
Who owns the contour of a visual hole?

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Abstract. Holes are useful in the study of shape, contour curvature, and border ownership. Several authors have suggested that holes have figural or quasi-figural status. I discuss three criteria to test the evidence that holes behave more like figures than like ground: (i) holes perceived as such; (ii) similar performance for holes and figures; (iii) different performance for holes and other ground regions. Using these criteria, I review the literature and conclude that holes do not have figural status in relation to border ownership. I also argue that holes are ideal stimuli to study figure–ground organisation.

1 Introduction

Holes provide a Rosetta Stone in the study of figure–ground phenomena. The Rosetta Stone has both hieroglyphic and Greek scripts, with the same content.⁽¹⁾ Similarly, a region perceived as an object or a hole provides a direct comparison between a figure (object) and a ground (hole) that are identical (congruent) in all other respects. One might say that such regions have the same shape, but, as we will see, this needs qualification.

A great effort went into deciphering hieroglyphs. Similarly, figure–ground has been a central theme in perception since the beginning of the last century (Koffka 1935; Rubin 1921) and current interest is undiminished. Figure–ground segmentation is also important in computational vision (Venkatesh and Rosin 1995) and neuroscience (Lamme et al 2002; Zhou et al 2000).

But there is a problem with the claim that holes are ideal stimuli to compare the properties of figure and ground. If regions perceived as holes were a special case of ground they would be more interesting in themselves (as a curiosity) but less interesting in the study of figure–ground. Does the visual system treat regions perceived as holes in a fundamentally different way from other regions of background? The idea that holes (not some holes, some times, but holes in general) are special and have figural or quasi-figural properties has been endorsed by several authors (Casati and Varzi 1994; Feldman and Singh 2005; Palmer 1999; Peterson 2003; Subirana-Vilanova and Richards 1996).

This paper focuses on figure–ground, and on shape information that changes with figure–ground reversal. Traditionally figures have been described as nearer, occluding the background, and owning their contours (see Palmer 1999). This last property, unidirectional border ownership, means that the contour cannot belong to figure and ground at the same time. Of particular interest is the sign of contour curvature: positive and negative curvature values distinguish convexities from concavities. The importance of convexity can be traced back to Gestalt psychology (Kanizsa and Gerbino 1976; Rubin 1921). There is currently great interest in this topic (some examples from the last few years: Barenholtz and Feldman 2003; Barenholtz et al 2003; Bertamini and

⁽¹⁾ Actually, the Rosetta Stone is written in two languages (Egyptian and Greek), in three scripts (hieroglyphic, demotic, and Greek), but to mention this would have spoiled the metaphor. Many people worked on deciphering hieroglyphs until François Champollion succeeded in 1822.

Croucher 2003; Bertamini and Farrant 2005; De Winter and Wagemans 2004; Fantoni et al 2005; Hulleman and Humphreys 2005; Xu and Singh 2002). If holes are treated as figures, a hole and its complement (a congruent region perceived as figure) have the same contour curvature. If holes are treated as ground, a hole and its complement have opposite sign of curvature at any point.

In section 2 I discuss what is a hole. In section 3 I list three criteria for deciding whether holes behave more like figures than ground. Section 4 reviews the evidence; my contention is that there is little empirical support for the idea that holes are special with respect to border ownership. In section 5 I review evidence that confirms that the curvature sign reverses for holes compared to their complements. I also discuss neurophysiological studies that have used holes as stimuli (although they may not have been labelled as holes). They confirm that holes behave as ground regions with respect to border ownership.

2 Definition

A visual hole can be defined as a 2-D region on a surface surrounded by a closed contour but perceived as an aperture (a missing piece of surface) through which a further surface is visible. The letter O nicely illustrates this topology. The letter C has a different topology and the inside of the C is not a hole. This definition is not controversial, and can be rephrased in more mathematical terms (“A hole in a mathematical object is a topological structure which prevents the object from being continuously shrunk to a point”—Weisstein 2005). Alternatively, if one takes the hole to be the contour rather than the region, it would be incorrect to say that the hole is a background region, as the contour would be in the foreground. Finally, it should be mentioned that in the 3-D context the definition of holes is more complex, and includes hollows and cavities as well as tunnels (Casati and Varzi 1994).

In summary, I define holes as background regions that are surrounded by a foreground figure. As background regions only exist relative to some foreground, enclosure is a defining criterion for a hole. Because the curvature sign is defined with respect to the figure, the contour surrounding a circular hole is strictly concave. For more complex contours there are both concavities and convexities, and their complements have a complementary set of concavities and convexities.

The conditions necessary for a hole to be perceived as such have been studied by Bozzi (1975), Cavedon (1980), Massironi (2002), and Nelson and Palmer (2001). Nelson and Palmer (2001) conclude that three factors are critical: (i) depth factors indicating that the enclosed region lies behind its surround; (ii) grouping factors which relate the

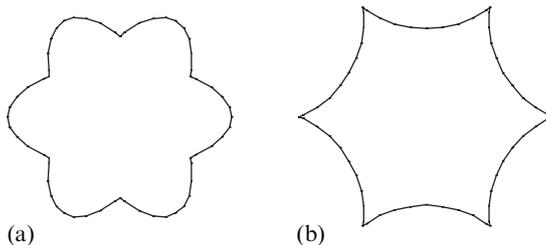


Figure 1. An early example of the use of holes to study figure–ground organisation: Arnheim (1954). Arnheim claimed that A tends to be seen as a figure because it is convex, and B as a hole because it is concave. In my drawing, A and B have the same area. To provide a simple empirical test, I asked twenty-two naive observers to choose the shape that looked more like a hole and 86% chose B. From a mathematical point of view, both regions are concave, because a shape is convex only if any segment connecting a pair of points on the contour is inside the shape. However, continuous measures of convexity, consistent with Arnheim’s intuition have been developed (eg Pao and Geiger 2001; Rosin 2000).

enclosed region to a surround; and (iii) figural factors, for example symmetry, convexity (see figure 1), or familiarity that may lead to the perception of a figure rather than a hole. Their absence helps the perception of a hole.⁽²⁾

3 Three criteria

Three criteria need to be met to show that holes have quasi-figural properties.

(i) *The stimuli must be perceived as holes.* This is a straightforward requirement for the validity of any claim about holes. It is worth mentioning because—together with symmetry, convexity, and familiarity (which I mentioned before)—closure is also a factor that contributes to the perception of a figure. When observers see monocularly a hole in a cardboard with a uniform background behind, they perceive a coloured patch (Cavedon 1980). Equally, it is not easy to draw with a pen a hole on a piece of paper. Therefore, as holes are enclosed regions, other factors must be present and strong enough to make this region belong to the ground (Nelson and Palmer 2001).

(ii) *On a given task involving shape perception, performance should be similar for holes and for figures.* An example would be Palmer's experiment (1999), which I discuss later, in which memory for shape was equal for figures and holes. Because this paper is about contours, some tasks are more interesting than others, in particular tasks in which the sign of contour curvature plays a role. If holes have figural status, they share the same curvature with their complements; conversely, if holes do not have figural status, there is a qualitative difference. Even if holes do not have quasi-figural status as far as border ownership is concerned, there might exist some tasks in which holes behave as figures. As figure-ground organisation is a dynamic process, influenced by many factors, observers may switch to seeing a hole as a figure more often than other ground regions because at least one factor (closure) leads in that direction. Holes may also behave like figures in tasks where figure-ground relationships do not matter.

(iii) *On the same task, holes should behave differently from other background regions.* If this criterion is not met, it would be hard to argue that holes have figural status. This criterion also ensures that the task is sensitive enough. For the sake of argument, imagine that a small and a large object are presented and observers are asked which is larger. Imagine then that a small and a large hole are presented and observers are asked the same question. Observers might be equally accurate in judging which is the larger region. This example might be trivial, but the only way to be sure that holes behave like figures is to compare them to non-enclosed regions of background. These stimuli should yield different results compared to both holes and figures. Put another way, many tasks exist in which holes, figures, and other background regions behave similarly; they in themselves do not make holes more similar to figures than ground regions.

There is a difficulty here: if holes and other regions of background differ because only the former are enclosed, it is hard to construct matched conditions. Therefore, if performance for holes and for other regions differs, one has to consider what factors could explain the difference. However, if performance for holes and for other regions is the same, this would undermine the claim that holes have quasi-figural status, in the sense that other regions of background could then lodge the same claim.

⁽²⁾ Richards and Hoffman (1985) have suggested another factor: we should see a hole as its complement (a figure) if that complement has fewer parts. Because of the role of minima of curvature in segmenting parts, the number of parts can change with a figure-ground reversal. The simplest example is an ellipse: a figure with an elliptical hole is segmented at the two negative minima, but an elliptical figure has no negative curvature (and therefore no parts). To my knowledge, no empirical study has yet tested this factor. Arnheim's example (1954) described in figure 1 raises some doubts. Richards and Hoffman's factor would predict the opposite effect, because the parts in A (seen as a figure) are more clearly segmented by the concave cusps than in B.

4 Examples from the literature in which holes behave like figures

4.1 *Casati and Varzi*

Holes have fascinated academics from many areas. Casati and Varzi (1994) tackled the problem of holes from an ontological perspective. They argue against a purely materialistic approach to shape, and holes are the perfect example of an entity that exists whilst at the same time it is not material. They criticise Lewis and Lewis (1983) for attempting a materialist solution, namely the fact that they equated holes with hole linings. As suggest by the title of their book, Casati and Varzi claim that holes are ‘superficialities’.

Although this is a book from two philosophers and the argument is ontological, Casati and Varzi (1994) are aware of the relevance of these issues to cognitive science. The emphasis on geometry and surfaces, in particular, sits well with an information-processing approach to vision (eg Nakayama et al 1995). Moreover, some of their claims are eminently testable. In particular, their claim that holes have shape is a precursor of Palmer’s claim (see later). Here is a quote: “there is a clear sense in which we can say that holes themselves have forms—forms that we recognise, measure, compare, and change” (page 5). They do not go as far as to say that the shape of a hole is the same perceptually as the shape of its complement, but this seems to follow from their examples, such as that of a fish-shaped hole.

It can be difficult to relate logical and ontological constraints to the working of the visual system. In this paper I leave this issue open. However, if logic suggests a similarity between holes and their complements it should be possible to test this idea experimentally. This evidence would need to meet the three criteria set out above.

4.2 *Subirana-Vilanova and Richards*

Subirana-Vilanova and Richards (1996) came to the problem of holes from a different direction. Their analysis starts from the issue of inside/outside, figure–ground organisation, and the focus of attention. They point out that inside/outside is not always well defined and fuzzy boundaries are common. Moreover, when concavities and convexities alternate, not all regions are equally important for shape analysis, for instance in similarity judgments. The evidence provided is phenomenological; in a series of figures they point out how most observers would answer certain questions.

Figure 2 is based on an example in Subirana-Vilanova and Richards (1996). If the shapes in A are figures and in B are perceived as holes, then it is surprising that the similarity judgment does not change (the central region is judged more similar to the top region than to the bottom region). If convexities on the outside have greater importance in similarity judgments, then the preference should reverse when the same region is perceived as a hole. This is because a figure–ground change reverses convexities and concavities. “Regardless of whether we view the combination as a donut with a hole, or as one shape occluding part of another, still we use the same portion of the inner contour to make our similarity judgment. The hole of the donut thus does not act like a hole” (page 1497). However, earlier the authors specifically stated that regions on the outside drive the similarity judgments, but these are not to be equated with convexities. Holes do not behave as holes in that their outside is not the outside of the figure, but the outside relative to the geometric centre of the configuration.

I have collected some data (reported in figure 2) to confirm this prediction. Thirty naive observers were screened for normal stereo acuity, then asked to describe the stimuli seen in a stereoviewer. They all confirmed that the stimuli were figures (A), holes (B), or an object with three regions missing (C). For half of the participants the position of what was at the top and at the bottom of the page was changed, and nobody saw more than one kind (A, B, or C). After the initial description, they made a similarity judgment (is the top one or the bottom one more similar to the standard in the middle?),



Figure 2. A comparison of figures (A), holes (B), and non-enclosed regions of background (C). The left and right pairs are for divergent and convergent fusers. Ten naive observers looked at the stimuli in A using a stereoviewer: when the two images are fused the grey shapes float over a checkerboard. The observers were asked to use the central shape as a standard and judge whether it was more similar to the one at the top or the one at the bottom (the spatial relationship was reversed for half of the participants). Another group of ten observers saw the stimuli in B which they described as holes, and a third group of ten saw the stimuli in C. A majority chose the top shape (80%, 90%, and 100%, respectively, for stimuli A, B, and C).

and most of them chose the spiky shape as more similar to the standard as predicted by Subirana-Vilanova and Richards; however, observers also chose the spiky shape in the case of background regions (C), suggesting that this phenomenon is not specific to holes.

Subirana-Vilanova and Richards (1996) claim that the match is with the region with spikes on the outside, even when these patterns “are regarded as textured donuts, with the innermost region a hole” (page 1497). They suggest that it is possible to make their pictorial stimuli look more like holes by increasing the subtended visual angle, or imagining putting a hand through the hole. Under such conditions, the similarity judgments may change because the attentional frame changes. Be that as it may, in figure 2

the similarity judgment is the same even for unambiguous holes (thanks to binocular disparity).

Holes are not central in Subirana-Vilanova and Richards' argument because the attentional frame may not be equated with what is perceived as figure. In their concluding remarks they suggest that recognition "proceeds by the successive processing of ... chunks of image structures lying outside the frame curve" (page 1500). This is a claim about how shape analysis and recognition work. The frame curve is the same for figures and holes; therefore shape analysis should be unaffected by such difference. Since the evidence suggests that the same is true for figures with shapes like a C, the effect is not specific to holes.

Subirana-Vilanova and Richards (1996) do not claim any qualitative difference for holes but rather a smooth transition from shapes with an outside (ie convex shapes) to shapes with an enclosed outside (ie holes). Their figure 7 makes this explicit by changing a rectangle into a semicircle (the shape of the letter C). Any configuration has a centre; in the case of holes (but also in the case of a C) this centre is in what is coded as outside but will still be the centre of the attentional frame. In conclusion, it seems that the focus of attention and contour curvature coding are separable phenomena. This, in turn, makes an interesting prediction for future research: the perceived sign of curvature should not depend on attentional factors.

4.3 Palmer

Palmer has discussed holes in his book (1999) and his results are cited by others to support the idea that holes have quasi-figural status as far as shape analysis is concerned (eg Feldman and Singh 2005).

Palmer (1999) sets out the problem with great elegance. It is believed that boundaries belong to figures, and that background regions are shapeless, an idea that can be traced back to Rubin (1921) and Koffka (1935). Figures are nearer the observer, and occluding the background. It is therefore fair to assume that holes are not figures (although this statement cannot be explicitly traced back to Gestalt psychology). But, if holes are background, they should be shapeless, so how do we recognise the shape of a hole? Palmer calls this the paradox of holes.

Can people recognise the shape of holes? Rock et al (cited in Palmer 1999, page 286) have tested memory for the shape of holes. Observers were shown cardboard cutouts. Some of them were figures and some of them were clearly holes in larger rectangular frames. Later, the observers were asked to recognise whether they had seen the shapes before, but were presented with figures (not holes). Observers are just as good at remembering the shape of a hole as remembering the shape of a figure.

Palmer's solution to the paradox is "the simple perception of a region as figural—and therefore as having a shape—may be quite different from the process of actually representing the shape of that region" (page 286). In other words, the holes are not figures and are not material, but they are "figures for purposes of describing shape" (page 287).

There is more than one possible interpretation of this suggestion. Perhaps observers extract shape information through a cognitive effort. After all, observers can switch what is perceived as a figure by a conscious effort, even when unambiguous information is present determining depth stratification (indeed intentional set was discussed at length in Rubin 1921). A stronger interpretation of this proposal implies that the principle of unilateral border ownership does not apply to holes, and that holes are qualitatively different from other types of background. However, the focus of Palmer's argument is on memory for shapes, and the idea is that the shape of a hole is a stable and non-accidental aspect of the stimulus. Therefore, this shape information is different from the shape of the accidental space between trees or people that is a more typical example of ground region.

I agree with Palmer on this point, but I have two comments. The first concerns to what extent this conclusion is specific to holes. Holes may have a shape that is stable and non-accidental, but other (non-enclosed) ground regions can have this property. Suppose that observers are asked to remember the size of the holes present in shapes like P and Q , they may perform well above chance. Performance may be unaffected by a figure–ground reversal, ie when the complements are presented at test time. Now suppose that observers are asked to remember the size (distance between horizontal lines) in the case of shapes like F and G . They may perform just as accurately and they may be again unaffected by a figure–ground reversal.

This shape property (size) is stable because it is not an accident of the viewpoint. This is true as long as the black lines are perceived as a single object, and not as separate objects at different depths. The example of size may be simplistic, but other aspects of shape could be used. Note that, if enclosure is not critical, the issue is not specific to holes. Of course, I may be wrong in my prediction, and enclosure always makes the task of judging and remembering shape easier. My point is that to know that conclusively we need a comparison between holes and other ground regions (the third criterion). It is also possible that there is a continuum with holes at one end, as implied by the idea that closure is not an all-or-none property (Elder and Zucker 1994).

My second comment is even more germane to the scope of this paper. Palmer's memory experiment is the strongest evidence for the figural status of holes, but it is a memory task and the implications of this evidence for border ownership are far from obvious. There is no doubt that memory for holes was well above chance. If holes are shapeless in the sense that they simply do not exist, memory performance should be at chance. But, if holes are only shapeless in the sense that the contours are assigned to the figure, the shape of the available figure will differ for different holes. Different holes imply different objects-with-holes. Therefore my thesis that the contour belongs to the enclosing object (the object-with-hole) does not predict chance performance.

4.4 Peterson

Peterson and collaborators have shown that shape recognition can occur before figure–ground organisation. That is, both figural and non-figural regions are processed to some extent, in particular when the non-figural regions have familiar shapes (Peterson 1994). This clearly is important as it paints a complex scenario for shape analysis and border ownership. In a recent chapter, Peterson (2003) claims that the non-figural side of a contour is subject to inhibition, that segmentation is not a process but an output, and that unidirectional border ownership is not obligatory. However, the latter point is controversial and a full discussion of this controversy is beyond the scope of the present paper.⁽³⁾ The rest of the argument is less controversial and in broad agreement with the fact that many factors contribute to figure–ground organisation, and that conflict between factors may be present. One type of conflict may come from the familiar shape of the ground regions.

Peterson (2003) discusses the example of a shaped aperture in a cardboard, not unlike the stimuli used by Palmer (1999). This cutout is used as a demonstration that, if the hole has the shape of a hand, observers would immediately recognise this as a hand, while at the same time seeing this as a hole: “the shaped aperture outcome is not a case of figure–ground segregation, which entails one-sided contour assignment. Instead, it is a special case of figure–figure segregation” (page 32).

⁽³⁾ Any theory (eg Feldman and Singh 2005; Hoffman and Richards 1984) that stresses the sign of contour curvature is threatened by the claim (in its strong version) that unidirectional border ownership is optional. If borders were not owned by one side, the sign of their curvature would be undefined. Moreover, if unidirectional border ownership were optional, we could concurrently see a vase and two faces in Rubin's figure, as well as the shape of a hole concurrently with the shape of the object-with-hole.

The term figure–figure segregation implies that both sides of the contour are processed with equal priority and without one side being subject to inhibition. If this were true, the shape of the region outside the hole would be processed as fully as the shape of the hole. Peterson’s demonstration does not address this; indeed extrapolating from Peterson’s experimental data one would expect that one region would be subject to inhibition. This hypothesis therefore needs to be tested. Note also that, in situations where two regions could claim ownership of a contour, Albert (2001) has found bistability rather than averaging.

Although the cited example of a cutout suggests that apertures (holes) are special, the actual experimental evidence reviewed in Peterson (2003) uses adjacent regions and is therefore not about holes. The evidence is that familiar shapes are processed also for the ground side of a contour. This applies not only to holes but to all ground regions.

4.5 *Feldman and Singh*

Feldman and Singh (2005) treat contour curvature from an information-theory perspective. There are various problems that need to be solved when curvature is measured along a closed contour. For example, curvature is not scale-invariant, and a larger circle has lower curvature than a smaller circle. The *surprisal* value as defined by Feldman and Singh is scale-invariant and increases monotonically with the magnitude of curvature (both welcome properties). Feldman and Singh also demonstrate that concavities carry more information than convexities. A polygon can have any number of convex and concave vertices, but the total convex angle (summed over all context vertices) must be larger than the total concave angle, otherwise the polygon will not close. Therefore, for a random location on a closed contour the prior probability is higher for convexity than for concavity. In this sense a concavity is more informative than a convexity.

At this point Feldman and Singh (2005) note that holes are a problem. For holes, the expectation about concavities can be reversed, since every region of a contour reverses from convex to concave and vice versa when we move from figures to holes. For holes, the *surprisal* value is higher for convexities than for concavities.

The solution to the problem of holes chosen by Feldman and Singh (2005) is to suggest that holes are special. Perhaps holes are treated as figures for the purposes of shape analysis: “Although the surrounding surface is given a figural status as far as depth and occlusion relations are concerned, the hole is given a quasi-figural status, as far as shape analysis is concerned” (page 248). In other words, even though a circular contour is convex when seen as a figure and concave when seen as a hole, perhaps observers do not code curvature differently for figures and holes. In support of such claim Feldman and Singh cite Subirana-Vilanova and Richards (1996) and Palmer (1999).

The starting point of Feldman and Singh’s argument is that we are dealing with closed contours. Clearly, in natural scenes object boundaries are often broken, for instance because of partial occlusion or lack of contrast, but, if these deletions are random, a probabilistic argument would still hold, namely that there is a tendency for contour curvature to be convex. This is not something discussed in the original paper, but, if it is correct, holes are not more of a problem than large concavities (ie a bay). If a large concavity is analysed *on its own*, it presents the same reversal of convex/concave relationships as a hole. But these exceptions are inevitably local and do not upset the global probabilistic claim. In other words, holes would only be a serious problem if they were as frequent in the world as objects are. We can safely assume that this is not the case.⁽⁴⁾

⁽⁴⁾ Holes are parasitic: a hole requires an object whilst an object does not require a hole. Therefore, one might be tempted to conclude that the number of objects must be equal or larger than the number of holes in the world, but this is not strictly correct because a single object can have a vast number of holes.

5 Holes and their complements are perceived differently

The discussion of the evidence in favour of the quasi-figural status of holes has shown that it depends on what one means, and I believe that with respect to border ownership holes do not have quasi-figural status. In this section I consider findings where holes behave like other background regions.

Gibson (1994) first provided some evidence that it is easier to judge the position of convex vertices than that of concave ones. Bertamini (2001) and Bertamini and Croucher (2003) have confirmed this convexity advantage. One experimental paradigm from this literature uses two simple shapes called barrel and hourglass (figure 3). The task is to look at the vertices on the outside and decide whether the left or the right vertex is lower (vertically). Responses are faster when the barrel is a figure and slower when the barrel is part of the background (between two outside figures). Conversely, responses are faster when the hourglass is part of the background than when it is a figure. This is consistent with a convexity advantage. This is true whether figure-ground reversal is achieved by telling observers which is the figure (by using a colour coding of figure-ground) or by closure of the contours (Bertamini and Friedenber 1999).

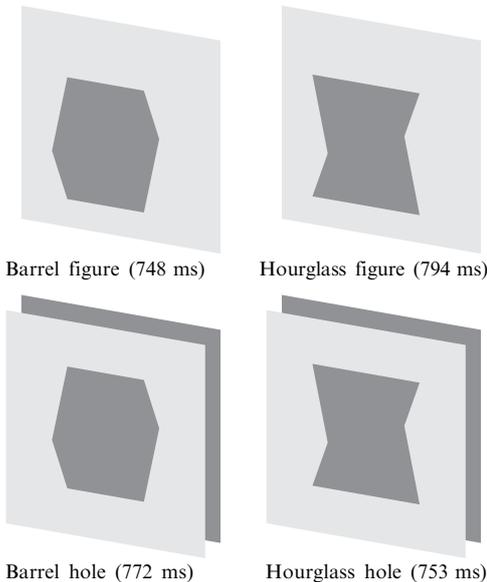


Figure 3. A description of stimuli used in Bertamini and Mosca (2004). The actual stimuli were random-dot stereograms. The important aspect is that the contours of the barrel and of the hourglass are the same in the figure and in the hole conditions. The task was to decide whether the vertex on the right or the one on the left was lower (vertically). In these examples the correct answer is left. Average response time for experiment 3 of Bertamini and Mosca is given next to the stimuli. The hole stimuli behave like regions of background in which convexity and concavity are reversed compared to the figure stimuli. The same interaction as shown here is present when figures are compared to regions of background (two figures and a central space), as reported for instance in Gibson (1994) and in Bertamini and Friedenber (1999).

Bertamini (2001) suggested that, if we accept that part structure is computed early (Singh and Hoffman 2001) and on the basis of contour curvature information (Hoffman and Richards 1984; Hoffman and Singh 1997), positional information may be more easily assessed for a convex vertex because it is a part (see also Koenderink 1990, page 251), as opposed to a concavity, which perceptually is a boundary between parts.

Bertamini and Croucher (2003) predicted an advantage for the barrel figure over the hourglass figure, but also an advantage for the hourglass hole over the barrel hole. This prediction was confirmed by Bertamini and Croucher and replicated by Bertamini and Mosca (2004) with random-dot stereograms (figure 3).

I do not see how this crossover interaction could be explained other than on the basis of a reversal of perceived convexity and concavity. Therefore, in this literature holes behave as regions of background (for instance those used by Gibson 1994, or Bertamini and Friedenber 1999) and differently from their complements. In other words, holes do not behave as their complements, even though the task was simple and could be performed quickly. This is a problem for any theory that claims that holes have quasi-figural status as far as shape analysis is concerned.

Fantoni et al (2005) have recently studied perception of partly hidden vertices, and compared convex and concave vertices. They found greater extrapolation for vertices perceived as concave. Interestingly, in their experiments 1 and 2 the vertices belonged to an object, but in their experiment 3 they belonged to an object-with-hole; nevertheless the results were compatible.

Hulleman and Humphreys (2004) have compared performance in a visual search for a given shape amongst holes and the same search amongst figures. One of their conclusions is that the search amongst holes is harder, even though the shapes (in terms of unassigned contours) were identical in both conditions. Unlike the interaction discussed above, this difference is quantitative; nevertheless, it suggests a difference between holes and their complements.

A final piece of evidence comes from neurophysiology. Lamme and collaborators have shown that figure-ground segmentation modulates responses in primary visual cortex (Lamme 1995). To determine figure-ground relationships Zipser et al (1996) used random-dot stereograms. In one study, a square frame with a hole was compared to a square moat with a figure by reversing the direction of the disparity. The frame/moat was outside the receptive field, and the fact that only disparity differs in the two displays insures that the critical factor is the 'perceived distal structure'. Neuronal response to a figure (surrounded by a moat) was higher than the response to a hole (surrounded by a frame). The response to a hole was not different from the response to a homogeneous background. The authors note that "this asymmetry of effect for the moat display compared with the frame display was highly consistent among the 14 single- and 132 multiunit sites that we studied" (page 7385); if anything responses to the uniform background were stronger than to the hole display, suggesting an inhibition of the ground side of a contour. Context modulation in V1 may be the result of extrastriate input, and the authors say that this is likely, given the time course of the effect. A more direct investigation of border ownership in V1 and V2 has been carried out by von der Heydt and collaborators (von der Heydt 2003). Many cells in V2 respond to the edge of a square figure whether the square is defined by luminance or binocular disparity (in a random-dot stereogram). Suppose one such cell responds when the edge has the figure to the right and the ground to the left. This cell will also respond to a square hole, but only if the hole is placed on the opposite side of the receptive field, so that the edge has again the figure to the right. However, there is no response to a square hole in the same location as a square figure, which is what would be expected if holes had quasi-figural status.

The random-dot stereograms used by Zipser et al (1996) are similar to those used by Bertamini and Mosca (2004). That is, in both cases a frame with a hole was compared to a figure with a moat. In both studies, the best explanation is that a hole does not exist as a surface because it does not own the surrounding contour.

More generally, the strategy adopted by Zipser et al (1996) and von der Heydt (2003) to compare figures and holes would be doomed if holes did not behave as ground regions. Instead, their findings suggest that holes are ideal stimuli to study the neurophysiology of figure-ground.

6 Conclusion

Many factors contribute to perception of figure-ground. Since closure is one of them, holes may not look convincingly as holes unless unambiguous information is present to determine figure-ground relations. In my work, I have resorted to random-dot stereograms as one way to achieve a compelling perception of holes. Another solution is to use cardboard cutouts (Palmer 1999). When holes are perceived as holes, I am not aware of any empirical data that show that holes own the surrounding contour. What is coded as convex and concave depends not on closure but on figure-ground segmentation.

To rephrase, there are dramatic changes in perceived shape due to changes of figure–ground, but there are no dramatic changes in perceived shape due to changes from enclosed ground regions (holes) to similar but non-enclosed ground regions.

Some questions remain unanswered. If contour curvature is important for shape analysis and recognition, how do observers recognise at all the familiar shape of a hole? One possibility is that multiple solutions for figure–ground are entertained by the system, and in some cases (not only holes) both sides are analysed. However, this does not fit the phenomenology of looking at a hole. When we perceive a hole, we do not experience multistability, the same way that we do for a Necker cube. Another solution is that the visual system is clever, and that, when it encodes contour curvature for a shape, it can code the sign as being the opposite of another shape but also register that the complete reversal means that the two shapes are related (complementary). This would explain for example how observers can notice the lock-and-key match of two shapes. Observers can detect a lock-and-key match of a pair of contours better than the same match within an object (Bertamini et al 1997). Even this hypothesis does not make holes quasi-figural, as it applies to other background regions as well.

More work is necessary. The demonstrations in the literature showing that people perceive the shape of holes (as similar to their complements) have in common that observers are allowed a long time to inspect and memorise the hole, whereas in the evidence showing that holes and figures behave differently speeded tasks have typically been used. It would be interesting to test to what extent the perception of a hole primes the response to its complement. We have started this study in my laboratory.

Finally, the examples given in section 5 show that holes remain uniquely useful stimuli to study the perception of shape, and, in particular, border ownership and contour curvature.

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