surfaceless ring). We noted that, in general, only when there was a static difference between the inside and the outside of the region did subjects report the presence of a surface (Shipley and Kellman 1994). We suggested that static differences are necessary for surface perception.

Cicerone et al (1995) employed unidirectional displays to examine the perception of surface color in dynamic displays. They too noted that unidirectional color transformations tended to produce the impression of a transparent colored surface (eg red elements changing to green elements on a white background resulted in the appearance of a moving green transparent surface). Perception of a colored transparent surface only occurred when the form was moving. They concluded that spatiotemporal changes are necessary to define surface color, but are not sufficient. Like us, they suggested that a static feature, the presence of colored elements within the boundaries of the form, determined the color appearance of the surface. They hypothesized that an interaction between the neural system that processes motion and the neural system that processes static information is responsible for the perception of a surface in dynamic displays.

Both we (Shipley and Kellman 1994) and Cicerone et al (1995) noted that the perceived surface color spreads between elements. Cicerone et al explain this color spreading by suggesting that the perceived color of the elements is "disassociated from the dots themselves" (page 774). This produces an amorphous region of color which is seen as moving. Cicerone et al do not state what produces this dissociation, other than the "activation of the motion pathway" (page 774).

Given the prevalence of color and motion signals, avoiding spurious dissociations would seem to require that the dissociation be restricted in some way. Perhaps dissociation of color only occurs when the spatiotemporal pattern of local element changes specifies the presence of a transparent surface. In such a case, differences in element appearances would be ascribed to the presence of a transparent surface and not to the presence of differently colored elements (Fuchs 1923/1950). If transparency could be specified dynamically, this would explain why transparent surfaces were seen in our (Shipley and Kellman 1994) and Cicerone et al's (1995) displays only when the figure moved.

What might this dynamic transparency information be? One candidate was suggested by Stoner and Albright (1996). When discussing perceived transparency of plaid gratings moving in an aperture, they noted that "The opacity of a foreground is directly encoded by the depth of the contrast modulation" (page 1307). It is possible then, that changes in texture elements provided information for a transparent surface in both Cicerone et al's (1995) and our (Shipley and Kellman 1994) displays. For instance, when elements change from one color to another, the degree of contrast modulation may specify a partially transparent surface. By extension, when elements disappear along a leading edge and reappear at a trailing edge, a completely opaque surface may be specified. Thus, the direction and type of element change might be crucial for the perception of transparent and opaque surfaces in dynamic scenes. We test the hypothesis that dynamic information alone is sufficient to define an extended, opaque surface in experiment 1, using dynamic displays where the static information is degraded to the point where subjects do not use it. In experiment 2, we show that dynamically specifying an extended, opaque surface improves subjects' shape-identification performance.

2 Experiment 1

Unidirectional and bidirectional displays differ in whether or not a surface is seen. The cause of this difference is not clear because the two types of displays differ in two critical ways. Specifically, unidirectional displays contain static surface information (eg global differences in luminance, hue, texture, etc), while bidirectional displays do not. It is possible that bidirectional figures do not appear to possess a surface because static surface information is necessary for surface perception (Cicerone et al 1995; Shipley and Kellman 1994). Alternatively, it is possible that differences in the dynamic pattern of changes that occur in the two displays are responsible for differences in surface perception. All of the elements in unidirectional displays change in the same direction. This is consistent with natural scenes: for all real surfaces (opaque and transparent) the change in luminance that occurs at a leading edge is always consistent. Displays where some luminance values increase at the leading edge while others decrease (ie bidirectional displays) are not consistent with any type of surface and do not occur in natural scenes.

If the dynamic pattern of change in the unidirectional displays is responsible for the perception of an opaque surface, removing the static surface information (ie the global differences in luminance and texture density) should not impair surface perception. Consider displays where white elements turn black inside the moving region, and the background is black. The only way to completely remove spatial differences between the inside and outside of the moving region in unidirectional displays, without altering the dynamic pattern of change, would be to add white texture elements inside the figure that move with it. While this would remove static differences, it would also introduce additional dynamic information that has been demonstrated to influence spatiotemporal boundary formation (Cunningham et al, in press). Therefore an alternative approach was required. For experiment 1 we developed displays in which spatial differences were reduced to a level where they were not detectable. This was achieved by superimposing an unchanging high-density texture array onto the entire display field. Conceptually, this is equivalent to adding an array of elements between the observer and the display field (see figure 2). Actually, the new elements were in the same depth plane as the display field and were visible both inside and outside the moving region where elements disappeared. If the density of this additional array is sufficiently high, any residual static luminance and texture-density differences would not be detectable. Thus, the static luminance and texture density would not affect the perception of an opaque surface.

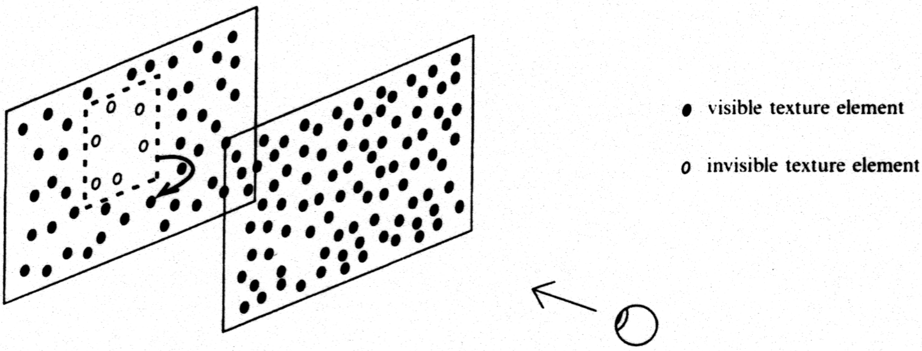

Figure 2. A side view of a unidirectional occlusion display with a superimposed mask. The circle on the right illustrates the viewer's position. The elements in the middle plane do not change; only the elements in the left plane are affected by the moving form.

2.1 *Method*

Four types of spatiotemporal-boundary-formation display were used: unidirectional, unidirectional with mask, bidirectional, and bidirectional with mask. The unidirectional and the bidirectional displays were identical to displays used for previous work on spatiotemporal boundary formation (Shipley and Kellman 1993, 1994, 1997), with the single exception that the moving form was a triangle in all displays. The unidirectional-with-mask and the bidirectional-with-mask displays were created by adding a high-density unchanging mask of elements to each unidirectional display and bidirectional display. The ratio of signal to mask elements was 1 to 6—for every element that would disappear when inside the moving form (ie signal element), 6 unchanging elements (ie mask elements) were added at random locations.

To explore the effect of spatiotemporal density of element change on dynamic surface perception, the number of signal elements present in each type of display was varied. Three levels of signal-element density (50, 100, and 200—1.3 mm dots in a 14.6 cm × 14.6 cm display area) were selected on the basis of previous research.

Sixteen subjects were shown the unidirectional and unidirectional-with-mask displays at each of the three texture densities. The order of presentation of the six displays was counterbalanced across subjects. For each display, subjects were asked to "describe the display as carefully as you can—as if you are trying to describe what you see to someone who is not in the room, and has never seen these displays". Subjects' reports were scored for whether or not they (i) reported a dark surface (only the terms 'black' and 'dark' were scored as reports of a solid dark surface); (ii) reported seeing a form (regardless of whether or not they reported a specific shape); and (iii) reported seeing a triangle.

A control group consisting of eight subjects viewed bidirectional and bidirectional-with-mask displays at the three texture densities. Order of presentation of the six displays was counterbalanced across subjects. These subjects performed the same task as those who saw unidirectional displays.

2.2 *Results and discussion*

The results of experiment 1 are shown in table 1. The frequency of reporting an opaque figure increased as the number of signal elements increased. Almost all subjects (fifteen of sixteen) reported seeing a dark surface in the 200-element unidirectional displays. Most subjects (twelve of sixteen) reported seeing a dark surface in the 200-element unidirectional-with-mask displays. While the difference in surface reports between unidirectional and unidirectional-with-mask displays was significant ($\chi^2 = 4.6$, $p < 0.04$), the high frequency of spontaneous reports of seeing a dark surface suggests that subjects could experience an extended opaque black surface in displays with negligible static surface information.

To confirm that the mask effectively removed static information, seventeen new subjects were shown a single frame from each animation sequence and asked to locate the triangular region. To make the task easier, subjects only had to indicate which one of four quadrants the triangle occupied. For the unidirectional-with-mask displays, subjects correctly identified the quadrant that contained the triangle on only 30.2% of the trials. This did not differ significantly from chance performance (25%) ($t_{16} = 0.41$, ns). Thus, the experience of an opaque triangle in the moving displays must have been a result of the dynamic information.

None of the eight subjects viewing bidirectional displays reported seeing a dark surface, and only one subject viewing bidirectional-with-mask displays did so. The difference in surface reports between bidirectional and bidirectional-with-mask displays was not significant ($\chi^2 = 1.07$, ns). Clearly, subjects do not simply describe triangles in displays with small flickering dots as "dark surfaces". The difference in surface reports

Table 1. The percentage of subjects who reported seeing a dark surface, a form, or a triangle in experiment 1.

Type of display	Number of signal elements	Percentage of subjects reporting		
		dark surface	form	triangle
Unidirectional	50	75	88	31
	100	88	100	63
	200	94	100	94
Unidirectional with mask	50	38	88	13
	100	63	94	50
	200	75	100	69
Bidirectional	50	0	50	13
	100	0	63	13
	200	0	88	50
Bidirectional with mask	50	0	38	0
	100	13	50	0
	200	13	88	38

Note: $n = 16$ for the unidirectional and the unidirectional-with-mask displays; $n = 8$ for the bidirectional and the bidirectional-with-mask displays.

between unidirectional and bidirectional displays was reliable ($\chi^2 = 240$, $p < 0.0001$), as was the difference between unidirectional-with-mask and bidirectional-with-mask displays ($\chi^2 = 58.08$, $p < 0.0001$). These results support our hypothesis that the different pattern of element changes present in unidirectional and bidirectional displays, apart from static spatial differences, causes the difference in surface appearance in these displays.

While the number of subjects reporting that they saw a surface differed between the displays with and without a mask, no subjects spontaneously reported any differences in surface quality, even though these displays differed substantially in average luminance and texture density inside the moving form. Although we did not directly ask subjects to make comparisons, subjects spontaneously noted a number of other differences across displays (eg many subjects noted that the shape was clearer at higher densities). Perception of an extended, opaque surface when static information has been effectively removed suggests that in natural scenes, where both static and dynamic changes may be available, the phenomenal appearance of stable moving surfaces may depend on spatiotemporally defined information.

3 Experiment 2

The results of experiment 1 are consistent with the notion that perception of a continuous opaque surface can be specified by local element transformations. Does this dynamic surface quality interact with other perceptual aspects of spatiotemporal-boundary-formation displays? In natural scenes, objects with continuous surfaces, as opposed to unfilled outlines, are the norm (Kennedy 1987). It is possible that perceptual encoding of object properties such as shape is superior when dynamic information specifies surface continuity than when it does not. The greater number of subjects reporting a triangle in the unidirectional-with-mask displays relative to the bidirectional displays found in experiment 1 suggests that consistent surface information facilitates perception of surface boundaries. In experiment 2 we test the influence of information for surface opacity on shape perception by means of an objective measure.

Previous research has revealed that shape identification for unidirectional displays is substantially superior to that for bidirectional displays (Shipley and Kellman 1994).

This finding has remained unexplained. It may reflect a facilitatory effect of consistent surface information, which is present in unidirectional displays but not in bidirectional displays. Alternatively, it might simply reflect the presence of static shape information (texture differences) in the unidirectional displays and their absence in bidirectional displays. It is, of course, possible that both dynamic surface information and static differences contribute to better performance in unidirectional displays. Following the logic of experiment 1, we investigated shape identification by using unidirectional and bidirectional displays with and without a mask to control for the presence of static spatial differences. If static texture differences between the inside and outside of the moving figure are the sole cause of greater shape identification in the unidirectional displays, then adding a mask to a unidirectional display should reduce performance to the level of a bidirectional display. In contrast, if surface perception facilitates shape identification, then performance in the unidirectional-with-mask displays should be superior to bidirectional displays.

3.1 *Method*

Fifteen subjects performed a ten-alternative forced-choice shape-identification task with four types of spatiotemporal-boundary-formation display: unidirectional, unidirectional with mask, bidirectional, and bidirectional with mask. One of ten mathematically defined shapes moved through the element fields on a given trial. Some shapes were familiar (eg square, triangle, circle), and others were unfamiliar. Previous research has shown that this set of shapes provides a reliable means of identifying variables that influence dynamic boundary and form perception (Shipley and Kellman 1993, 1994, 1997).

Signal-element-field density was varied by using the same levels as in experiment 1. A factorial combination of ten figures, three signal-element-field densities, two types of transformation (unidirectional and bidirectional), and two levels of mask (none and a 1 : 6 ratio) yielded 120 trials. Each subject was shown the 120 displays in a different random order.

3.2 *Results and discussion*

The results of experiment 2 are shown in figure 3. Unidirectional-with-mask displays produced better shape-identification performance than bidirectional displays ($F_{1,14} = 91.0$, $p < 0.0001$). Neither unidirectional-with-mask displays nor bidirectional displays have noticeable texture differences between the inside and outside of the moving figure, so the large difference in performance indicates that the difference in dynamic information influences shape perception. These results, along with those of experiment 1, indicate that the same source of information (the local coherency of element transformations) influences both boundary clarity and the perception of an extended, opaque surface.

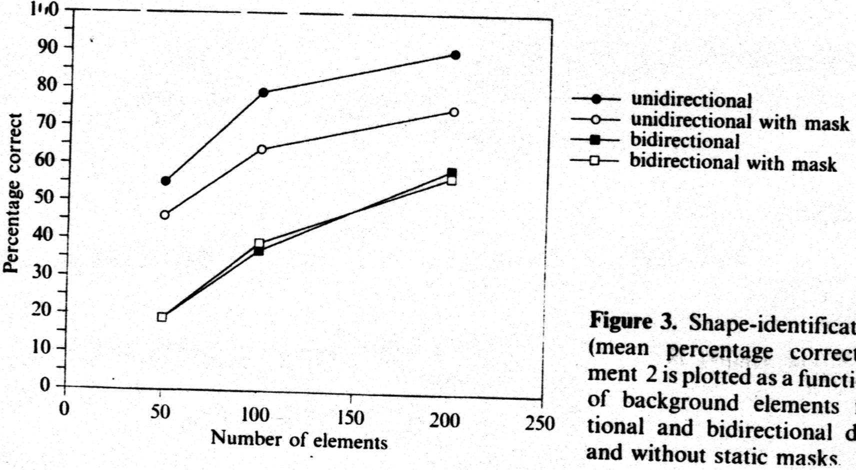

Figure 3. Shape-identification accuracy (mean percentage correct) in experiment 2 is plotted as a function of number of background elements for unidirectional and bidirectional displays, with and without static masks.

The dynamic information that specifies an extended, opaque surface appears to facilitate boundary formation.

Shape-identification performance was lower in the unidirectional-with-mask displays than in the unidirectional displays ($F_{1,14} = 25.5$, $p < 0.0002$). This result suggests that the mask impairs edge perception (but not surface perception). The lack of a difference in shape-identification performance between the two bidirectional displays ($F < 1$) is consistent with this hypothesis that the mask is removing some form of static shape information, as there is no static information to remove in those displays.

To confirm the effectiveness of the mask in this shape-identification procedure, the shape-identification performance of five naive graduate students was compared between unidirectional-with-mask, bidirectional, and bidirectional-with-static-difference displays. The bidirectional-with-static-difference displays were identical to the bidirectional displays, with the single exception that bidirectional-with-static-difference displays contained the same average luminance and relative density differences between the inside and the outside of the moving form as the unidirectional-with-mask displays. Subjects were significantly better at identifying the figure in the unidirectional-with-mask displays than they were in either the bidirectional-with-static-difference display ($F_{1,8} = 12.71, p < 0.008$) or the bidirectional display ($F_{1,8} = 24.38, p < 0.002$). Furthermore, overall performance was not significantly different between the bidirectional-with-static-difference and the bidirectional displays ($F_{1,8} = 1.88$, ns). Clearly, the performance differences between the unidirectional-with-mask and the bidirectional displays were the result of differing spatiotemporal patterns.

These objective data confirm the phenomenal observations of form visibility made in experiment 1. The relatively large superiority of unidirectional-with-mask displays over both bidirectional displays is consistent with the hypothesis that the presence of information for a dynamically defined extended, opaque surface improves form perception.

For all four types of display, shape identification increased as the number of signal elements increased from 50 to 100 to 200. This replicates previous work showing that signal-element density is an important variable in spatiotemporal boundary formation (Andersen and Cortese 1989; Bruno and Bertamini 1990; Hine 1987; Shipley and Kellman 1993, 1994). There was no evidence of an interaction between signal-element density and mask ($F < 1$). This suggests that the relative importance of static and dynamic information does not change with increases in signal-element density.

4 General discussion

In experiment 1 we demonstrated that the dynamic pattern of element changes in unidirectional spatiotemporal-boundary-formation displays is sufficient to support the perception of an extended, opaque, dark surface. In both the unidirectional and the unidirectional-with-mask display, subjects consistently reported seeing a moving figure with a dark surface. The presence of a mask that effectively removed static surface information did not eliminate the perception of an extended, opaque surface. In experiment 2 we demonstrated that the same dynamic information that specifies an extended, dark surface improves shape-identification performance.

Beyond defining the presence of a fully opaque surface, the dynamic pattern of element changes may also specify the degree of opacity (ie the degree of transparency). While there is little evidence to indicate whether the perception of opaque and transparent surfaces are the result of a single perceptual mechanism or two different mechanisms, physical transparency may be thought of as a continuum with fully opaque surfaces on one end and completely transparent (ie invisible) surfaces on the other. Here we develop an account of how transparency might be specified dynamically by using the same information that we have shown to be effective in defining completely opaque surfaces—the spatiotemporal pattern of element changes.

Perception of surface transparency has ordinarily been treated as depending on static information (eg Bressan 1993; Gerbino et al 1990; Metelli 1974; Nakayama et al 1990; Redies and Spillmann 1981). Considering briefly how transparency is determined statically will help illustrate how it might be determined dynamically. Determining the transparency of a static surface is generally achieved by noting how the projected edges of other objects change at the boundaries of the potentially transparent surface. Identifying a fully opaque object is fairly straightforward: it will produce discontinuities in the first derivative of the projected edges of all objects that are more distant (Kellman and Shipley 1991). Identifying partial transparency is more complicated since light coming from within a transparent surface is influenced by both the degree of transparency and the reflectance of the partially transparent surface. Disambiguating the relative contributions of reflectance and transmittance requires identifying corresponding regions inside and outside a surface so that the light coming from these regions can be compared [see Gerbino et al (1990) for an update of Metelli's equations relating image luminance to transparency and reflectance]. Figure 4 illustrates the physical relationships that allow

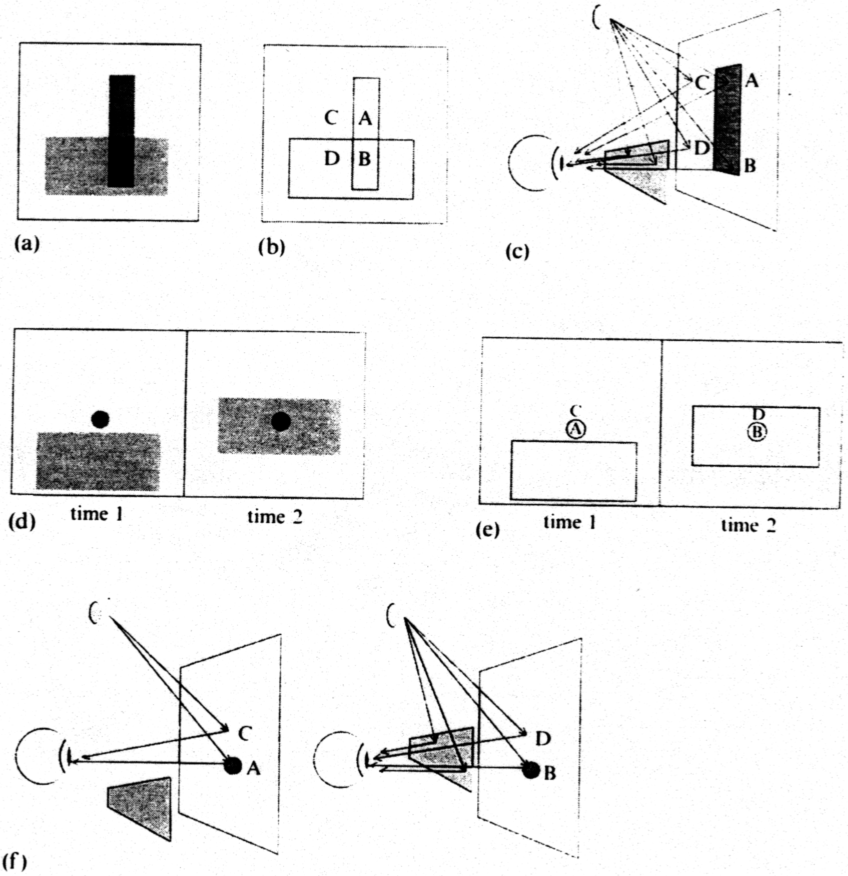

Figure 4. (a) An illustration of a static transparent surface. (b) Transparency of a static surface may be determined by comparing the light coming from the transparent surface (regions B and D) with light coming from corresponding regions outside of this surface (regions A and C, respectively). (c) The physical combination of light in the transparent region is illustrated schematically with light rays traveling from a small light source and reflecting off of the transparent surface and the more distant opaque surface. (d) An illustration of a moving transparent surface. (e) and (f) The regions A, B, C, and D are analogous to the regions shown in (b) and the combination of light is analogous to that illustrated in (c).

the visual system to identify the degree of transparency. Figure 4a illustrates a partially transparent horizontal rectangle in front of a vertical rectangle. The regions with different luminance values are labeled A, B, C, and D (see figure 4b). Figure 4c illustrates the combination of light that occurs when the horizontal rectangle is transparent. The light coming from regions B and D is a combination of the light that reflects off the transparent surface and light that comes through the transparent surface. This combination is illustrated with pairs of rays approaching the observer along the same line of sight. Identifying corresponding regions can be achieved in most static displays by using the alignment of edges across the partially transparent boundary. The alignment identifies corresponding elements inside and outside the surface. By comparing the light coming from corresponding regions (eg comparing the light from A and C with the light coming from regions B and D, respectively), it is possible to determine the transparency of the horizontal rectangle. The importance of alignment in such displays was noted by Kanizsa (1979). In displays where alignment is not present, transparency failed [however, see Adelson (1993) for some counterexamples].

Theoretical analyses of transparency have been focused on static displays, presumably because of the requirement that the system be able to match corresponding regions. In dynamic displays, where only small texture elements are present (illustrated in figure 4d), reflectance and transparency cannot be separated by using static alignment of edges because no portion of the element is partially visible outside of the transparent surface. The pattern of change over time, however, provides direct information for the correspondence across moving boundaries. The correspondence of an element (eg region A at time 1 corresponds to region B at time 2—see figure 4e) is provided by its continuity over time. So, it is possible to separate the effects of transparency and reflectance (see figure 4f), and determine the transparency of a surface by noting how elements sequentially change color when covered by that surface. If the luminance change is large then the surface is mostly opaque, if small then very transparent.

In their examination of plaid gratings moving through an aperture, Stoner and Albright (1996) suggested that the transparency of large extended surfaces could be specified by the depth of contrast modulation "within the non-Fourier elements" (page 1307). Their focus on contrast modulation in the non-Fourier-motion domain offers the potential for a formal account of how achromatic transparency could be specified by the sequence of luminance changes over time. The rules for determining achromatic and chromatic opacity and reflectance in moving displays may be analogous to those developed for static achromatic displays (Gerbino et al 1990; Metelli 1974).(1)

Depth of contrast modulation alone, however, can not account for the differences reported here between bidirectional and unidirectional-with-mask displays. The level of contrast modulation is identical in the two displays. They differ in the direction and local consistency of the modulation. The dynamic specification of transparency must depend on the *pattern* of contrast modulation.

This account of the dynamic specification of transparency suggests an extension to Cicerone et al's (1995) model of surface-color perception in dynamic scenes. In their model, they suggested that the surface color may be dynamically specified when "the activation of the motion pathway triggers reorganization of the stimulus features so

(1) In static neon-color-spreading and spatiotemporal-boundary-formation displays, where the background inside and outside the forms is identical in luminance and greater than zero, there is no physical solution to the equations that specify reflectance and transparency. However, the inside of both types of forms may differ in apparent brightness from the background (de Weert and Kruysbergen 1987). So, a reflectance and transparency solution based on apparent brightness differences might be possible. Our previous displays (Shipley and Kellman 1994), as well as those used for the present experiments, avoid this problem because a black background was used. When the background luminance is zero, a solution for reflectance and transparency is possible—such luminance values are consistent with a surface that is partially transparent and has zero reflectance.

that new configurations are perceived" (page 774). In the first step of the model, the color of the surface-to-be-seen is dissociated from the individual texture elements. What causes this separation of color? Cicerone et al do not specify a mechanism beyond suggesting that it is based on the processing of motion signals. This dissociation may require the perception of a surface (Fuchs 1923/1950). On the basis of our results we suggest that the dynamic pattern of changes in contrast or spectral distribution that define boundaries in spatiotemporal boundary formation may also define the degree of transparency of an extended surface, and thus allow color signals to be dissociated from individual elements. The results of the experiments presented here suggest a further modification of Cicerone et al's model. Perceived surface transparency seems to depend mostly, perhaps exclusively, on signals produced by changing elements; not all of the elements inside the boundary of a form influence the apparent surface transparency. Further research involving more subtle measures are needed to determine when and how the static (internal) elements interact with dynamic changes in affecting the perceived surface color.

In this paper we have shown that the dynamic element changes in spatiotemporal boundary formation are sufficient to define an extended, opaque surface as well as boundaries. The results suggest a potential dynamic determinant of surface transparency. In this paper, however, we only begin to outline how dynamic-surface perception occurs. Surfaces of objects have a number of distinct qualities in addition to transparency, such as lightness, color, and texture (Katz 1935). While local luminance, spectral distribution, and texture transformations can define surface boundaries, it is uncertain which surface qualities other than degree of transparency can be defined dynamically. Characterizing which spatiotemporal patterns can specify surface properties and understanding how this information is integrated in natural-scene perception are important questions for future study.

Finally, the research presented here links several facets of perception in spatiotemporal-boundary-formation displays, specifically shape and surface quality. The direction and local consistency of element changes, which may specify surface transparency, also influence the dynamic specification of depth (cf Kaplan 1969). A fully developed model of the perception of surfaces in dynamic scenes may require an understanding of what properties of a surface may be specified by spatiotemporal information and how the perceptual processes that use this information interact.

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