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The Role of Genericity in the Perception of Illusory Contours

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Abstract

Visual images are ambiguous. Any given image, or collection of images, is consistent with an infinite number of possible states of the external world. Yet, the human visual system seems to have little difficulty in reducing this potential uncertainty to one, or perhaps a few perceptual interpretations. Many vision researchers have investigated what sort of constraints—assumptions about the external world and the images formed of it—that the visual system might be using to arrive at its perceptions. One important class of constraints are those based on *genericity* or *general position*.

We propose a theory of illusory contours in which general position assumptions are used to infer certain necessary conditions for the occurrence of illusory figures that appear to occlude their inducers. Experiments with human subjects are described. The results of these experiments suggest an important role for general position assumptions in understanding the perception of illusory contours. It is also demonstrated that *parallelism* of contours of "blob" type inducers is an important determinant of illusory contour strength.

Introduction

Illusory contours are contours that are perceived in regions of the visual field where there are, in fact, no physical contours, i.e., where there are no sharp gradients in any image property. For example, in Figure 1 most observers perceive a rectangular illusory surface that is brighter than the surrounding white area, and is partially occluding the black elements in the display. The theory of illusory contour perception presented in this paper has its roots in other theories proposed in the literature on human and machine vision. These theories have all used "general position" or "generic view" assumptions to understand some aspect of human perception, or to constrain the design of a computer vision algorithm. Roughly speaking, these assumptions are satisfied when the eye of the observer (or TV camera), and the physically independent objects in a scene are placed "randomly" with respect to each other, so that the image received by the eye is not in any way qualitatively "special" or improbable. These assumptions are closely related to the theory of perceptual preference proposed by Rock (1983).

Previous theories of illusory contours (IC's) fall into three main categories; peripheral, central and Gestaltist. Theorists in the peripheral group (Brigner and Gallagher, 1974; Frisby and Clatworthy, 1975) believe that IC's can be accounted for primarily in terms of peripheral neurobiological processes in the visual system. Theorists of the central group (Gregory, 1972; Rock and Anson, 1979; Coren, 1972) have pointed out that many of the properties of IC's do not fit with purely peripheral explanations. They claim that IC's are created higher up in the visual system, and that a "cognitive" sort of explanation is more appropriate. Our theory perhaps best fits in this category. Finally, the Gestaltists (Kanizsa, 1955, 1974) believe that the phenomena are best understood in terms of the Gestalt laws of perceptual organization.

Transversality

The Transversality Principle is central to the field of differential topology in mathematics (see, for example, Guillemin and Pollack, 1974). For our purposes we can state a special case of that principle as follows: If two differentiable curves in $\Re^2$ (i.e., the plane) are independently and randomly selected, then the probability that the derivatives of those curves will agree at any intersection point of the curves is zero. In other words, *generically* at all points where they inter-

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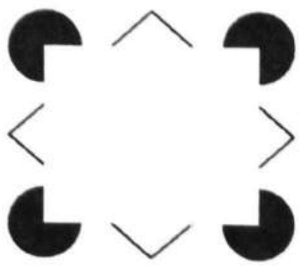


Figure 1

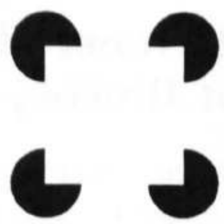


Figure 2

Figure 3

sect they intersect transversely.

The Transversality Principle is used in the work of Hoffman and Richards (1984) on the decomposition of physical objects into parts. For occlusion the Transversality Principle implies that, generically, the tangents to the curves that bound the objects in an image differ at all intersection points of those curves. In displays with "blob" inducers, we can use this observation to derive a necessary condition for the occurrence of a special class of IC's, viz., IC's that appear to partially occlude some or all of their inducers (ICO's).

The standard examples of IC's consist of some black regions on a white background in which an illusory "whiter than white" surface appears to partially occlude the black regions (e.g., Figure 2). By the Transversality Principle we can conclude that if the illusory surface occludes the black regions in a generic way, then each point of intersection of the IC with the contour of a partially occluded black region is a point of transverse intersection. We now make the following

General position assumption for illusory contours: ICO's are generated by the visual system only if the occlusion is generic.

If this assumption is correct, then a necessary condition for the occurrence of an illusory white surface that appears to partially occlude black inducers is the presence of *convex discontinuities* in the tangent lines to the contours of the inducers (also see Brady and Grimson, 1981; Kellman and Shipley, 1991).

Using magnitude estimation, 25 naive human subjects rated the IC in Figure 2 to be much stronger than in Figure 3, and they all said that the black elements appeared to be occluded in Figure 2, whereas 22 out of 25 said that they did not in Figure 3. Typically, subjects described the inducers in Figure 3 as pushed up against or crowded around the illusory square.

Line Drawing Interpretation

A number of theories of line drawing interpretation have been proposed by researchers in human and machine vision. Many of these theories have used the generic viewpoint assumption. In particular, Binford (1981) showed that a lot of information about the relative depth of curves in an image can be inferred by applying rules based on this assumption. These rules can explain, for example, why "special" viewpoints on a Necker cube lead to 2-D rather than 3-D interpretations. Two rules that will be useful for us are: 1) If three or more curves intersect at a common point in an image, then their preimages intersect at a common point in space and, 2) If two or more curves terminate at a common point in an image, then their preimages terminate at a common point in space.

Suppose we take a display that generates a strong ICO using line-end inducers, such as Figure 4. For each inducing line ending, we add to that display another line that terminates at a common point with it, as in Figure 5. If the human visual system generated an IC in Figure 5, then, treating the IC on an equal footing with the real lines in the display, and applying rule 1, it would conclude that the intersection point of the IC and the inducers in the image must correspond to an intersection of their preimages in space. So the IC and the lines would appear to be at the same depth where they meet, and the illusory surface would not appear to be occluding the inducers (also see Kennedy, 1978). Our experiments show that human subjects perceive the IC in Figure 5 to be much weaker, or nonexistent compared to that in Figure 4, and the appearance of occlusion is gone. This is true despite the fact that the inducers in Figure 5 are just as "well aligned" as in Figure 4 (see Rock and Anson 1979). In fact, the additional lines might lead one to expect a *stronger* IC in Figure 5 than in Figure 4. Thus, genericity seems to be important not only for the interpretation of ordinary line drawings, but also in determin-

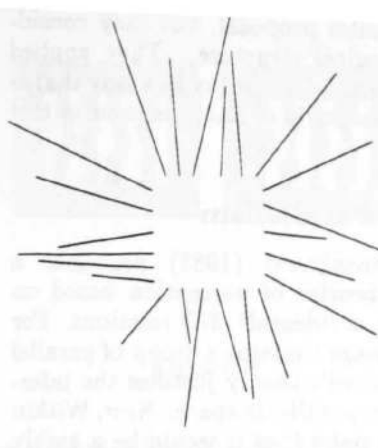


Figure 4

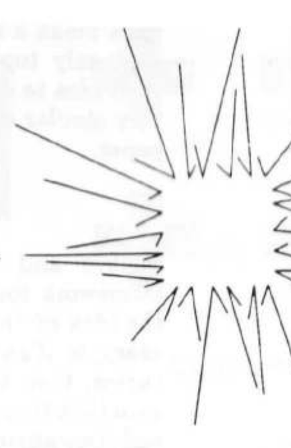


Figure 5

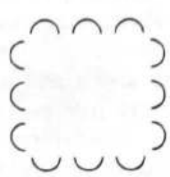


Figure 6

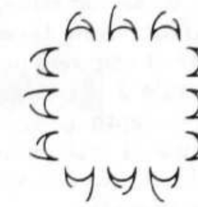


Figure 7

ing the stimulus conditions for IC perception (for more details see Albert, submitted).

In Figure 6 subjects perceive an ICO defined by the endings of the semicircular arcs. In Figure 7 we have added another coterminating arc for each ending of a semicircular arc in Figure 6 in such a way that their tangents agree at the cotermination points. Thus, the strong impression of line endings is preserved. Yet the IC has all but vanished. This seems inconsistent with the line-end contrast theory of IC perception put forward by Frisby and Clatworthy (1975), and with the theory of Grossberg and Mingolla (1985). However, using the genericity principle we can readily understand why Figure 6 produces an ICO and Figure 7 does not.

Analogous results can be obtained with the "neon color spreading" effect (van Tuijl, 1975). If we start with a display that produces neon color spreading using colored lines, and then add to it lines that intersect the original lines at their points of color change, then the neon color spreading is greatly reduced, and the perception of transparency disappears (see Albert and Hoffman, to appear).

While we have stated our theory in terms of the generic viewpoint assumption, analogous arguments can be made using the assumption that the physically independent objects in a scene are placed "randomly" with respect to each other in space. This constraint can explain the effects discussed above even if the illusory surface is seen as being only "infinitesimally" closer to the observer than the inducers when occlusion is perceived. Perhaps both constraints are influencing our perceptions.

In addition, although we have stated the theory in terms of "rules" for image interpretation and ICO perception, we do not claim that it is impossible to perceive an occluding illusory figure in displays for which such a percept in nongeneric. We only claim that, other things being equal, such a percept is much less likely, especially for naive subjects, than it is in displays in which the percept is generic. Similarly, it is possible to perceive "special" viewpoints on Necker cubes as cubes, but such interpretations are rarely made by naive subjects. Genericity is only one among many factors that are weighed by the visual system when it interprets images. It can be violated when other factors, which contradict its prediction for a particular image, are given greater weight by the visual system. We do not believe that constraints such as genericity (or, for example, rigidity in structure from motion) are strict rules of image interpretation. Our view is that these constraints can interact and compete with each other and with other visual cues to determine image interpretation.

Figures 4, 5, 6, and 7 were used in experiments with 25 naive human subjects. They rated the IC's in Figures 4 and 6 as much stronger than those in Figures 5 and 7, respectively. For Figures 4 and 6, 21 subjects said that the black elements were occluded, whereas only 2 said so for Figure 5, and none for Figure 7.

Many researchers have pointed out that outlines of pac-men (or other blob inducers) fail to generate IC's. Using genericity we can understand this outcome as follows: The short line segments that follow the potential IC cannot be seen as being partially occluded by an illusory surface because if they are viewed as being part of a larger blob-like element, then it is highly improbable that just a very thin edge of that blob would be visible (see also Kellman and Shipley, 1991). On the other hand, if they are viewed simply as line segments, then if any of them were at a different depth from the illusory edge which they appear to lay on (or next to) in the image, it would imply that our viewpoint on the scene was highly improbable. Thus, the short line segments must be at the same depth as the illusory edge, possibly interpreted as a highlight, or a surface irregularity, or as something attached to the side of the surface. Now those short segments also terminate at common points with the circular arcs, so by rule 2 the circular arcs must also be at the same depth as the short line segments at their points of intersection. Therefore, the potential inducers cannot appear to be occluded by an illusory surface.

Kanizsa (1974) has argued that "closure" can explain the perception of IC's with line-end inducers. Supporters of this theory might claim that the effects seen in our displays could be explained in this way (since the curves in Figures 5 and 7 are, at least, closed "on the side of the potential IC"). However, we believe genericity to be a more satisfactory explanation, since it is a valid ecological constraint. It also predicts certain perceived depth relations which closure cannot (see Albert, submitted).

Mathematical Formalization

Koenderink (1990) has proposed a theory of object recognition based on the the idea of generic versus accidental views. In his theory the ambient space of possible viewpoints on a scene is divided into "cells". The cell which contains a particular viewpoint is the largest connected region of the ambient space within which all viewpoints give rise to topologically equivalent images. Intuitively two images are topologically equivalent if the junctions among the image curves (excluding L junctions) have the same qualitative structure. The "cell walls" in this theory define surfaces in space. When an observer crosses a cell wall the qualitative structure of the image changes.

We believe that not only topological structure, but also first order differentiable structure is perceptually important. This entails that corresponding image curves have corresponding tangent discontinuities (i.e., transversality is taken into account). We make the following hypothesis: The visual system prefers not to interpret images in a way that places its viewpoint on a scene within a "cell wall" with regard to first order differentiable structure. The justification for this hypothesis is that if a viewpoint on a scene is chosen "at random", then the probability of ending up in a cell wall is zero. So if the features defining the cells and cell walls are perceptually salient, the visual system can use this probabilistic information in selecting interpretations for images. Nakayama and Shimojo (1990) have made a similar proposal, but they considered only topological structure. They applied their idea to a particular display in a way that is very similar to the style of analysis used in this paper.

Parallelism

Witkin and Tenenbaum (1983) proposed a framework for theories of perception based on the idea of "non-accidental" *3-D* relations. For example, if an image contains a group of parallel curves, then Binford's theory justifies the inference that they are parallel in space. Now, Witkin and Tenenbaum claim that it would be a highly improbable coincidence that they are all parallel to one another, unless they all arouse from a single "cause" or process. And this explains why the visual system is, in a sense, "correct" to group such curves together.

Lowe (1985) used the ideas of Witkin and Tenenbaum to construct a computer vision system. When Lowe's system saw two parallel lines in an image which could plausibly represent edges of objects in the scene, and if those lines were relatively close to each other in relation to the overall density of line segments at that scale in the image, then the system inferred that those lines were opposing edges of a single 3-dimensional object in the world. That is, Lowe instantiated Witkin and Tenenbaum's idea that the two lines arose from a single cause, to the inference that they represented edges of a single object.

Rock (1983) has pointed out that human subjects group parallel curves together to form the boundaries of regions more readily than they do non-parallel curves. For example, in Figure 8a most people see the black regions as figure and the white regions as ground, whereas the reverse is true for Figure 8b.

Now, consider Figure 9. This display has been discussed by many researchers going back to Kanizsa (1955). Note that 1) this display contains more black area than Figure 2, 2) there are equal amounts of the contour of the blobs along the potential IC in both displays, and 3) the length of the IC to be interpolated is the same. However, in spite of this, human subjects perceive an IC only weakly, if at all, in Figure 9, and a strong IC in Figure 2. Kanizsa claimed this as strong supporting evidence for his theory of IC's based on Gestalt ideas. He believed that the visual system creates an illusory surface in Figure 2, for example, so that the pac-men can be amodally completed to disks, which are "good", symmetrical forms. On the other hand, in Figure 9 the crosses are already quite symmetrical, and amodally extending them behind

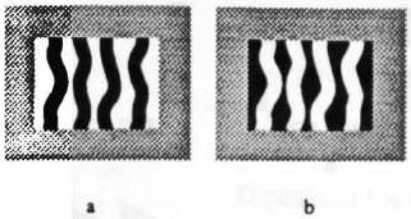


Figure 8

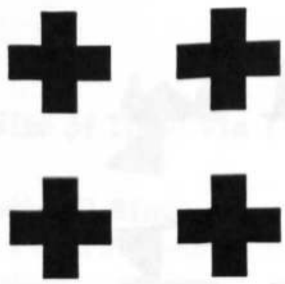


Figure 9

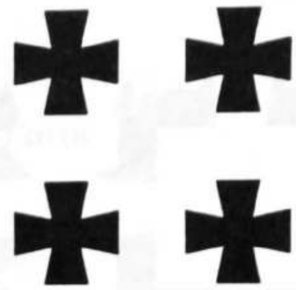


Figure 10

a potential illusory surface would destroy their symmetry. However, it was subsequently shown by Kanizsa and others that strong IC's occurred in displays in which the inducers could not possibly be amodally completed to entities possessing figural "goodness" in the Gestalt sense.

So, the theoretical position researchers found themselves in was the following: Potential amodal completion of inducers into good, symmetrical forms was not a major factor in *causing* IC's to occur. But, if the shape of the inducers was already good and symmetrical, then this *inhibited* the emergence of IC's.

However, consider Figure 10. In this display the inducers are just as symmetrical as in Figure 9, and there is much less alignment of the physically present edges, a factor that is known to have a considerable impact on IC strength (Rock and Anson, 1979). Yet, for most subjects the IC is stronger in Figure 10 than in Figure 9.

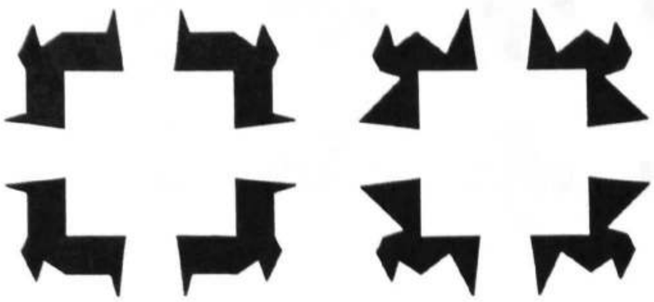
We would like to suggest that the major factor inhibiting the emergence of an IC in Figure 9 is *parallelism*. We claim that IC's should be weakened in displays with blob inducers if part of the contour of a blob is reasonably close to, approximately parallel to, and opposite the part of the blob's contour that is along the potential IC (e.g., Figure 11a). The theoretical ideas and psychophysical demonstrations presented above support this claim in the following way. When an IC occurs in a display with blob inducers, the part of the contour of a blob that is contiguous with the illusory surface must be interpreted by the visual system as being "owned" by the illusory surface, and the remainder of the contour interpreted as owned by the blob. Now, if the part of the contour that was meant to be owned by the illusory surface is parallel to and opposite a part of the contour that was meant to be owned by the blob, then the IC should be weakened if the visual system is biased towards interpreting parallel and opposite contours as both belonging to the same object.

We asked 25 naive human subjects to say whether Figure 11a or 11b had a stronger IC. The contours of the blobs in the two displays differ only in edges that are not along and do not intersect the potential IC. However, parts of the contours of the blobs in Figure 11a are parallel to and opposite the parts of the contours that lie along the potential IC. In our experiments 22 out of the 25 subjects said that the IC was stronger in Figure 11b than in Figure 11a. The same 25 subjects were also asked to rank order Figures 12a, b and c in terms of IC strength (from strongest to weakest). Here 20 out of the 25 subjects ordered them as 12c, 12b, 12a, 4 subjects ordered them as 12c, 12a, 12b, and one subject ordered them as 12a, 12b, 12c. Note that Figure 12c has half as much black area as Figure 12a, and that there are 6 possible orderings of the three displays.

Summary and Conclusion

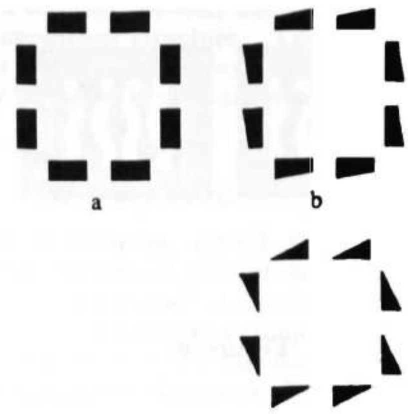
We have explored the hypothesis that the visual system applies the principle of genericity to the whole collection of contours that are perceived in an image. This includes contours that are given by real contrast edges, as well as illusory ones. In addition, we have shown that parallelism strongly influences IC perception, and that displays which had previously been thought to confirm the importance of symmetry might best be understood in terms of the influence of parallelism on the perceived "ownership" of contours.

What is the overall significance of the principle of genericity for understanding IC perception? Of course, it cannot predict the exact strength and perceptual quality of the IC's seen by observers in arbitrary displays. However, we feel it does provide important constraints for a more comprehensive theory.



a b

Figure 11



a b c

Figure 12

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