

BREATHING ILLUSIONS AND BOUNDARY FORMATION IN SPACE-TIME

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ABSTRACT

Human observers are remarkably adept at detecting and identifying surface boundaries despite incomplete optical information. There is a general consensus that this ability is instantiated by mechanisms of visual interpolation across spatio-temporally sparse elements, a process that may be termed spatiotemporal boundary formation (SBF). If adequate information is available, SBF generally produces veridical boundaries. In some special cases, however, SBF fails. Such failures are theoretically relevant in that they provide crucial information about underlying processing constraints. In the chapter, I define and analyze a class of motion illusions (the breathing illusions). In breathing illusions, rigidly rotating surfaces appear to pulsate or deform, even though a straightforward process of geometrical interpolation across space would reconstruct the veridical surface boundary. It is generally believed that such nonrigid outcome depends on a failure to apply a rigidity constraint across spatiotemporal discontinuities. The chapter reviews measurement methods and main findings in the area, and discusses the theoretical implications of breathing illusions for the current theory of SBF.

INTRODUCTION

Many animals have evolved skin patterns that resemble those present in their ecological niches. Under appropriate conditions, when such animals stand still in front of a background, observers (and predators) fail to detect them. Camouflage usually breaks down, however, when a camouflaged animal moves. The sudden revelation of the previously unseen shape is a prototypical example of a cognitive process known as spatiotemporal boundary formation, or SBF (Shipley & Kellman, 1994). When the animal stands still, spatial unit formation processes such as those described by the Gestalt laws of similarity, proximity, and good continuation prevent a predator's visual system from segregating the animal from its background. As soon as motion starts, spatiotemporal processes of unit formation cause the silhouette of the animal to become visible. Thus, SBF phenomena consist of surface boundaries seen during a motion sequence, but not in any of the static frames that compose the sequence. The motion sequence may be caused by either object relative motions or by displacements of the viewpoint relative to static objects, or both. Whatever the origin of the relevant optical motions, it is easy to demonstrate (Kaplan, 1969) that SBF requires that two conditions be met. First, the motion of individual pattern elements on the animal's skin must be distinguishable from the motion of other patterns in the image. If patterns belonging to both regions all move randomly, boundary formation does not occur. Second, as the animal moves over the ground surface, patterns on the latter must undergo some coherent transformation (in the example, progressive occlusion and disocclusion of local patterns).

Perhaps the most striking aspect of SBF is the appearance of a clear, crisp contour in regions of spatially homogenous luminance. This contour appears as the boundary of an occluding figure having a color in the surface-mode of appearance (Katz, 1935). The surface-character of the figure color may be described as perceived opacity and solidity. (Cunningham, Shipley & Kellman, 1998). In addition, the emerging figure appears brighter than the background. Finally, SBF tends to yield the impression that the emerging surface is somewhat detached from its background, as if there was some empty space between the layers. This latter impression may be more or less compelling depending on the stimulus conditions. A number of investigators have noted that SBF may be considered as a prototypical case of *modal* completion, and that the modal character of the emerging occluding surface is accompanied by the *amodal* completion of the perceptually underlying surface or surfaces. In what is perhaps the first investigation of SBF, Sampaio (1943), a student of Belgian psychologist Albert Michotte, showed observers a simple animation involving progressive occlusion and disocclusion. In the animation, a black disk moved horizontally across an homogeneous field. For the first portion of the motion path, the whole disk was always visible. But, as it moved on a sequential transformation began: The area of the disk that had passed across a line was deleted progressively, until the whole disk had disappeared (Figure 1). Geometrically, what Sampaio did was to destroy geometrical

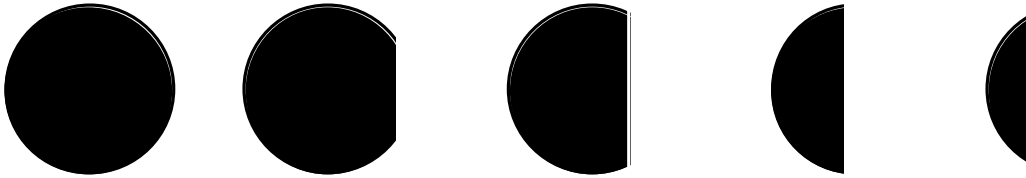


Figure 1. A example of the motion sequence that produces the "screen" effect.

congruence and projective identity for the disk, generating a sharp transition from a regular to an irregular figure, and then sequentially destroying congruence and identity for successive versions of the truncated disk. However, this is not what observers reported. Quite unanimously, observers described the event as depicting a disk passing behind a surface, a screen. The screen had a clear, crisp boundary (modal completion) which appeared in the physically homogeneous background, and the disk continued to be perceived as a circular figure despite its partial occlusion (amodal completion). Both kinds of completion seem to be invariably present in SBF -- a direct consequence of the occlusion interpretation that always accompanies the appearance of a SBF surface.

VARIETES OF SBF

This bulk of this chapter is devoted to an exploration of the theoretical implications of a particular class of illusions observed in SBF. To introduce and define this class of illusions, a brief review of SBF phenomena is in order. Examples of SBF can be classified according to the manipulation used to generate the appropriate spatiotemporal structure in the optic array. In principle, this operation leads to a potential classification into four categories: (1) manipulations of texture discontinuities, such as accretions and deletions, relative motion, changes in element shape, color, and so on (see Shipley & Kellman, 1994); (2) manipulations of the shape of filled surfaces, (3) manipulations of the length and position of lines, and (4) manipulations of combinations of two or more of the above.

Texture Manipulations

In a seminal demonstration, Kaplan (1969) presented two regions of homogeneous texture side by side, and moved them as if they corresponded to two separate surfaces at different depths. This motion sequence (see Figure 2) produces a characteristic transformation at the implicit edge, known as accretion and deletion of texture. Accretion of texture takes place due to sequential uncovering by a trailing edge, whereas deletion takes

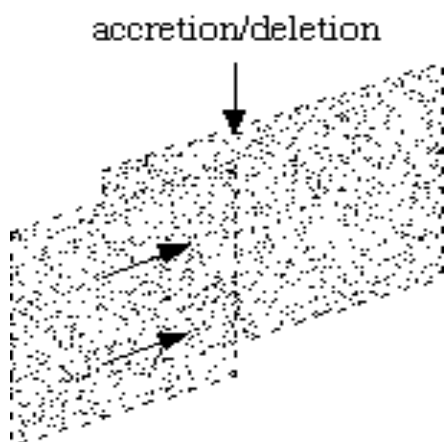


Figure 2. Generating a boundary from accretion/deletion of texture elements.

place due to sequential covering by a leading edge. At the loci where accretion and deletion occurs, a crisp, compelling edge appears. As soon as motion is halted, however, the edge stops for a brief moment and then disappears. Concurrently, the appearance of two surfaces separated in depth also vanishes, and a single homogeneous surface reappears. (Interestingly, the disappearance is not instantaneous -- to my knowledge, no measures have been attempted of this "permanence time" nor of the factors that may affect it.)

The discovery of occluding edges specified by accretion and deletion of texture played an important role in the development of the ecological approach to visual perception (Gibson, 1979), because they provided one instance of visual distance that does not need to be cognitively inferred (see Gibson, 1976) but may be picked up directly from the spatiotemporal structure of the optic array. Edges from accretion and deletion are inherently relational -- they can not occur on the basis of any single aspect of the display but require changes over time -- and thereby provided an important case for the ecological theory of perception. The role of accretion and deletion in SBF has been demonstrated in a variety of spatial tasks in adults (Andersen & Braunstein, 1983; Andersen & Cortese, 1989; Bruno & Bertamini, 1990; Kaufmann-Hayoz, Kaufmann & Stucki, 1986) and 5-month old infants (Craton & Yonas, 1988; Granrud, Yonas, Smith, Arterberry, Glicksman & Sorkes, 1984).

Besides accretion and deletion, some investigators have argued that crucial information for retrieving a SBF surface lies in the relative motion of texture elements and a boundary (Thompson, Mutch & Berzins, 1985), a source of information that has been dubbed the boundary flow cue (Yonas, Craton & Thompson, 1987). Information from relative motion stems from the basic constraint that, as a textured object sequentially occludes a textured background, elements on the object surface and the object boundaries move in unison. However, Craton & Yonas (1990) reported a series of experiments involving displays with two rigidly translating textures. The textures translated horizontally and were separated by a textureless gap, preventing the accretion and deletion of texture elements. Results suggested that observers were less likely to report the formation of one surface in front of another as the

width of the gap increased. If horizontal lines were added to define an illusory contour at the gap, however, observers again reported a surface in front independent of gap width.

These results seem to point to a role of relative motion as information for depth order, but not as information for the formation of the boundary. Some models of spatiotemporal boundary formation have proposed to distinguish between a depth segmentation and a boundary formation stage in SBF (Kellman & Shipley, 1991). To account for the latter stage, Shipley & Kellman (1997) presented an edge-orientation-from-motion (EOFM) model which extracts local boundary orientations from local motion vectors defined by the sequence of disappearances and appearances during accretion and deletion of texture, as well as other kinds of spatiotemporal discontinuities (see also Shipley & Cunningham, this volume). Supporting the notion that the crucial information for SBF in textured displays lies in local discontinuities, Kojima (1998) recently reported that discrimination between spatiotemporally defined vertical and horizontal figures was best at high spatial frequencies whereas it was significantly reduced in low-pass versions of the same displays.

Manipulations of Filled Shapes

Spatiotemporal boundary formation can be induced by sequential transformations of filled surfaces in otherwise homogeneous fields. Suppose that a set of four filled circles is placed on a homogeneous background on the perimeter of a circle, and that a triangle having the same color as the background is rotated over this circle so that its vertices are never in front of more than two circles at the same time. Although the triangle is invisible in any of the frames that make up the sequence, it becomes clearly visible when the sequence is animated. The sequential transformation of each circle in this kind of animation is similar to that of the original demonstration of the screen effect (Sampaio, 1943). However, in addition to seeing local occlusions at each circle as the triangular screen passes in front of them, observers also perceive a whole, modally present figure with a color different from the background. This figure appears to be the outcome of spatiotemporal interpolation and may be considered the SBF analog of Kanizsa's triangle (Kellman & Cohen, 1984).

The temporal and spatial characteristics of such interpolation have not been studied in a systematic fashion so far, although some relevant data can be found in Petersik & McDill (1981). An alternative manipulation of filled shapes has been reported by Klymenko & Weisstein (1986), which described the formation of a boundary of a 3D cube whose vertices were defined by dots. However, it could be argued that such boundaries are of a different kind from SBF in that the inducing motion sequence does not involve breaking projective correspondence. In fact, it is precisely because of the preservation of projective correspondence (no elements appear or disappear over time) that a 3D object emerges from the sequential transformation. The appearance of a border at the edge of the object may then be a direct consequence of the 3D interpretation rather than a form of visual interpolation.

Manipulations of Line Segments

Spatiotemporal boundaries can emerge from appropriate manipulations of line segments. In an early observation, Bradley and Lee (1982) superposed a white equilateral triangle on a black outline equilateral triangle. They also placed three black dots at the vertexes of the white triangle. Finally, they sequentially rotated the white triangle and the three dots, took successive snapshots of the transformations, and used them to construct an animation film (see Figure 3). When the animation was presented to 37 observers, 35 of them reported that the moving illusory triangle was more compelling than the static counterpart. Bradley and Lee took these results as evidence for an involvement of temporal information in the formation of the illusory triangle. In a variation of their basic display, however, they also tried removing the dots and they observed that the triangle appeared to have rounded corners when in certain positions relative to the inducing lines. The significance of this latter observation will be discussed in a later section.

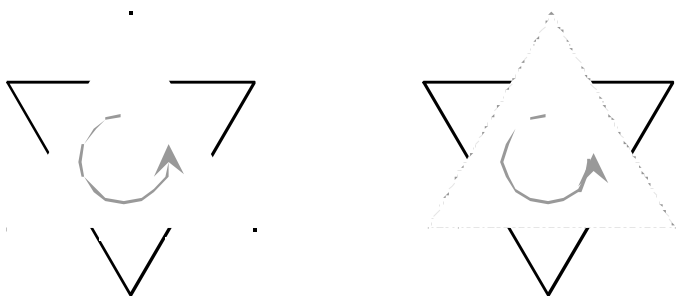


Figure 3. Spatiotemporal boundaries emerge from manipulations of line segments.

Given that the illusory boundary was already visible in the static frames, the observation of Bradley and Lee was not properly an instance of SBF. However, with a straightforward extension of their methodology (Bruno, 1989a,b) I have been able to demonstrate SBF boundaries from changes in length and position of lines as well as from simple changes in length. I employed thin luminous lines radiating from a common center attached on a black cardboard background. In front of the lines, I placed a black cardboard triangle centered on the radiating center. When observed in a dark environment, this pattern consisted of no other optical discontinuity but the set of luminous lines, which had different lengths depending on the position of the invisible triangle in front of them. However, the appearance of the pattern changed as a function of the number of lines employed. With more than 8 equidistant lines, all observers reported seeing an illusory triangle (Kanizsa, 1955). But with less than 5 lines, no observer saw a triangle and they all reported simply lines of different lengths.

I then animated the 5-line display using a rotor. When animated, all observers reported that they could see a clear, crisp boundary despite the fact that in the static views they could

see none. In addition, and much to my surprise, the boundary was triangular and rigid when the lines were rotated behind the stationary triangle, whereas it was amoeba-like and nonrigid when the triangle was rotated in front of the stationary lines (Figure 4). The asymmetry was surprising, because the two kinds of events entailed the same physical relative motions. Further studies (Bruno & Bertamini, 1990; Bruno & Gerbino, 1991) demonstrated that the ability to reconstruct the physically correct occluding shape is a function of spatial and temporal factors when the lines move, but of spatial factors alone when the figure moves. Thus, SBF is usually successful in retrieving the implicit occluding edge but it can fail under certain conditions.

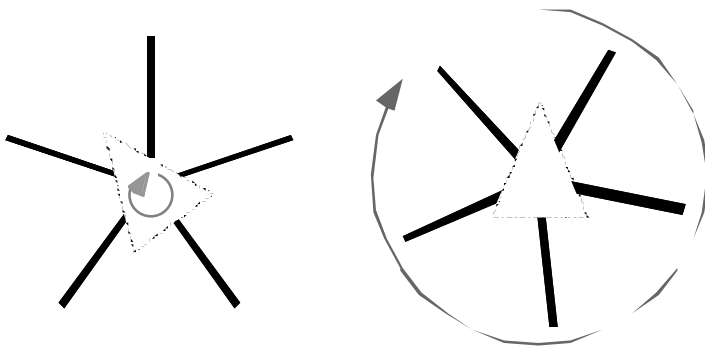


Figure 4. Rotating the figure vs. rotating background lines in a SBF display.

Combinations

In natural vision, occlusion and disocclusion of background elements by a moving surface often involves concurrent temporal transformations of texture, contours, and extended areas. For this reason, it is somewhat surprising that little attention has been devoted to SBF involving combinations of the classes of stimulus transformations described above. In a recent series of experiments (Bernardis & Bruno, 1999), we have started investigating the joint effect of textural transformations and of transformations of extended surface areas.

Experiments involved a square target surface rotating over across-like pattern. With a square having the same color as the general background, this pattern is equivalent to that investigated elsewhere (Bruno, 1989; Bruno & Bertamini, 1990; Bruno & Gerbino, 1991) and discussed in the previous section. Accordingly, the retrieval of the correct rotating shape depends on the size of the sequentially occluded cross arms, as demonstrated by a matching experiment. A set of eight small comparison squares was presented next to the experimental pattern. All these squares rotated around their centers 45 deg/s while physically changing their size. The change in size varied from 70% to 0% of the maximum square area, in steps of 10%. At small arm sizes, observers failed to retrieve the veridical, rigid rotating square and instead matched the rotating pattern to squares changing in size. The amount of size change

reduced monotonically as arm size was increased, and disappeared when the width of the cross arm was around 50- 60% of the side of the rotating square.

Taking rigidity matches for the standard SBF pattern as a baseline, we then tried several combinations of potential spatiotemporal information for surface boundaries. In the first of these, we added random-dot textures at a number of different densities. When a square defined by random-dot texture is rotated over a stationary background covered with texture having the same density, a rigid square is readily perceived even with very sparse textures (see section on texture information above). In our matching paradigm, we found essentially perfect rigidity matches even with textures as sparse as .004%. Thus, when the same texture patterns are superimposed on the cross pattern, the resulting pattern of temporal occlusion and disocclusion contains rich information about the rigid boundaries of the rotating square. However, and rather surprisingly, the square keeps deforming. In our matching paradigm, we found that adding sparse textures is essentially ineffective in reducing the temporal deformation. Increasing texture density, the temporal deformation reduces somewhat, but is still significant even at 50% densities.

In addition to manipulations of texture, we also investigated the effect of constraint points on the spatial interpolation of the occluding boundary. This we did by adding just four dots to the rotating square in different positions along its contour. Given that the presence of several hundreds of dot patterns in the random dot texture had such a minimal effect on reducing the deformation, one would predict that just four dots would be even less effective. However, the contrary occurs. When four dots are positioned at the vertices of the rotating square, the temporal deformation is significantly reduced even with very small dots and essentially neutralized as soon as the dots become larger. On the other hand, if the dots are positioned at the middle point of the square side, the deformation is as strong as without the constraint dots. Thus, the effect of adding four constraint dots on the temporal deformation of the rotating square appears similar to the effect of constraint dots on the spatial interpolation in static illusory contours (Vezzani, 1999). The theoretical implications of these preliminary findings will be discussed in a later section. Given the diverse findings that are brought together in these later sections, a brief review of the methods that have been used to quantify SBF phenomena is presented first.

MEASUREMENT ISSUES

Methods for quantifying spatiotemporal boundary formation have met with a typical dilemma of research on perceptual representations. On one hand, SBF surfaces can be assessed directly, by asking subjects to rate their vividness or clarity, or by collecting numerical rigidity ratings in the cases where SBF produces illusory deformations (see section on the breathing figure illusion below). Such direct ratings are typically performed as a

function of several physical parameters, such as spatiotemporal alignments of inducing elements or surfaces, contrast, and speed. Resulting functions appear to summarize well how the strength of SBF depends on such parameters, but their interpretation is often difficult because of the demand character (Orne, 1962) of these tasks.

Suppose that in one experiment an investigator varied the spatial alignment of inducing elements and asked observers to rate the clarity of the contour of the SBF surface. In such an experiment, one typically gets a monotonic curve whereby the clarity decreases as a function of departure from perfect alignment. It seems plausible to interpret this result as evidence that clear, crisp SBF contours are best obtained from spatially aligned inducers. However, one simply cannot rule out the possibility that what observers do in this task is not to judge the clarity of the SBF contour, but alignment itself. The latter perceptual quality is, after all, clearly available in the stimulus pattern, whereas the former is less clearly defined and it may require a certain amount of expertise to rate.

As an alternative to direct ratings, a number of investigators have sought to employ performance measures. An example of such measure is the ability to distinguish between straight and sinusoidal SBF contours bounding surfaces of equal area (Bruno & Bertamini, 1990). Other examples are the ability to distinguish between a vertical and a horizontal SBF surface (Kojima, 1998) or to identify which of a set of several shapes is induced by a current SBF display (Andersen & Cortese, 1989; Hine, 1987; Shipley & Kellman, 1997).

Performance measures provide an objective, quantitative assessment of dimensions that are presumably related to contour quality and vividness. For instance, it seems reasonable to assume that the more vivid the SBF contour, the better one should be able to discriminate it from other contours and to identify it. However, discrimination may also be possible on the basis of local properties of the inducing elements. If this is the case, then objective performance measures are even more problematic than direct ratings, for in performance paradigms observers are simply told to try to discriminate or identify shapes as well as they can, which may actually encourage them to use inducer features if available. In direct ratings, one at least tells observers to pay attention to a certain aspect of their experience, and can hope that observers will comply with that request. In performance measures, there is simply no way to be assured that observers are basing their responses on the SBF surface unless careful controls are employed.

One such control is the assessment of static versions of the induced figures. If these show a different pattern from the motion versions, one can at least conclude that discrimination was not based on spatial local properties of the inducers. Another approach would be to use the same animation sequence used for the SBF condition but slowed to a frame rate (e.g., 300 msec per frame) where no one reports seeing an SBF contour. It is still possible, however, that observers base their discriminations on temporally local properties, or on a combination of spatial and temporal features. I cannot think of a suitable control for these possibilities at present.

As yet another alternative to both direct reports and performance measures, some investigators have used paradigms involving indirect methods. For instance, Bernardis & Bruno (1999) evaluated the amount of nonrigidity in a SBF figure by asking observers to select, among a graded set of pulsating comparison figures, that which best matched the amount of pulsation seen in the current SBF display. In an earlier paper, Shiffrar & Pavel (1991) measured the amount of nonrigidity by an elegant nulling method, whereby observers changed the amount of perceived nonrigidity by manipulating the actual change in size of a rotating figure.

Such indirect methods combine the objectivity of performance measures with the possibility of directing the observer's attention to the perceptual variable one wishes to measure. However, it may not always be possible to find an appropriate procedure for all kinds of SBF surfaces and this may limit the applicability of the latter approach. In conclusion, direct assessments as well as performance measures are sometimes difficult to interpret. Indirect methods potentially provide unbiased measures of SBF clarity, but they may not always be possible. For these reasons, it seems advisable that theoretical conclusions be supported by converging evidence (Garner, Hacker & Ericksen, 1956) from as many paradigms as possible.

BREATHING ILLUSIONS

The human visual system can use spatiotemporally sparse information efficiently to detect and identify surface boundaries. Presumably, this ability is rooted in constraints originating from the ecology of our visual world (Parks, 1984). Environmental conditions such as transparent layers, fog, mist, reduced illumination, or camouflage can minimize the amount of spatial structure specifying surface boundaries in the optic array. In addition, most surfaces are subjected to partial occlusion by other opaque objects. That humans and other animals (Bravo, Blake & Morrison, 1988) are able to exploit additional constraints from the temporal structure of the optic array to reconstruct otherwise invisible boundaries is therefore useful and adaptive.

However, the ability to reconstruct surface boundaries from spatiotemporal patterns of occlusion and disocclusion is not perfect. In several documented cases, observers are unable to perform the reconstruction correctly because of insufficient spatiotemporal density of the visible elements (Andersen & Cortese, 1989; Bruno & Bertamini, 1990; Hine, 1987). These cases are interesting, in that they provide information concerning what is the minimum amount of information necessary for SBF. Of even greater interest, however, are cases where the available spatial information is potentially sufficient for veridical retrieval of the boundaries, but this is not used or it is misused.

In this section, the claim is developed that there is a class of motion illusions that has

precisely such characteristics. These illusions have to do with SBF in rotary patterns similar to those investigated by Bruno & Gerbino (1991), and consist of compelling impressions that the rotating figure, which is actually rigid, pulsates or breathes during the rotation. Following a terminology that has somehow made its way into popular science catalogs, I propose to refer to this class as the breathing illusions. Animated examples of such illusions can be viewed on the world-wide-web at <http://www.illusionworks.com>. A web tutorial specifically devoted to spatial effects on motion perception, including examples of breathing figure illusions, may be found at the web site of the Perception Laboratory of the University of Trieste, at <http://www.psico.univ.trieste.it/labs/perclab>.

Varieties of Breathing Figures

Instances of breathing illusions have been known for about a decade. To the best of my knowledge, the first report of illusory pulsation in a rigidly rotating figure is due to Meyer and Dougherty (1987, 1988), who described an illusion that they called contours that contract. Their illusion was generated by a white square rotating over a white background and four equidistant black-filled disks (Figure 5). The pattern yields a Kanizsa-type illusory square which is readily perceived in the stationary frames, but appears as a pulsating figure when in rotation. The pulsation is cyclical, with the perceived area reaching its maximum when the corners of the square are visible within the disks, and its minimum when the sides of the square produce perfectly horizontal and vertical cuts on the disks.

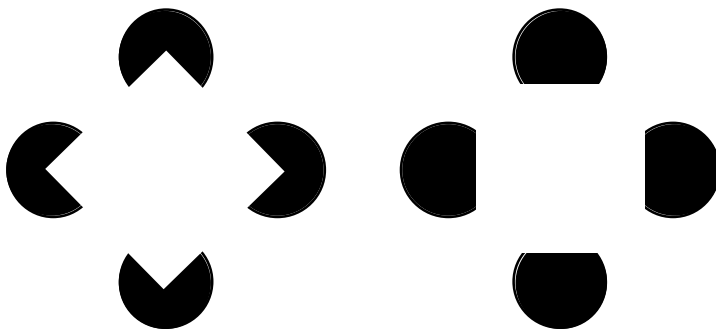


Figure 5. Two frames from a sequence generating a "breathing" illusory square.

In a later paper, Meyer & Dougherty (1990) also reported a related illusion obtained by rotating a black square behind four stationary white disks on a white background (Figure 6). The latter pattern produces the same cycle of visibility/invisibility of the square vertices as the original illusion, but with an inversion of the resulting surface stratification (the square is seen as occluded instead of occluding). The perceptual outcome of this manipulation is comparable to that of the original illusion, with the addition of figural bistability. Because of

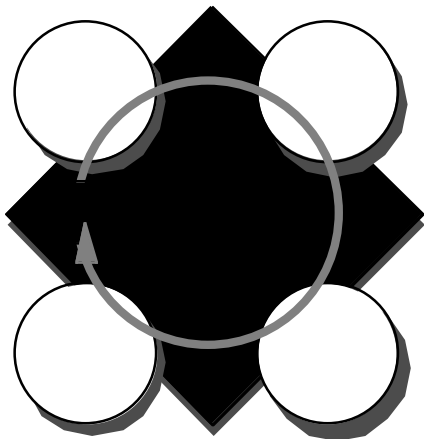


Figure 6. A bistable display perceived as a breathing occluded square or as an unoccluded "oozing" cross (the boundaries of the four disks were not visible in the actual motion sequence).

the figural characteristics of the pattern, most notably those having to do with the Gestalt law of closure, the perceptual interpretation of this pattern oscillates between two possibilities. The first of these consists of four stationary occluding illusory disks and a square behind them. When observers perceive these four illusory occluding disks, they also see that the rotating square breathes as in the original illusion. The second interpretation consists of an irregular object without occluders. If no occluders are perceived, this irregular object changes shape over time and it is perceived as a sort of rubbery or oozing cross. The two percepts seem to alternate for all observers although the second is somewhat easier to achieve.

A more exact analog to Meyer and Dougherty's breathing illusory can be created by simply adding a line around the four disks (Shiffrar & Pavel, 1991). Given that the circumference is always visible in these displays, the inversion of the surface stratification is stable in this case, causing the four disks to appear as four holes in a homogeneous surface. Through the four disks, one continuously perceives a square that completes behind the surface. However, the temporal transformations that occur within the four holes while the square is rotated behind the surface are exactly equivalent to those caused by the occluding surface of Meyer & Dougherty and the same illusory breathing is perceived.

Shiffrar & Pavel (1991) interpreted this finding as evidence that the breathing square illusion of Meyer & Dougherty is due to constraints on the spatial integration of motion signals. According to their proposal, when the corners of the square are not visible within one of the disks, because of the aperture problem the center of rotation for each of the visible contours is misperceived and placed near to, or at, the local center of the rotating side. As a consequence, local motion signals that are oriented toward or away from the actual center of rotation become available. These signals signal a change in size, and this causes the apparent breathing. There is, however, an alternative explanation for their observed equivalence. It could be that the same process of spatial completion is involved in both forms of the illusion. The hypothesis that the modal completion of an illusory border and the amodal completion of

a partly occluded border are mediated by the same unit-formation process is supported by a number of observations (Bradley & Petry, 1977; Kellman & Loukides, 1987; Kellman & Shipley, 1991; Petter, 1956; Shipley & Kellman, 1992). In a later section, I speculate that this equivalence of modal and amodal unit formation is actually crucial to an explanation of breathing figure illusions.

The breathing square displays of Meyer & Dougherty are not proper instances of SBF in that one can see an occluding square shape in each of the static views that compose the animation sequence. As such, they differ from the kinetic illusory triangle reported by Kellman & Cohen (1984). However, the relation between the two displays becomes obvious if one substitutes the three filled disks of the Kellman & Cohen animation with three filled rectangles similar to those studied by Bernardis & Bruno (1999). Figure 7, based on observations by Shiffrar and Pavel (1991), illustrates this point.

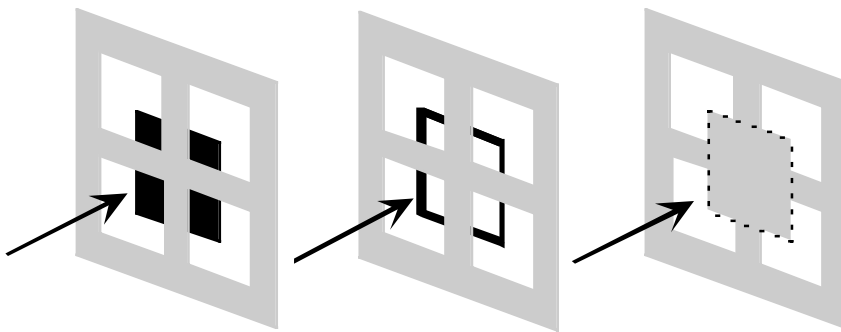


Figure 7. Generating an occluded filled square, an occluded square contour, or a square illusory figure with comparable spatiotemporal discontinuities.

The observation of motion sequences using these displays is especially instructive. When the rectangles are sufficiently wide, the substitution produces the same local transformations over the endings of the rectangles as those that are produced within the disks of Kellman and Cohen. As soon as rectangle width is decreased, however, a point is soon reached where the triangle appears nonrigid. Moreover, if the three rectangles are equidistant from each other, defining three 120 deg sectors, the triangle appears to breath exactly as the square of Meyer and Dougherty. Finally, by decreasing the width of the rectangles even more, one can produce the thin line display studied by Bruno (1989a; b) and by Bruno & Gerbino (1991) and described in the above section on SBF from line manipulations. Thus, all illusory deformations of rigidly rotating surfaces may be viewed as special cases of a general manipulation of the same stimulus dimensions, involving the size and density of the filled elements that are sequentially occluded and revealed. Parametric data collected by Bruno & Bertamini (1990) and, more recently, by Bernardis & Bruno (1999) suggest that the conditions of occurrence for breathing figure illusions depend on both these spatial

parameters, whereas they do not depend on rotation velocity.

Ravioli

Meyer and Dougherty (1987) also reported that if their square is replaced with a serrated square, a sort of illusory post-stamp or illusory *raviolo*, the breathing impression disappears. Observations from our laboratory indicate that this fact may not to be true in general. Data collected using the methodology of Bernardis & Bruno (1999) demonstrated that the pulsation is visible in the rotating ravioli, over a range of serration widths and not just when the serrations are so small as to make the corners difficult to perceive, as claimed by some (Shiffrar & Pavel, 1991).

In general, transitions between three, phenomenally distinct percepts can be observed when one measures breathing as a function of serration width. None of these entail a recovery of rigidity proper. With very small serrations, the breathing is clearly visible and the serrations appear to slide over the rotating sides in the opposite direction relative to the rotation direction. The sliding is similar to the so-called sliding effect observed when one places a dot on a contour viewed through a circular aperture, suggesting that very small serrations are perceived as elements placed on a straight contour, which becomes their proximal frame of reference independently of the overall rotation of the square, an instance of separation between perceptual systems (Duncker, 1923). With middle-sized serrations, the breathing is also very clear and only slightly less strong than the smaller cases. However, middle-sized serrations do not slide but appear as proper jagged edges. With very large serrations, finally, the spatio-temporal interpolation of the jagged lines fails, and one has a confusing impression of an incomplete figure flashing and then disappearing, occasionally rotating in one direction, occasionally rotating in the other.

Background Superiority

Breathing square illusions share another common element. They are readily experienced when a surface is seen rotating in front of stationary background elements or behind stationary holes, whereas they are much less compelling when exactly the same relative motions are produced by rotating the background element or foreground holes relative to a stationary figure. In a previous paper (Bruno & Gerbino, 1991), I have proposed to call this asymmetry in the perceptual result of displays having equivalent relative motions the background superiority effect or BSE for short.

Background-motion superiority in veridically specifying the shape of an occluding figure has been reported by a number of investigators. Bruno & Bertamini (1990) measured shape discriminations from occlusion events involving thin lines as a function of rotation speed and line density. They found that in figure-motion conditions discrimination was

essentially a step function of spatial density whereas it did not depend on velocity. In background motion conditions, on the other hand, discrimination performance was superior within comparable spatial conditions, and depended on both spatial density and velocity. Meyer and Dougherty (1991) reported that their 'oozing cross' was perceived only when the sequence was generated by rotating the square behind the circles. When the circles themselves were rotated, a rigid square was perceived with only a momentary loss of identity (not of rigidity) when the disks covered the square vertices. Shiffrar & Pavel (1991) measured the strength of the illusory breathing in both figure- and background-motion conditions and found essentially no breathing in the latter. Bruno and Gerbino (1991) analyzed the thin-line display investigated by Bruno (1989a, b) and found that a rotating triangle could yield a number of nonrigid percepts depending on the density of the occluded thin lines, whereas equivalent displays where the lines were moved behind the triangle yielded essentially rigid percepts. Even in related displays that do not yield the breathing illusion, it has been noted that the SBF figure appears sharper and clearer when the background moves (Kellman & Cohen, 1984; Kellman & Loukides, 1987).

Translatory Motion

A final element common to breathing figure illusions is their confinement to rotary displays. If the patterns studied by Meyer and Dougherty and Shiffrar and Pavel are modified to yield a cyclic oscillation along a rectilinear path, the translating square appears rigid. If they are modified to depict translation along the perimeter of a small square centered at the middle of the configuration, the square also appears rigid. Some nonrigidity can be perceived if a figure is translated over thin, sparse line elements, but not if it is translated over a random-dot texture (Bruno & Bertamini, 1990). Even in this case, however, discrimination performance is better with translations than with rotations.

THEORETICAL IMPLICATIONS

In this chapter, a claim is made that several motion illusions should be viewed as members of one general class. The class of breathing illusions consists of a number of compelling percepts of nonrigidity that are perceived when a moving figure is incompletely specified by the spatial structure of the optic array, so that its shape must be retrieved by processes of visual interpolation across spatially sparse elements. In most of the cases discussed above, the impression of nonrigidity consists of a cyclical change in size (i.e. breathing). However, alternative percepts are also possible, involving the perception of deforming blobs. Whatever the resulting type of nonrigidity, in all cases nonrigidity is perceived only if the figure moves and only if the motion is a rotation. If the background

moves relative to a stationary figure, or if the motion is a translation, then the illusion is absent or greatly reduced.

Relatability Theory

Although instances of breathing figure illusions have been known for some time, their theoretical implications have not been clarified. According to the current theory of SBF, observers reconstruct incompletely defined edges by means of an integration process that connects occlusion discontinuities across space or time, or both. The view that modal and amodal boundaries could be thought of as resulting from perceptual interpolation over space is found in early computational work (Brady & Grimson, 1981; Ullman, 1976). However, the development of a general theory of boundary formation across relatable discontinuities (henceforth: relatability theory) proceeded mostly from visual psychophysics and phenomenological observations (Kellman & Loukides, 1987; Kellman & Shipley, 1991; Shipley & Kellman, 1994, 1997). Relatability theory may be regarded as consisting of three key elements: the assumption of a common unit formation stage for modal and amodal boundary formation, the definition of spatio-temporal discontinuity, and the definition of constraints on interpolation. Let us consider them in detail against the characteristics of breathing figure illusions.

Consider first the hypothesis of a common unit formation stage. According to relatability theory, a common unit formation stage is involved in the formation of both modal and amodal boundaries. The phenomenal difference between these two types of boundaries is not due to the properties of the unit formation process, but to the properties of a second stage having to do with edge classification. If an edge is classified as being an occluding edge, then it becomes a modally perceived (albeit illusory) surface edge. If it is classified as an occluded edge, then it becomes an amodally completed edge. However, the actual reconstruction of boundary characteristics such as orientation, curvature, and motion is performed by one and the same process. In support of the claim of a single unit formation process underlying modal and amodal boundaries, it has been noted that in a number of displays both kinds of boundaries can form across the same discontinuities. For instance, in Petter's (1955) spontaneously splitting black-on-black figures, both a modal occluding boundary and an amodal occluded boundary are perceived, but their placement can flip over time as in a bistable pattern. Similarly, in Bradley & Petry's (1977) illusory Necker cube one sees modal boundaries belonging to an occluding cube, but the same configuration can also appear as an occluded cube seen through several holes. In this latter case, the boundaries of the cube are completed amodally.

Inasmuch as they can be produced both with modal and amodal boundaries, breathing figures are fully consistent with relatability theory in this respect. For instance, in Meyer and Dougherty's (1987) breathing square, the same spatial and temporal discontinuities yield

occluding, modal boundaries or, applying Shiffrar and Pavel's (1991) modification, occluded amodal boundaries. Yet, the breathing impression is identical, suggesting that the process that generated boundary properties yielded exactly the same results in both cases. The same considerations apply to the thin line displays studied by Bruno and Gerbino (1991). With training, it is possible to see the lines as thin slits on a homogeneous surface, with a figure moving behind such surface and seen through the slits (Maloney, personal communication). Again, the breathing impression is the same in the two cases.

Consider now the notion of discontinuities. Within the relatability framework, perceptual interpolation is triggered by specific properties in the structure of the optic array. These properties, called discontinuities, are defined separately for spatial and temporal domains. Let us consider them in turn. Spatial discontinuities are abrupt changes of direction in a contour specified by a luminance step. Such changes are identifiable as loci where functions describing contour curvature are not differentiable, that is, loci where the contour is not locally smooth. All t-junctions resulting from the superposition of two surfaces correspond to a spatial discontinuity and generate processes of amodal visual interpolation. However, any abrupt change in direction in a surface contour can function as a discontinuity, even without a t-junction defined by luminance steps. Thus, missing sectors or gaps in inducing surfaces can also trigger interpolation, as in the modal formation of illusory boundaries. Temporal discontinuities are temporal positions marking a sudden breakage of projective identity. Again, such losses of projective identity take place every time a surface undergoes partial occlusion and disocclusion by another opaque surface. However, such losses can take place even with a single surface. In the screen effect, for instance, initial views of the moving disk are projections of the same figure. As soon as the occlusion event begins, however, part of the disk is cut off and the resulting stimulus region is no longer a possible projection of the initial disk. Such interruption of projective identity is a temporal discontinuity.

Are breathing figure illusions consistent with process that interpolate across spatial and temporal discontinuities? At first blush, it would seem that the answer is no. After all, one of the defining characteristics of the class is that simple geometrical interpolation always reproduces the veridical occluding shape when applied to the static frames that compose the breathing animation. Thus, a trivial spatial interpolation process would predict rigidity in both figure- and background motion conditions. It is possible, however, that (potentially veridical) interpolation of spatial discontinuities is affected by a conflicting interpolation solution across temporal discontinuities. This is, in a nutshell, the explanation put forth by Shiffrar and Pavel (1991) for breathing figure illusions. In the next section, however, I argue that there are empirical reasons to conclude that this proposal may not be entirely correct.

Finally, consider constraints on interpolation. Within relatability theory, visual interpolation across spatial and temporal discontinuities is constrained by two factors: pairwise connectability and monotonicity. Pairwise connectability means that interpolation

can take place between two discontinuities, provided that no other discontinuity is in between. Monotonicity means that the connection between the two discontinuities must progress continuously, without changing direction or doubling back onto itself. The implications of these constraints for spatial relatability are straightforward. Their meaning for temporal relatability has been less clearly developed, but it seems to imply temporally continuous change of paired temporal discontinuities.

Breathing figure illusions are generally regarded as a consequence of a failure to apply a rigidity constraint against a potential nonrigid alternative, when this alternative is supported by specific processes of spatiotemporal interpolation (Shiffrar & Pavel, 1991). According to this account, the rotation of individual occluding contours is misperceived by observers because of a tendency to locate the center of rotation on the contour itself even when this is physically outside of the area where the contour is visible. Because of the aperture problem, such misperception yields significant motion components oriented away or toward the actual center of the configuration. Interpolating across the corresponding temporal discontinuities generates a nonrigid alternative to the rigid solution yielded by spatial interpolations. For some reason the system fails to apply a rigidity constraint across the temporal and spatial changes, and the perceptual result is a breathing figure.

Spatial vs. Spatiotemporal Interpolation

The explanation put forth by Shiffrar and Pavel (1991) is attractive, in that it ascribes the illusion to known constraints on the processing of local motion (i.e., the aperture problem, see Shiffrar, this volume), thereby providing an elegant proposal for the observed equivalence of the modal and amodal version of the breathing square illusion. Contrary to the above explanation, however, a number of facts suggest that breathing figures are not due to misperceiving the center of rotation. Consider the background superiority effect. Given that figure- and background-motion animations consist of exactly the same sequence of relative motions, it is not clear why center misperception should apply to the former, but not the latter. In fact, the temporal changes that occur as an occluding contour rotates over a stationary surface are identical to those that occur as the stationary surface rotates behind the occluding contour. Thus, the corresponding discontinuities (spatial and temporal) are the same, and local misperception of the center of rotation for contours should take place in both cases. It could be, however, that retrieving a stationary occluding figure lends more readily to a rigid interpretation, if available. This bias may result simply due to the stability of the occluding figure and its boundaries relative to a retinotopic frame of reference. Thus, the two motion conditions are not fully comparable, and the same explanation cannot be applied to both. This appears to be, albeit implicitly, the position of Shiffrar and Pavel (1991). Alternatively, it has been proposed that background motion conditions contain qualitatively different kinematic information about the occluding contour (Bruno & Gerbino, 1991).

Next, recall that compelling breathing illusions can be achieved using thin line displays (Bruno & Gerbino, 1991). Given that any 2D line is a possible projection of some line oriented in space, this type of display contains spatial, but not temporal discontinuities by the current definition. Therefore, either we conclude that temporal interpolation is not involved in the illusion, or we conclude that the definition of temporal discontinuities cannot be purely local. Under a global definition, the thin line displays investigated by Bruno and Gerbino (1991) could be regarded as involving the occlusion of a larger pattern, consisting of lines radiating off a common center. The global changes of this pattern do involve temporal breaking of projective identity, and would therefore constitute a temporal discontinuity by the current definition. However, two recent observations from our lab seem to provide definitive arguments against center misperception. These concern the effects of texture (Bernardis & Bruno, 1999) and of constraint dots (Bruno & Bernardis, in preparation) on the breathing illusion in patterns involving thin line elements.

Recall descriptions of these results in the section on SBF phenomena above. If random dot texture is added to the breathing square pattern, such that the spatiotemporal pattern of accretion and deletion veridically specifies square rotation, the square keeps breathing. This fact is problematic for the explanation based on misperceiving +the center of rotation, because textural optic flow unambiguously specifies this center in these displays. On the other hand, adding just four constraint dots on the vertices of the rotating square greatly reduces the breathing. This fact is even more problematic for the center misperception hypothesis, because no local information is available about the center of rotation of each square side in these displays. In conclusion, conditions that should allow accurate perception of the center can fail to stop the breathing, whereas conditions that should be consistent with its misperception can stop it. When considered together, these two results demonstrate a causal dissociation between misperceiving the center of rotation and the breathing impression.

The above facts suggest that breathing illusions are due to constraints on the multiscale interpolation of spatial, not spatiotemporal discontinuities. Consider the case of the breathing square. As the square rotates, it occupies one of two qualitatively different positions relative to the four disks. In one of these, the square covers the disks with its vertices. In the other, it covers them with its sides and its vertices are not specified in the luminance domain. These two positions correspond to different phases of the breathing impression. When the vertices are visible, the square reaches its maximum apparent size. As soon as they disappear, the square appears to shrink reaching its minimum size when the middle point of the side reaches the midpoint of the occluded disk. These phasic changes are consistent with transitions between different spatial interpolations of the discontinuities produced at the disks by the occlusion events. When the vertices are visible, each side is also partly visible and interpolation can be performed along a straight path. Accordingly, a Kanizsa-type illusory square is perceived in the stationary frames. When the side are visible, however, the vertices are not. Each of the visible sides is oriented at 90 deg relative to contiguous sides. Thus, in

this position continuous interpolation across spatial discontinuities must be along a curved path. Accordingly, in frames where only the sides are visible one does not tend to perceive a square but a square with rounded corners or, with sufficiently thin occluded elements, an illusory circle.

The fact that thin line inducers produce curve illusory contours has been known for a long time (Ehrenstein, 1941; Sambin, 1987) and has been often regarded as evidence for the constraints proposed by relatability theory (Kellman & Shipley, 1991). However, the implications for the explanation of breathing illusions have not been recognized. Breathing illusions may be simply due to cyclic transitions between different spatial interpolations, which in turn imply figures of different sizes and shapes. This proposal can be put to test by generating a breathing square animation employing four rectangular occluded elements in a crosslike pattern, and paying attention to the phenomenology of the apparent deformation. With relatively thin rectangles, one can indeed perceive a square turning into a circle. As the rectangles get wider, one no longer perceives a circle and the breathing impression weakens (Bernardis & Bruno, 1999). Further tests are also possible. For instance, it is known that adding constraint dots to an illusory circle induced by thin line elements turns the circular figure into a figure with vertices defined by the dots themselves (see Vezzani, 1999). We have found that if constraint dots are added to the breathing square animation to define the vertices of the rotating square, the illusion is greatly reduced relative to comparable textured animations that contain many dots instead of four (Bruno & Bernardis, in preparation). This finding is also consistent with a causal role of purely spatial interpolation.

Finally, discrimination studies suggest that the ability to retrieve the veridical shape from the sequential occlusion of lines or texture elements depends on spatial factors, such as line density, but not on temporal factors, such as rotation velocity (Bruno & Bertamini, 1990). Readers can easily convince themselves of this by again generating a breathing square animation employing four rectangular occluded elements in a cross like pattern. As the rectangles get wider, the reduction in the breathing impression is obvious. As the rotation is sped up within comparable widths, however, no reduction is seen.

Rigidity Constraints

In my initial definition of breathing illusions, I suggested that in these illusions a spatial interpolatory process should always produce a rigid, veridical interpretation. Although this is true in a purely geometrical sense, the above considerations imply that this is not equally true from the standpoint of the edge representations that are produced at early stages of visual processing. These representations entail a temporal transition between shapes having different shapes and sizes. Thus, in terms of these representations there simply is no rigid alternative in these displays. Breathing figures are not a counter example to the validity of a rigidity assumption in motion processing, because the system is not in the position of

making a choice between a rigid and a nonrigid alternative in these cases. The nonrigid interpretation is the only interpretation available given the early edge representations, their temporal unfolding, and binocular information about the position in depth of the rotating figure. If the salience of the latter is reduced by closing one eye, sitting far enough from the monitor, or simply by attentively ignoring it, then a rigid alternative exists and it is readily perceived: looming. An interesting test of these implications would be to assess the relative frequency of the looming vs. breathing interpretations, for monocularly viewed animations, as a function of rectangle width. With narrower rectangles, looming should be harder to perceive in that one can easily perceive the change in shape of the rotating figure.

Pursuit Eye Movements

The bulk of this chapter has been devoted to an analysis of breathing illusions within the framework of SBF theory. The examined data supported a causal role of spatial, not spatiotemporal interpolatory processes as claimed by earlier proposals (Shiffrar & Pavel, 1991). In addition, the present analysis suggested that breathing illusions should not be regarded as a counterexample to a rigidity assumption in motion processing. There is, however, one characteristic of the class that could appear as evidence against an explanation based on pure spatial interpolation. This characteristic is the confinement of breathing illusions to figure rotation conditions. Occlusion events involving the same sparse elements give rise to breathing illusions if they result from a rotating figure in front of a stationary background, but not if they result from a rotating background behind a stationary figure.

In an earlier paper, Bruno and Gerbino (1991) suggested that this asymmetry may be due to the nature of the stimulus transformations involved in the two conditions. Consider a breathing figure display with thin-line occluded elements. In figure rotation conditions, the stimulus transformations correspond solely to changes in length of the lines. The visual system has been shown to generally resist interpreting such one-dimensional change as due to occlusion (Rock & Gilchrist, 1975). Accordingly, observers report a deforming shape that closely follows the temporal transitions between spatial interpolations of line endings. In background rotation conditions, however, the stimulus transformations correspond to changes in length and position for each line. This two-dimensional transformation can be used to generate a motion vector oriented along the occluding contour by a simple vector summation operation (Bruno & Gerbino, 1991). Given that their analysis can be readily extended to any occluding element possessing a contour, the asymmetry appears consistent with a spatial explanation of breathing.

Bruno and Bertamini (1990) investigated the role of spatial density and velocity in four kinds of occlusion events: rotations with thin line backgrounds, horizontal translations with thin line background, rotations with textured backgrounds, and horizontal translations with textured backgrounds. They found that contour discriminations improved with spatial density

in all conditions, whereas they improved with density and velocity only with translatory displays, texture yielding the most marked improvement and thin lines yielding a somewhat weaker effect. To account for this difference, they speculated that observers might use pursuit eye movements to register contour information. As an illusory surface is translated over background elements, observers can produce a retinal transformation akin to background motion conditions if they maintain fixation on the figure itself. Such ocular pursuit would be most accurate with random dots peppered at all positions around the spatially undefined figure, less accurate with thin lines that occupy only specific positions and essentially impossible for rotary motions given that the eye can perform only limited rotations around its optical axis. The hypothesis of a role of pursuit in SBF is consistent with earlier reports of eye movement effects in anorthoscopic perception (Rock, Halper, Divita & Wheeler, 1986).

Direct tests of the role of pursuit in SBF would require eye-tracking equipment and have not been performed so far. However, indirect tests are possible. In unpublished experiments (Bruno, 1990) using the methodology of Bruno and Bertamini (1990), I investigated contour discriminations as a function of texture density, velocity, and duration. Given that the initiation of smooth pursuit involves latencies of about 100-200 ms (Robinson, 1965; Lightstone, 1973), I predicted that shorter durations would remove velocity effects in figure translation conditions, where pursuit is hypothesized to be critical for SBF, but not in background translation conditions. Three levels of density (12, 18, and 24 dots per cm² on a Macintosh screen viewed at an approximate distance of 50 cm), two levels of velocity (7 cm and 1.5 cm/s) and four stimulus durations (150, 300, 450, 600 ms) were investigated in both figure- and background-translation conditions. Percentages of correct identifications of the occluding contours were at chance at 150 ms and improved monotonically with density at longer durations in both conditions. However, the time course of the velocity effect was markedly different as a function of motion conditions. In background motion conditions, higher velocities allowed significantly more accurate identifications at 300 ms, and produced marked improvements at 450 and 600 ms. In figure motion conditions, velocity produced no effect at 300 and 450 ms, whereas it had a weak effect only at 600 ms durations.

These results are consistent with an account of identification as requiring two kinds of perceptual activity: retinal stabilization of the candidate contour, and acquisition of contour information. The first activity involves ocular pursuit, whereas the second implies stimulation of motion detectors. The extent to which an observer needs to perform these activities depends on motion conditions. With background motion, the figure is stationary and appears in correspondence with a fixation mark. Consequently, no pursuit movements are needed to stabilize the contour. All that is needed is to maintain fixation as the contour begins to be revealed by motion components from the moving background. If the motion is sufficiently fast, after approximately 300 ms enough of the contour has been revealed for discrimination. With figure motion, on the other hand, the figure must be pursued to reveal motion components that are informative about contour direction. The initiation of pursuit involves

an initial stage of about 200 ms to overcome inertia and begin the movement. Additional time may be needed to fine-tune eye motion in register with stimulus motion (Hallet, 1986). Thus, after another 300-400 ms, enough of the contour is revealed and performance begins to improve with velocity.

Adopting a more general theoretical stance, the potential role of pursuit could be regarded as a form of active exploratory behavior allowing observers to pick up spatiotemporal information. Such information can be retrieved only if the appropriate relationship is established between the perceptual system of an organism and the actual motions occurring in the environment. If this is correct, then SBF and its failures in breathing illusions may be considered as a theoretically important paradigm for investigating interrelations between perception and action (Gibson, 1979, E.J. Gibson, 1988).

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