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The generic-viewpoint assumption and illusory contours

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Abstract. Visual images are ambiguous. Any image, or collection of images, is consistent with an infinite number of possible scenes in the world. Yet we are generally unaware of this ambiguity. During ordinary perception we are generally aware of only one, or perhaps a few of these possibilities. Human vision evidently exploits certain constraints—assumptions about the world and images formed of it—in order to generate its perceptions. One constraint that has been widely studied by researchers in human and machine vision is the generic-viewpoint assumption. We show that this assumption can help to explain the widely discussed fact that outlines of blobs are ineffective inducers of illusory contours. We also present a number of novel effects and report an experiment suggesting that the generic-viewpoint assumption strongly influences illusory-contour perception.

1 Introduction

Illusory contours (ICs) are contours seen where there are no corresponding gradients in the stimulus. Although ICs were first reported around the turn of the century, interest in this phenomenon dramatically increased after Kanizsa (1955) presented his striking demonstrations. Since then ICs have received a great deal of attention both experimentally and theoretically (for reviews see Parks 1984; Purghé and Coren 1992; Lesher 1995). Figure 1 is a typical example. Most observers see a rectangular illusory surface partially occluding the black inducers in the display. The illusory surface also appears brighter than the surround. Von der Heydt et al (1984) found that many cells in area 18 of monkey visual cortex respond to such illusory edges when they are placed in the cell's preferred position and orientation for ordinary luminance gradients.

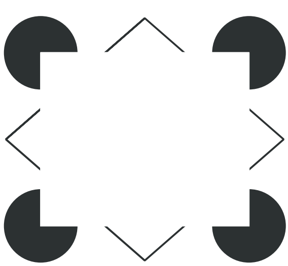

Figure 1. A Kanizsa illusory rectangle (after Kanizsa 1955).

Does IC perception have adaptive value, or is it simply a byproduct of visual mechanisms that *usually* provide useful information? Although ICs often go unnoticed during ordinary perception, we suggest that they aid visual perception of objects that have partly invisible boundaries owing to low contrast in the retinal image. For example, when the illumination of a scene is dim or spotty (eg moonlight streaming through trees), or when objects in the foreground are in shadow while the background is well lit, some sections of the occluding contour of an object may have contrast that falls below threshold, especially if the occluding and occluded surfaces have similar reflectances.

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In such cases the visual system needs to synthesize ICs through the low-contrast image regions in order to recover these object boundaries. In particular, IC perception would be useful for silhouette perception (Nakayama and Shimojo 1992).

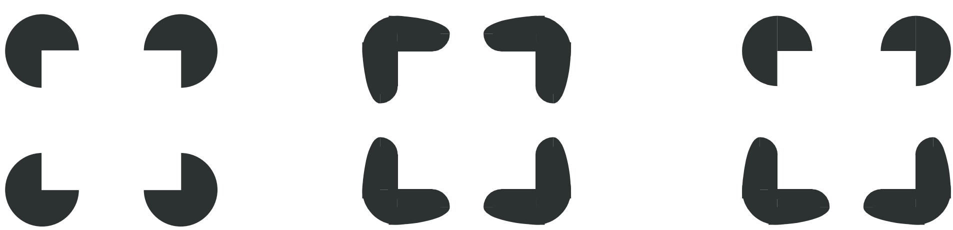
2 The generic-viewpoint assumption

It has been suggested that the assumptions of general position and generic viewpoint can help to explain various perceptual abilities, such as edge classification (Binford 1981), object recognition (Koenderink and van Doorn 1979), and scene perception (Witkin and Tenenbaum 1983; Nakayama and Shimojo 1990, 1992). These assumptions hold, roughly, when the viewpoint of the observer and the positions of the physically independent objects in the scene are placed at random relative to one another, so that the image received by the eye is not in any way qualitatively special and improbable. These assumptions are closely related to the coincidence-explanation principle of Rock (1983). We suggest that the generic-viewpoint assumption (GVA) can provide a number of useful insights into IC perception:

Hypothesis: *The visual system generates ICs that appear to be interposed in front of their inducers only if this interposition is generic.*

If this hypothesis is correct, then a necessary stimulus condition for perceiving an overlaying illusory figure induced by blobs is the presence of tangent discontinuities in the image contours of the blobs (eg an illusory square induced by pacmen—see figure 2).

Kellman and Shipley (1991) proposed that image tangent discontinuities are necessary for IC perception (also see Brady and Grimson 1981). In contrast, we suggest that tangent discontinuities are necessary only for the case of ICs that appear to be interposed in front of their inducers.(1) In fact, Shipley and Kellman's (1990) experiments showed that observers can see ICs in displays without tangent discontinuities, although these ICs tend to be relatively weak. Their observers did not report whether these illusory surfaces appeared to be interposed in front of their inducers.



(a) (b) (c)

Figure 2. ICs induced by 'blobs'. Interposition is not seen in (b) where the blobs do not contain tangent discontinuities.

From a theoretical point of view, the GVA implies that tangent discontinuities should be necessary *only if there is to be an appearance of interposition.* However, we agree with Kellman and Shipley that ICs induced by blobs without tangent discontinuities are often relatively weak. We suggest that IC stimuli that produce a percept of generic interposition generally produce stronger ICs than otherwise similar stimuli that do not.

Some examples of applications of the GVA to IC perception that go well beyond the work of Kellman and Shipley will be given below. In the next section we review some implications of the GVA for line-drawing interpretation. Following this, we show that these results can provide useful insights into the perception of ICs induced by line-endings, and we report an experiment using these stimuli. Finally, we show how this theory can help to explain why outlines of blobs produce much weaker ICs than filled blobs (eg pacmen).

(1) We use the terms 'overlay occlusion' and interposition interchangeably in this article. This should be distinguished from 'conformal' or penetration occlusion (see Tse and Albert 1998).

3 Line-drawing interpretation and the GVA

Several theories of line-drawing interpretation have used the GVA to justify rules for inferring 3-D structure from image curves (eg Binford 1981; Lowe 1985; Lowe and Binford 1985; Malik 1987). The following rules were suggested by Binford (1981):

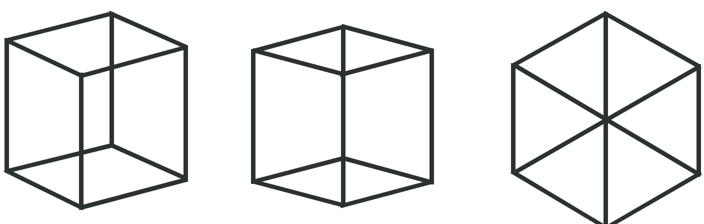
(i) The stem of a T-junction cannot be closer to the observer than the top. This rule would fail only if the 3-D surface containing the viewpoint of the observer and the top of the T also contained the upper endpoint of the stem. If the viewpoint of the observer is chosen at random, then the probability of this happening is zero.

(ii) If two curves co-terminate[2] in an image, then they co-terminate in 3-D space. Otherwise the viewpoint of the observer would have to lie on the line in 3-D space defined by the endpoints of the curves. If the viewpoint of the observer is chosen at random, then the probability of this happening is zero.

(iii) If a curve is continuous in an image, then it is continuous in 3-D space (ie there are no breaks). This rule generalizes rule (ii) if we consider an L-junction to be a tangent discontinuity in a single continuous curve. As with rule (ii), it would be violated only if the observer's viewpoint was along the line in 3-D space defined by the two endpoints constituting the break.

(iv) If three or more curves intersect at a common point in an image, then they intersect at a common point in 3-D space.

These rules can explain why figure 3a is easily seen as a cube, whereas figures 3b and 3c tend to look flat.



(a) (b) (c)

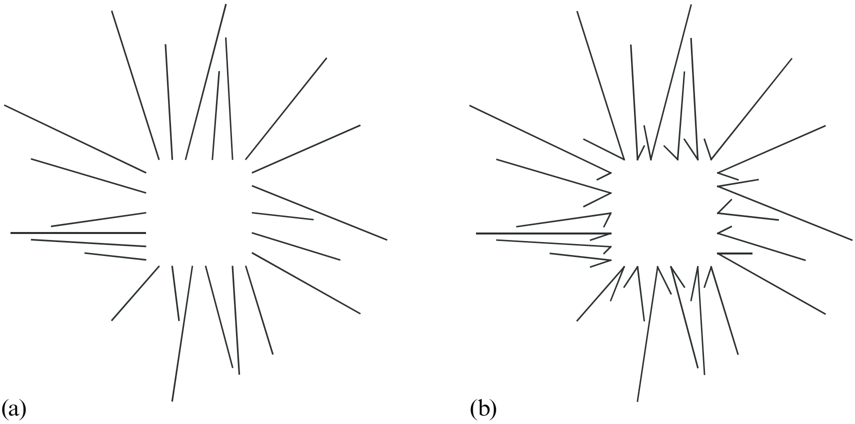
Figure 3. A Necker cube is seen in (a), but is more difficult to see in (b) and (c).

4 Illusory figures induced by line-endings and the GVA

Figure 4a generates a strong IC from line-endings. This display contains implicit T-junctions (Watanabe and Cavanagh 1993) at each point where an inducing line meets the IC: The inducing line forms the stem of the T and the IC forms the (implicit) top of the T. Thus, according to rule (i), the percept of overlay occlusion or interposition of the illusory surface in front of the lines is generic here.

Now, suppose that at each inducing line-ending in figure 4a we add another line that co-terminates with the original line-ending, as in figure 4b. Most observers perceive a much weaker IC in figure 4b than in figure 4a. Why do these additional lines weaken the IC? Usually ICs become stronger by adding more inducing lines. Moreover, the inducing line-endings in figure 4b are just as well-aligned along the potential IC as they are in figure 4a (Rock and Anson 1979). We suggest that this effect can be explained in terms of the GVA: Suppose that an illusory square were perceived to be interposed in front of the inducing lines in figure 4b. Then at each point where the inducing lines meet the potential IC we would have implicit K-junctions, rather than implicit T-junctions as in figure 4a. Each inducing L-junction forms the oblique lines of an implicit K-junction, and the IC forms its long stroke. If this stimulus generated an illusory square that was perceived as interposed in front of the inducing lines, then by

[2] We say that two curves *co-terminate* if they end at a common point (ie if they form an L-junction).

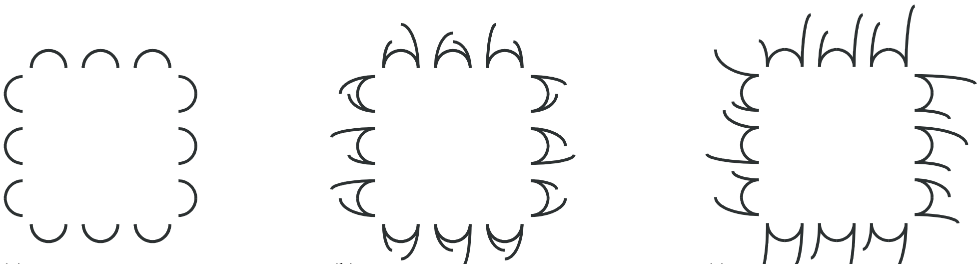


(a) (b)

Figure 4. The GVA applied to ICs induced by line-endings. A strong IC is seen in (a). Changing the inducing line-endings into L-junctions by adding more lines weakens the IC and eliminates the perception of interposition (b). This change can be explained by the GVA (see text for details).

rule (iv) this interposition would not be generic (also see Kennedy 1978; Finkel and Edelman 1989). The intuition here is that if the viewpoint of the observer is chosen at random, then it is highly improbable that the occluding edge of the interposed illusory figure would pass exactly through intersection points of the background lines.

Similarly, in figure 5a most observers perceive an illusory square defined by the terminations of the semicircular arcs. In figures 5b and 5c we have added an additional co-terminating arc for each terminator in figure 5a. In fact, not only do the additional arcs co-terminate with the semicircles, but their tangents also agree with those of the semicircles at the junction points. Thus, the local structure of the line-endings in figure 5a is preserved in figures 5b and 5c. Yet the IC has all but vanished. Many neural models of IC perception (eg Grossberg 1994) appear to depend primarily on the local structure of such terminators, and it is unclear whether they could account for these findings.

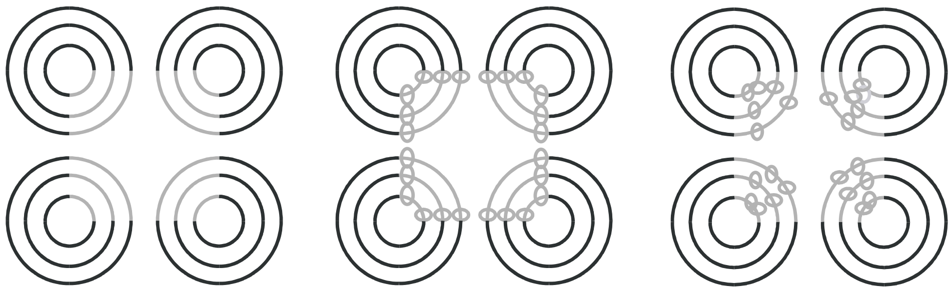


(a) (b) (c)

Figure 5. The GVA applied to ICs induced by arc-endings of semicircles. A strong IC is seen in (a). Changing the inducing arc-endings into L-junctions by adding more arcs, as in (b) and (c), weakens the IC and eliminates the perception of interposition. This change can be explained by the GVA.

Similar phenomena occur with the so-called neon color spreading effect (van Tuijl 1975). If we start with a display that produces neon color spreading using colored lines, and then add 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. An achromatic example is shown in figure 6 (see a chromatic example on the Perception website www.perceptionweb.com/perc0300/albert.html).

To quantify these effects we conducted the following experiment.



(a) (b) (c)

Figure 6. Neon brightness spreading can be seen in (a) and (c), but not in (b). This perceptual difference can be explained by the GVA.
For a color example see the website www.perceptionweb.com/perc0300/albert.html

5 Experiment

5.1 *Methods*

Figures 4a and 4b and figures 5a and 5b were shown to twenty-five naïve undergraduate psychology students. All displays were paper photocopies of laser printouts. They were viewed under ordinary room illumination at a distance of approximately 2 m. The test stimuli were presented in pseudorandom order.

Observers were asked to rate the IC strength of the test stimuli on a scale of 0 to 10. They were told to give a stimulus a rating of 10 if they perceived an illusory square as strong as or stronger than the one in figure 1, and a rating of 0 if they did not perceive any illusory square. Observers were also shown figure 7 and told to consider its IC strength to be a 0 or at most a 1. For each stimulus in which they perceived an illusory square they were asked to report whether or not it appeared to be interposed in front of its inducers. They were told that most observers see the illusory rectangle in figure 1 as interposed in front of its inducers.

The illusory figure region in figure 1 measured 6.3 cm by 7.8 cm. The width of the square region in figure 7 measured 5 cm on a side. The illusory square regions in figures 4a and 4b measured 4.8 cm on each side. Those in figures 5a and 5b measured 6 cm on each side.

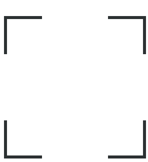


Figure 7. Line segments placed along a potential IC are ineffective inducers by themselves.

5.2 *Results*

The mean rating of IC strength for figure 4a was 5.8. Twenty-one out of the twenty-five observers said that the illusory surface appeared to be interposed in front of the lines, three said that it did not, and one observer did not see any IC. The mean rating for figure 4b was 2.5. Here two observers said that the illusory surface appeared to be interposed in front of the lines, seventeen said that it did not, and six did not see any IC. Thus, only two of the twenty-five observers saw the IC as interposed in front of its inducers in figure 4b. The difference in mean strength ratings was significant ($t_{24} = 4.786$, $p < 0.001$).

For figure 5a the mean rating of IC strength was 5.2, and twenty-one of the twenty-five observers said that the illusory surface appeared to be interposed in front of the arcs. In figure 5b the mean rating of IC strength was 1.1. Eleven observers saw no IC, and the remaining fourteen observers said that the illusory surface did not appear to be interposed in front of the arcs. Thus, none of the twenty-five observers saw an illusory surface that appeared to be interposed in front of the arcs in figure 5b. The difference in mean strength ratings was significant ($t_{24} = 7.033$, $p < 0.001$).

5.3 *Discussion*
These results strongly support our hypothesis (see above). Also, the stimuli that were inconsistent with generic interposition produced relatively weak ICs. However, stimuli that contain cues suggesting conformation of the inducers around the potential illusory surface can produce strong illusory surfaces. For example, a relatively strong illusory square (with rounded corners) can be seen in figure 8a. Similarly, the blobs in figure 8b appear to *conform* around an illusory pole.

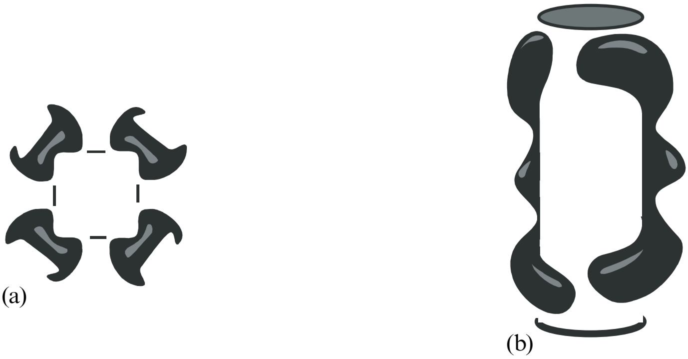


Figure 8. Relatively strong ICs can be seen in displays that are non-generic for interposition when the inducers appear to conform to the shape of the illusory surface. (a) An illusory square with rounded corners. (b) An illusory pole (Tse and Albert 1998).

The reader might question whether it is appropriate to apply the GVA to figures 1, 2, 4, and 5, since these illusory surfaces generally appear to be only slightly separated in depth from their inducers. If an observer were actually viewing a scene in which an occluding surface was only slightly in front of background surfaces and/or lines, then the image seen by the observer would change very slowly as a function of changes in viewpoint. We suggest that arguments analogous to those given above based on the GVA can also be made on the basis of the "principle of common physical processes". Assume that the physically independent objects in a scene are placed at random with respect to each other in 3-D space (Witkin and Tenenbaum 1983). Suppose that an illusory square is perceived in figure 2b, and that the inducing blobs do not appear to be in physical contact (directly or indirectly) with the illusory square. Then the smooth continuations of the boundaries of the blobs into the boundary of the illusory square would be unexplained coincidences.

These coincidences demand a perceptual interpretation which accounts for them in terms of some common physical cause or process. For example, suppose that the blobs in figure 2b were perceived to be somewhat flexible and deformable objects that were pushed up against the sides of the illusory surface and conforming to the shape of the square. This interpretation would account for the smooth continuation of these contours in physical terms. Similar arguments can be given for figures 4 and 5. The general principle is that any coincidental arrangement of features in the world should be explained in terms of some physical interaction (Rock 1983; Witkin and Tenenbaum 1983). We use the term genericity to denote the theory which combines the GVA with the principle of common physical processes.

Although we have stated our theory in terms of rules for image interpretation, we do not claim that it is impossible to perceive an overlaying figure in displays for which the interposition would be non-generic. We only claim that, other things being equal, such a percept is much less likely, especially for naive observers. For example, the dominant percept in figure 9a (ie two cubes) entails that three of the straight lines in the 2-D image (shown as dotted lines in figure 9b) are seen as containing sharp corners in 3-D. Similarly, it is possible to perceive figures 3b and 3c as cubes, but such interpretations are rare for naive observers. The GVA is only one among many factors that influence visual perception. We suggest the GVA provides soft constraints or perceptual preferences for vision.

(a) (b)

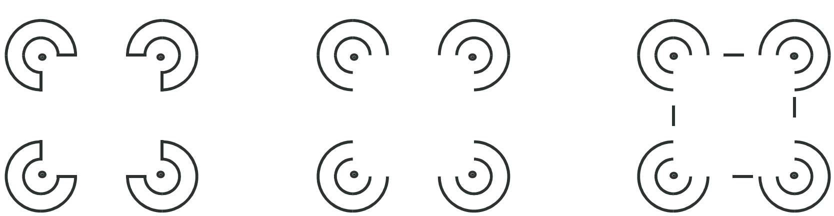
Figure 9. (a) This figure is generally seen as two cubes with different orientations touching at a corner. This percept entails that the three straight lines shown as dashed lines in (b) are not seen as straight in 3-D. In particular, the diagonal dotted line must have a very sharp corner in 3-D. Other junction cues and a bias towards convexity seem to have overruled the GVA in this percept.

Of course, the visual system cannot detect with infinite precision whether two lines terminate at precisely the same point, or whether a contour of a blob is smooth in the precise mathematical sense. Since the visual system has finite resolution, non-generic interpretations which would have zero probability if visual resolution were perfect, would have small, non-zero probability in practice. This is consistent with the idea that the GVA provides perceptual preferences rather than strict rules.

6 Why outlines of blobs do not induce strong ICs

Why do outlines of blob inducers, such as the stimulus in figure 10a fail to generate strong ICs? This question has been widely discussed in the IC literature over the past 30 years. In figure 10b we have removed the short line segments that connect the inner and outer circular arcs at each of the corners. This display produces a strong IC. Why do these short line segments make such a big difference? We suggest that the GVA can provide useful insights into these questions.

According to the GVA, if an illusory square is perceived in figure 10a, then the short line segments lying along the ICs cannot be perceived as the visible parts of partly occluded blobs, since it would be highly improbable that only very thin edges of those blobs would be visible (also see Kellman and Shipley 1991). On the other hand, if they are viewed as complete, unoccluded line segments, then they must be seen at the same depth as the ICs. Otherwise the fact that they coincide with the ICs in



(a) (b) (c)

Figure 10. (a) and (b) Outlines of blobs do not induce strong ICs (after Kanizsa 1974). (c) Strong ICs that appear to occlude the arcs but not the line segments. These percepts are consistent with the GVA (see text for details).

the image would be a coincidence of viewpoint. They could be interpreted as "lowlights", surface irregularities, or features attached to the sides of the illusory surface. Now these short line segments co-terminate with the circular arcs. So by rule (ii) (see above) the short line segments must also be perceived as lying at the same depth as the circular arcs at the L-junctions. Therefore, the potential IC must also be seen at the same depth as the circular arcs at the L-junctions, so the potential IC cannot appear to be interposed in front of its inducers. A similar argument can be used in the case of outlines of pacman inducers (figure 12a).

Intuitively the idea is that if an illusory surface appeared to be interposed in front of the circular arcs in figure 10a (as it does in figure 10b), then the visual system would have to wonder why the short line segments terminate exactly where the circular arcs pass underneath the illusory surface.

Kanizsa (1979, pages 217 – 218) used similar displays to contrast his theory of ICs with Gregory's (1972):

> "According to Gregory the sense data are used by the brain according to certain strategies, in order to decide which object has the highest probability of being present. But then, comparing the perceptual effects of figures 12.26a and 12.26b [similar to our figures 10b and 10a respectively], one should conclude that for the brain [a corner of the type in figure 12.26b] is more probable than [a corner of the type in figure 12.26a], a conclusion that seems to me rather implausible."

In our view it is not that the inducers in figure 10a are more probable than those in figure 10b, but that those in figure 10a would be highly *improbable* if there were a square (the potential illusory square) interposed in front, whereas the inducers in figure 10b would not. In other words, since the GVA provides necessary (in the soft sense described above) but not sufficient conditions for perceptual interposition, it helps to explain why an IC is not seen in figure 10a, but it is not *sufficient* to explain why an IC is seen in figure 10b.

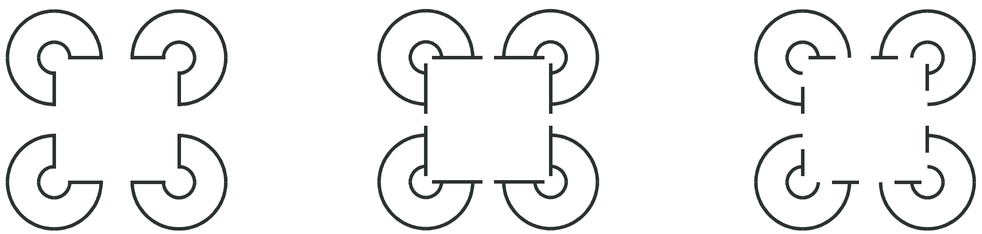
Rock (1987) discusses these same figures in relation to the internal consistency stage in his theory of perception as problem solving:

> "If the [perceptual] solution is that a white opaque figure is present on a white background, then its physical borders will only be visible where it happens to occlude a region (fragment) of a differing lightness. It would be inconsistent, then, if certain other parts of the borders of the hypothesized figure were included in the stimulus pattern. Why are they visible and not the remainder of the figure, the homunculus would have to ask."

However, in figure 10c parts of the borders of the hypothesized figure are also present. In contrast to figure 10a, a strong IC is perceived in figure 10c, perhaps stronger than the IC in figure 10b. Note that in figure 10c the circular arcs appear to be partially occluded, whereas the line segments that lie along the IC do not. Instead, these line segments appear to be somewhat closer than the circular arcs, lying at the same depth as the IC. This is what would be predicted on the basis of the GVA argument given above, since the L-junctions in figure 10a are not present in figure 10c. On this view, the presence of parts of the borders of the hypothesized figure and the absence of others does not represent a perceptual inconsistency per se. It can be accounted for in terms of highlights (or lowlights), surface irregularities, or other entities attached to the sides of the hypothesized figure. (Dots and very short line segments at illusory corners may play a similar role.) What we believe is operating in figure 10a is a perceptual preference along the lines of Rock's coincidence explanation principle (Rock 1983).

However, it might be argued that the inducing line-endings are covered up by the short line segments in figure 10a, and not in figures 10b or 10c, and that this might explain why the IC is weak in figure 10a. We have two responses to this suggestion.

First, the perception of occlusion in figure 11a, which contains L-junctions, is significantly less than that in figures 11b and 11c, which contain T-junctions that also "cover up" line-endings. Although figures 11b and 11c may not produce strong ICs, they do give an appearance of interposition. This is consistent with the predictions of the GVA. Second, the idea that the line-endings are covered up does not explain why the outlines of blobs in figure 12a (similar to figures 10a and 11a) produce weaker ICs than the filled blobs in figure 12b.



(a) (b) (c)

Figure 11. Interposition is stronger in (b) and (c) than it is in (a).

(a) (b)

Figure 12. Outlines of blobs do not induce strong ICs.

Kanizsa (1974) has argued that closure can explain ICs induced by line-endings. It might be argued that only weak ICs are seen in figure 4b, figures 5b and 5c, and figures 10a, 11a, and 12a because the lines and curves in those displays cannot increase their closure by generating an illusory square (cf figures 4a and 5a). However, we suggest that the GVA is a more satisfactory explanation, since it is based on a valid ecological constraint. It also predicts perceived depth relations among inducers which closure does not (eg see discussion of figure 10c). Also, since outlines of blobs tend to be interpreted as the boundaries of figures, one can ask why they should be regarded as complete (in the Gestalt sense) if the corresponding blobs are to be regarded as incomplete. The blobs in figure 12b have identical closed boundaries to the blobs in figure 12a. Thus, we think that the GVA provides a better and a more principled explanation for our results.

7 Summary and conclusion

We have proposed theoretical constraints on IC perception using the assumption that the visual system applies the GVA to the whole collection of contours seen in an image (both real edges and ICs). We have shown that the GVA helps to resolve a long-standing issue discussed in the literature on ICs, and correctly predicts some surprising new percepts.

The ideas we have proposed are in the tradition of cognitive theories of perception (Gregory 1972; Rock 1987) and the computational approach of Marr (1982). Although the representation of ICs is believed to begin relatively early in the visual pathway (von der Heydt et al 1984), top–down processes may also be very important. On the other hand, the rules for IC perception based on the GVA could be hard-wired or learned at a relatively low level. For example, junction detectors and cells that detect abrupt changes in contour direction could be combined through relatively simple networks to implement many of the rules we have discussed. However, at the present time such cells have not been shown to exist.

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