Perception, 2004, volume 33, pages 35 – 48

DOI:10.1068/p5024

Early computation of contour curvature and part structure: Evidence from holes†

Marco Bertamini, Fauzia Mosca
Department of Psychology, Eleanor Rathbone Building, University of Liverpool, Liverpool L69 7ZA, UK; e-mail: M.Bertamini@liverpool.ac.uk
Received 12 December 2002, in revised form 14 August 2003; published online 14 January 2004

Abstract. We used holes to study unilateral border ownership and in particular the information carried by the sign of the curvature along the contour (ie the difference between convex and concave regions). When people perceive a hole, its shape has a reversed curvature polarity (ie a changed sign of curvature) compared to the same region perceived as an object. Bertamini (2001 *Perception* **30** 1295 – 1310), and Bertamini and Croucher (2003 *Cognition* **87** 33 – 54) suggested and found evidence to support the hypothesis that, because convex regions are perceived as parts, positional information is more readily available for convex regions. Therefore a change is predicted when a given region is perceived as either a hole or a figure. We confirm that finding in this study, using holes defined by binocular disparity. We conclude that a change from figure to hole always reverses the encoding of curvature polarity. In turn, polarity obligatorily affects perceived part structure and the processing of position.

1 Introduction

It is generally accepted that contours convey much of the information about solid shape, as in the case of line drawings. Contours do not exist in the visual scene until contour information is extracted, for instance on the basis of colour or luminance changes. However, even after locating the contour, this type of information can be encoded and used in more than one way. Consider the curvature measured along a contour. Attention has been given in the literature to the peaks of curvature, such as maxima points (Attneave 1954, 1974; Kennedy and Domander 1985; Norman et al 2001), the sign of the curvature which distinguishes convex and concave regions (Hoffman and Richards 1984; Kanizsa and Gerbino 1976), the minima of curvature as a special case in relation to the traversality principle (Hoffman and Richards 1984; Singh et al 2000), and even discontinuities in changes of curvature, as can be found in the second derivative of curvature (Kristjánsson and Tse 2001). In this study we are interested in the sign of the curvature, and its relationship to part structure.

To encode curvature with a nonarbitrary sign, it is necessary to know what is the inside and what is the outside of a region. For example, a circle has a constant value of curvature along its contour, and the sign is always positive. However, if a circle were to be a circular hole within a larger object, the sign would be negative because curvature is measured along the object. In other words, a circle perceived as a figure is strictly convex (positive curvature) and a circle perceived as a hole is strictly concave (negative curvature). This implies that curvature sign can only be computed after, or at the same time, as figure – ground organisation, and that a change in figure – ground organisation will change the sign of the curvature.[1]

The relationship between figure – ground organisation and convexity has already been considered in Rubin's classic book (1921) and tested by Kanizsa and Gerbino (1976),

† Preliminary results were presented at the ECVP conference in August 2002 in Glasgow.

[1] One may be tempted to assign one curvature to the figure and the opposite to the ground or hole, but this goes against the principle of unilateral border ownership. As argued by Rubin (1921) and Koffka (1935) only figures have shape, whilst background regions are shapeless. However, for memory effects on figure – ground organisation before conscious recognition, see Peterson et al (2000).

but more recently the analysis has developed in new directions. In particular, there is one important way in which the sign of curvature affects what we see. On the basis of differential geometry, Hoffman and Richards (1984) have shown that arbitrary solid shapes that interpenetrate create concave creases (ie they meet in a transversal intersection), and in a smoothed version this crease is a peak of curvature located exactly where the two solid shapes interpenetrate. This fact about solid shapes is reflected in their projected image in a lawful way (Koenderink 1984, 1990). The saddle region corresponding to the smoothed crease will project a concave contour in the 2-D image, and the peak of curvature will be a negative peak (a minimum). On this basis, Hoffman and Richards (1984) proposed that shapes are parsed into parts at points of minimum curvature (the minima rule). The rationale is that concavities (and minima in particular) mark boundaries between parts of solid shapes. In contrast, convexities mark the parts themselves.

The idea that objects are represented as structural descriptions, consisting of parts, has a long history. Important contributions have been made by Sutherland (1968), Barlow et al (1972), Marr and Nishihara (1978), Hoffman and Richard (1984), and Biederman (1987). Empirical support for the special role of parts in the recognition of novel objects has also been reported recently by Foster and Gilson (2002). A growing body of evidence supports the early computation by the visual system of part structure on the basis of curvature information (for a review, see Singh and Hoffman 2001). To summarise, parts can be extracted by early processing of the 2-D image, and contours and contour curvature can be analysed by the visual system to solve the fundamental problem of extracting 3-D information about opaque surfaces without relying on template matching with stored volume primitives (Singh and Hoffman 2001).

Recently, Bertamini (2001), and Bertamini and Croucher (2003) have suggested that as a consequence of the early computation of parts, positional information of a contour is more readily available when the contour is perceived as defining a part (see also Gibson 1994). Bertamini (2001) found evidence to support this hypothesis using a task where the position of a vertex had to be compared to a reference line, and Bertamini and Croucher (2003) used a task in which the vertical position of two vertices on irregular hexagons had to be compared. They found a crossover interaction due to figure – ground reversal; that is, performance was better when the contours were perceived as convex (figure 1). The figure – ground reversal was achieved by making the region appear as an object (figure) or as a hole in a larger object (ground). We use similar stimuli and provide further evidence for this convexity advantage by comparing shapes that are perceived either as figures or ground. Unlike Bertamini and Croucher (2003), we specify what is an object and what is a hole by binocular disparity.

The task we used was to compare the relative position of two vertices. This task and hexagons similar to those in figure 1 have been used in previous studies (eg Baylis and Driver 1993; Elder and Zucker 1993; Gibson 1994), and it is known that in a direct comparison between what we call barrel and hourglass shapes, participants perform better when judging the position of the vertices of the former. This is true even though, if the area is constant, the vertices of the barrel are farther removed from each other. However, Bertamini and Croucher (2003) found that this advantage for the barrel can be reversed when these same regions are perceived as holes. It is this crossover in the performance that supports the critical role of convexity and concavity in judgments of position.

The literature on the perception of the shape of holes is limited, but some important contributions relative to the factors that lead to the perception of a region as a hole have been made by Bozzi (1975), Cavedon (1980), Nelson and Palmer (2001), and Palmer (1999). We have taken these factors into account in designing our stimuli. A more philosophical (but nevertheless relevant to the study of perception) treatment of holes can be found in Casati and Varzi (1994).

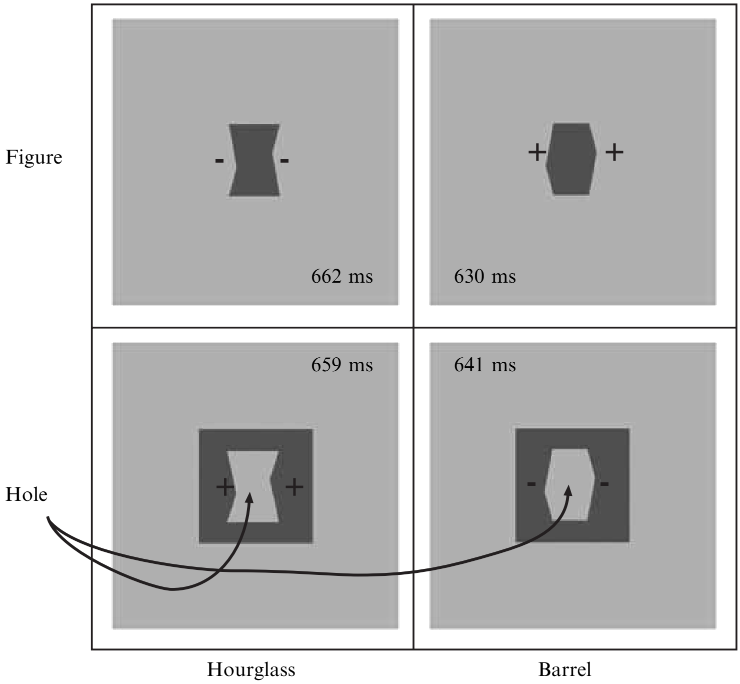

Figure 1. Examples of stimuli used by Bertamini and Croucher (2003). The stimuli are shown in dark and light gray which represent red and green colours, respectively. The arrows indicate that in the hole condition it is assumed that observers perceive the central region as a hole in a larger rectangular object. The plus and minus signs indicate regions that are perceived as convex (plus) or concave (minus). Finally, the numbers are average RTs from experiment 2 of Bertamini and Croucher (2003). Although this interaction was replicated in separate experiments, there was no independent validation of whether observers always perceived the holes as holes.

As we said earlier, contours can be computed on the basis of colour or luminance changes. However, there are also contours defined by other sources of information, they include modal contours without a luminance gradient such as those perceived in Kanizsa's illusory figures (Kanizsa 1979) and in random-dot stereograms (Julesz 1971); amodal contours of partly occluded shapes (eg Bruno et al 1997; Fantoni and Gerbino 2003); and virtual contours defined by the chaining of isolated elements (eg Field et al 1993). It is an open question whether curvature information and part structure is encoded in the same way for all of these contours. We provide a contribution on the issue of comparing different types of contours, because curvature effects are tested for modal contours defined only by stereopsis. There are also two other advantages in using random-dot stereograms: the first is that no ambiguity is present about what is foreground and what is background, the second is that the context (ie the rectangular frame in figure 1) can be eliminated so that regions seen as objects and holes can be compared without any other difference in stimulus properties.

Our first experiment replicates Bertamini and Croucher's (2003) findings. Their task relied on figural factors to create the percept of a hole, as can be seen in figure 1. If the perceived depth stratification is the critical factor, the interaction between type (figure versus hole) and shape (barrel versus hourglass) will be present when stereograms are used instead of red and green regions. The use of stereograms also allows a direct comparison of regions that differ only on the basis of binocular disparity (experiment 2). In other words, thanks to binocular disparity we can eliminate any gross changes in first-order stimulus properties. Experiment 3 differs from experiment 2 only in that no negative disparity is present in the stimuli, and experiment 4 tests whether there is any change in the interaction with a change of scale of the stimuli. The four experiments together test for the generality and robustness of the interaction between type and shape.

2 Experiment 1: Random-dot stereograms

In this experiment depth was specified by binocular disparity alone. We created a barrel and an hourglass shape which existed only when the images seen by the left and the right eyes were fused. We believe that the convexity advantage is a fundamental property of shape perception and it will apply to any contour, including those in a random-dot stereogram. Moreover, and perhaps more importantly, since fusion is necessary to perform the task, there is no ambiguity about what is seen as foreground and what is seen as background, and therefore what is the sign of curvature.

2.1 *Method*

2.1.1 *Participants and procedure.* Nine observers participated in return for course credit or a small monetary reward. They all had normal or corrected-to-normal vision and their ability to see stereograms was checked before the experiment started. Participants sat in a quiet room under conditions of normal illumination.

Each participant completed two sessions on different days. In each session they saw 24 practice trials, followed by five blocks of 144 trials each. Participants had to wear stereoscopic glasses throughout the experiment and were encouraged to take breaks, if necessary, at the end of each block. In figure 2, the left and the right images need to be fused to see an example of the stimuli. The reader can do this with the use of a stereoviewer; the figure also provides a diagram of the different layouts. In the diagram, gray levels specify different depth planes; middle gray is the zero-disparity plane.

2.1.2 *Stimuli and equipment.* Stimuli were generated on a Macintosh G4 computer, and presented on a Sony F500T9 monitor with a resolution of 1280 by 1024 pixels at 120 Hz. Two stereo images were presented with the use of a NuVision infrared emitter and stereoscopic glasses. The effect of interleaving left and right images was that effective vertical resolution and refresh rate were halved (512 pixels at 60 Hz). The computer recorded whether each response was correct and the reaction time in milliseconds with the Videotoolbox functions (Pelli 1997).

A rectangular area of background (16 deg by 10 deg) was always present on the screen. In the standard stratification version, the barrel and the hourglass shapes were 4.5 deg of visual angle tall (figure condition) or the same shapes were holes in a larger rectangle (8 deg by 5 deg) (hole condition). The angles formed by the vertices were chosen randomly to be 150° or 162° (to minimise learning effects that could take place when a given angle was presented in hundreds of trials), but the vertical offset was fixed at 0.5 deg.

Although the size of the vertical offset was fixed, in half of the trials the left vertex was lower and in the other half the right vertex was lower. Participants were instructed to press the '/' key if the lower vertex was on the right, or the 'z' key if the lower vertex was on the left.

For the inverted-stratification version, the barrel and the hourglass shapes were holes in the background, 4.5 deg tall (hole condition) or the same shapes were figures in a larger rectangular hole (8 deg by 5 deg) (figure condition) (see below for further explanations on stratification).

2.1.3 *Design.* In addition to the shape (barrel versus hourglass) and type (figure versus hole) factors, we used two versions of the random-dot stimuli, presented to the participants in separated sessions of the experiment. In the *standard stratification*, the figure was in front of a random-dot background, and the hole was created by a rectangular object with a hole similar to the stimuli in Bertamini and Croucher (2003). In the *inverted*

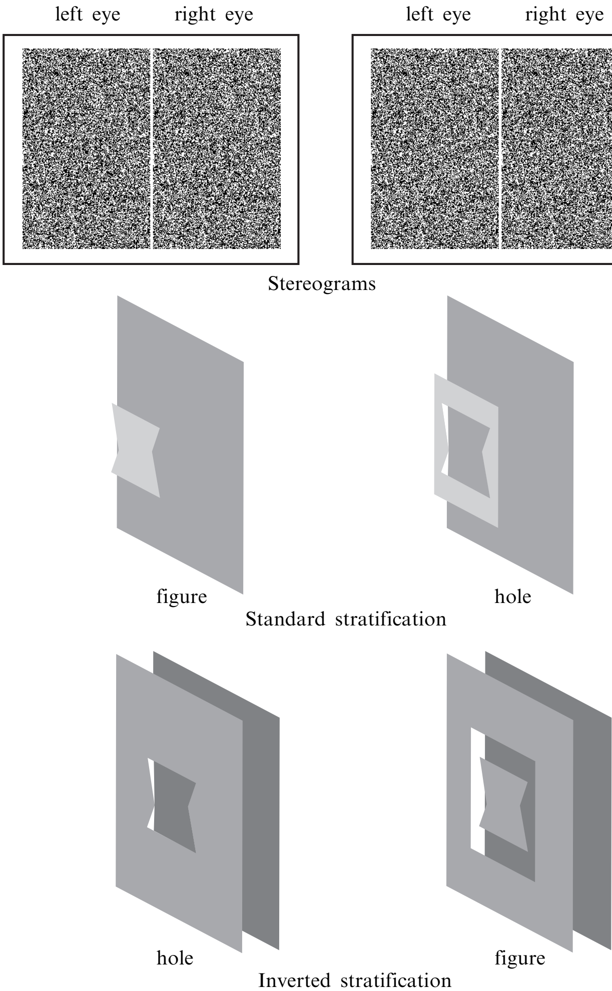

Figure 2. Examples of stimuli used in experiment 1. Random-dot stereograms for the figure and the hole conditions are shown at the top for the hourglass shape. The background was unchanged from trial to trial but the dots used to define the figure or hole changed from trial to trial. This means that, if the texture was taken into account, observers on each trial saw a new figure appear on a constant background, or a new plane become visible through a hole in a constant background. The hourglass shape is used again in the bottom part of the figure to illustrate the difference between figure and hole but also the difference between the standard and the inverted stratification. Middle gray represents the zero-disparity plane.

stratification, what were figures before, became holes cut through the background, and allowed a second background to be seen underneath. What we called figure in the figure condition was a piece of background left floating in the middle of a hole cut around it. To see examples of the inverted stimuli, it is sufficient to swap the right and the left random-dot images in figure 2. However, the diagram at the bottom of figure 2 also depicts both the standard-stratification and the inverted-stratification conditions.

The stratification manipulation is an interesting control, because by swapping disparity what was a figure in the standard version became a hole in the inverted version, and what was a hole became a figure. In terms of the transient onset in each trial, a larger change (ie a larger region) was now present at the onset of the figure stimulus compared to the onset of the hole stimulus. In summary, this manipulation affected contour polarity in a simple but powerful way. We predicted an interaction between shape and type and expected the same type of interaction to be present for both stratifications (if conditions are labelled on the basis of what was seen as a figure).

2.2 *Results and discussion*

The results for both reaction times and errors can be seen in figure 3. A logarithmic transformation of RT values was applied to normalise the distribution [for theoretical reasons to expect lognormal RT distributions see Ulrich and Miller (1993)]. Values higher than 2000 ms were deemed outliers and removed (1.9% of the data). We ran a within-subjects ANOVA on transformed RT for correct responses. The factors were shape, type, and stratification, a $2 \times 2 \times 2$ within-subjects design. Shape was not a significant factor ($F_{1,8} = 2.61$), but there was an effect of type ($F_{1,8} = 40.93$, $p < 0.001$). The responses were faster on average in the figure condition. More importantly, the interaction between shape and type was also significant ($F_{1,8} = 35.37$, $p < 0.001$).

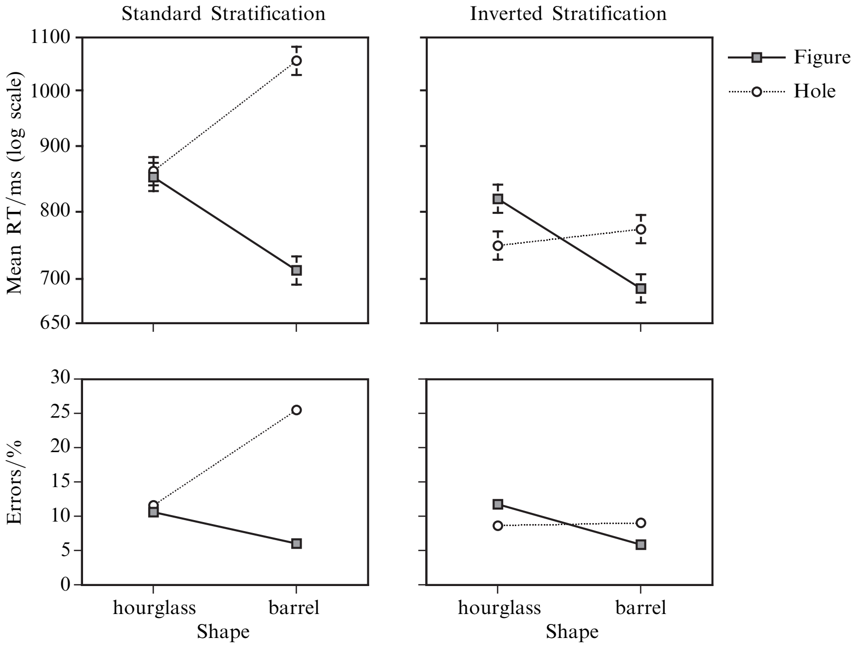

Figure 3. Data from experiment 1, for both RT and errors. RT data were analysed after a logarithmic transformation, and the scale is therefore logarithmic. Arithmetic means in this case correspond to geometric means of the untransformed RT data. The error bars are within-subjects standard errors of the mean (Loftus and Masson 1994).

Stratification also had a main effect ($F_{1,8} = 18.97$, $p = 0.002$), showing that performance in the inverted condition was better. Stratification also interacted with shape ($F_{1,8} = 7.22$, $p = 0.028$) and type ($F_{1,8} = 54.42$, $p < 0.001$). There was also a three-way interaction between stratification, shape, and type ($F_{1,8} = 22.23$, $p = 0.002$).

The graphs in figure 3 show that the pattern for accuracy was exactly the same as that of RT. An ANOVA on the percentage of errors confirmed the same significant effects as for RT.

Looking at the interaction between shape and type in more detail, we performed Sheffé a posteriori tests on the means, separately for the two stratifications. (a) Standard stratification: for the barrel, the figure condition was faster than the hole condition ($p < 0.001$), whilst for the hourglass the figure condition was not significantly different from the hole condition ($p = 0.558$). (b) Inverted stratification: for the barrel, the figure condition was faster than the hole condition ($p < 0.001$), whilst for the hourglass the figure condition was slower than the hole condition ($p < 0.002$).

This experiment replicated and extended the findings of Bertamini and Croucher (2003). Contours were defined exclusively by binocular disparity, and the interaction between shape and type suggests that polarity is an attribute of any contour. Although this may be uncontroversial, to the best of our knowledge this is the first demonstration of an effect of structural shape representation (namely, curvature polarity) for contours defined by binocular disparity alone.

There were also some effects of stratification. However, the fact that observers were faster in the inverted version may have been an artifact, as all participants performed this condition second. All other effects of stratification should be understood by a close inspection of figure 3. It appears that in the standard stratification case the hole condition (for both shapes) was hard. This may be a consequence of the large rectangular stimuli. On the other hand, in the inverted stratification there never was a large object; this is because what was larger in the figure condition was now a hole. Irrespective of this possible effect of the size of the stimulus, the shape by type interaction was strong for both stratifications, and we suggest that the only effect of stratification was a change in the relative difficulty of the figure and hole conditions.

3 Experiment 2: Stereograms with and without luminance edges

Experiment 1 revealed an effect of figure – ground organisation (the difference between a figure and a hole) when binocular disparity was used to define the contours. In experiment 1 the stratification was varied in separated blocks, therefore there was no direct comparison of a given shape when only direction of disparity changed [because the hole was created in a larger rectangular object, to replicate Bertamini and Croucher (2003)]. In experiment 2 the barrel and hourglass shapes specified as either figures or holes were present in the same block, so as to compare the two shapes when only direction of disparity changed. A diagram of the stimuli is shown in figure 4.

As in experiment 1 we used stereograms, but we included a version in which the random dots on different planes changed in average luminance (the luminance condition).

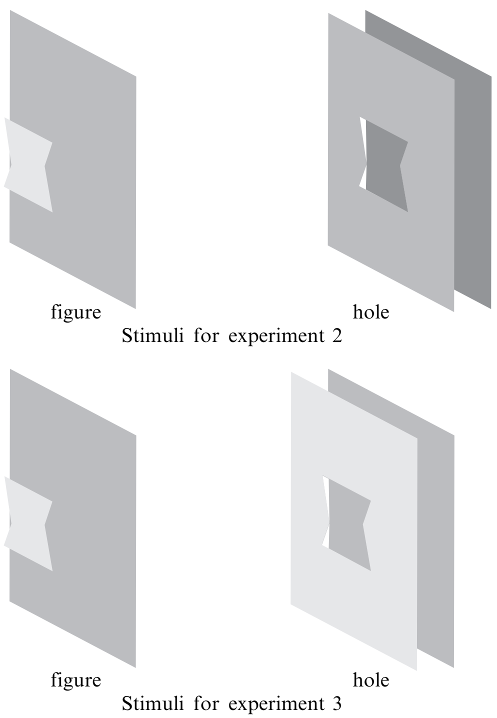

Figure 4. Examples of stimuli used in experiments 2 and 3. Only the hourglass stimuli are shown. In experiment 2 the figures were the same as the figures in the standard stratification of experiment 1, and the holes were the same as the holes in the inverted stratification of experiment 1. In experiment 3 the same stimuli were used except for the disparity information which placed the planes as illustrated. Middle gray represents the zero-disparity plane.

Two scenarios are possible, either the luminance difference helps in defining the two surfaces and therefore leads to an even stronger interaction between shape and type, or the luminance difference allows for a faster response which (if based on luminance alone) will lead to a reduced interaction effect because more ambiguity is present as to what is a figure and what is a hole. In other words, when the luminance contours are present, the role of disparity may be weaker because a response can be initiated irrespective of stereo information.

3.1 *Method*

Eighteen University of Liverpool students participated. Nine participants saw stereograms without any luminance information (the RDS condition), and nine participants saw similar stereograms with luminance-defined contours (the luminance condition). To create a change in average luminance, dark-gray and light-gray dots were used instead of black and white dots. Average luminance in the RDS condition was approximately 40.45 cd m^{-2}, and in the luminance condition the two planes had average luminance of 40.45 and 20.93 cd m^{-2}.

We used two shapes (barrel versus hourglass) × two types of stimuli (figure versus hole). Unlike experiment 1 a new background as well as a new foreground were generated on each trial, but the background was visible for about 500 ms before the foreground. The procedure was the same as in experiment 1, and the stimuli were similar but no rectangular region was present around the two shapes (see figure 4).

3.2 *Results and discussion*

Figure 5 shows results for both reaction times and errors. Following the same steps as in experiment 1 (1.9% of the data were removed as outliers), we ran a within-subjects ANOVA on transformed RT. The factors were shape, type, and luminance, a 2 × 2 × 2 mixed design. Shape ($F_{1,16} = 3.90$), type ($F_{1,16} = 1.30$), and luminance ($F_{1,16} = 4.30$) were not significant, but the interaction between shape and type was significant ($F_{1,8} = 46.07$, $p < 0.001$). No other interaction was significant.

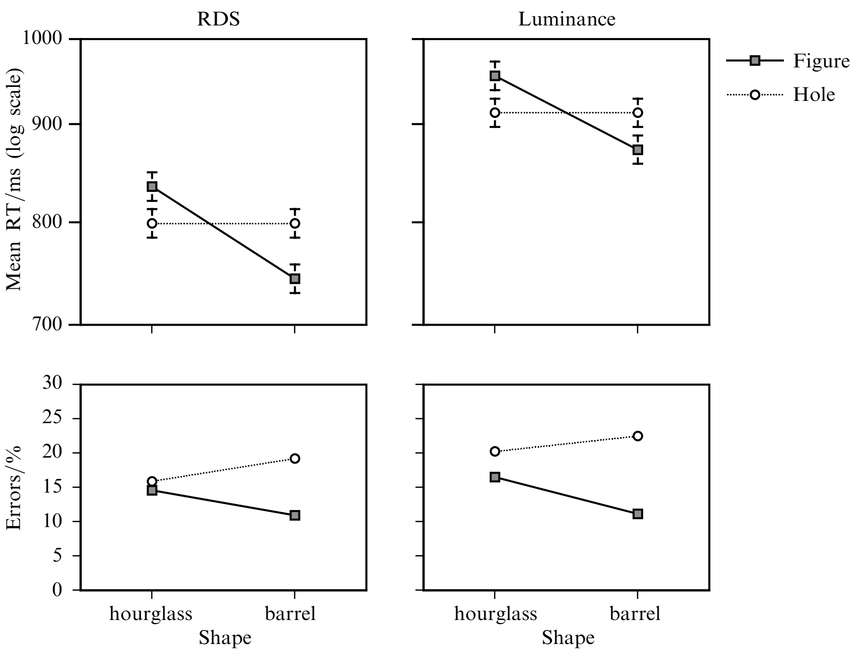

Figure 5. Data from experiment 2, for both RT and errors. RT data were analysed after a logarithmic transformation, and the scale is therefore logarithmic. The error bars are within-subjects standard errors of the mean.

The interaction between shape and type was confirmed when we analysed the percentage of errors ($F_{1,16} = 19.42$, $p < 0.001$). There was also a main effect of type ($F_{1,16} = 39.49$, $p < 0.001$) indicating more errors in the hole condition. No other factor or interaction was significant. The pattern of errors shows no indication of a speed–accuracy trade off.

This experiment replicated and extended the findings of experiment 1. Figure 5 shows that responses for the luminance condition were similar to those in the RDS condition.

4 Experiment 3: Coplanar holes and figures

In experiment 2, the only change between the figure and the hole conditions was the direction of the disparity (positive or negative). Although this manipulation had the advantage that it left the stereograms unchanged (except for the direction of the disparity) it had the disadvantage that the depth plane of the figure was closer to the observer than the depth plane of the hole. Moreover the comparison between figures and holes was also a comparison between positive and negative disparity. In experiment 3 we presented holes which were located at the same depth as the figures, as can be seen in figure 4 (middle gray is the zero-disparity plane). No negative disparities were present in experiment 3.

4.1 *Method*

Nine University of Liverpool students participated. They were naïve with respect to the problem and the hypotheses until after the data were collected. We used two shapes (barrel versus hourglass) × two types of stimuli (figure versus hole). Stimuli and procedure were similar to those used in the RDS condition of experiment 2. The critical difference was in the values of disparity used for the foreground and the background. The difference between the stimuli used in experiments 2 and 3 is illustrated in figure 4.

4.2 *Results and discussion*

The results for both reaction times and errors can be seen in figure 6. Following the same steps as for previous analyses (3.2% of the data were removed as outliers), we ran an ANOVA on transformed RT with shape and type as factors, a 2 × 2

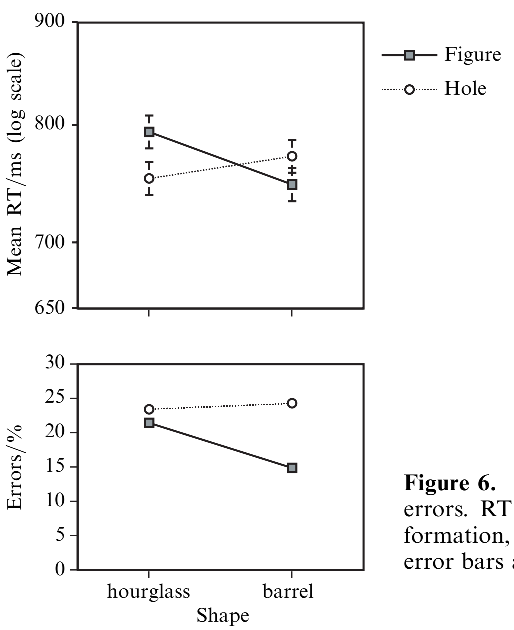

Figure 6. Data from experiment 3, for both RT and errors. RT data were analysed after a logarithmic transformation, and the scale is therefore logarithmic. The error bars are within-subjects standard errors of the mean.

within-subjects design. Shape ($F_{1,8} = 0.47$) and type ($F_{1,8} = 0.51$) were not significant but their interaction was significant ($F_{1,8} = 28.78$, $p < 0.001$). A similar ANOVA on the percentage of errors confirmed the same significant interaction ($F_{1,8} = 10.89$, $p = 0.011$). This experiment confirmed that the findings of experiment 2 extend to stimuli arranged differently, that is, always at or nearer than the zero-disparity plane.

5 Experiment 4: Size

In this experiment we investigated the effect of the size of the stimuli, interleaved within the same block. It is possible that the onset of a large object may slow down the responses more than the onset of a large hole (as speculated in the discussion of experiment 1). There is also another reason why we were interested in size. Although hard to convey in the diagrams, there may be a slight difference in perceived size between a figure and a hole with a congruent shape. Consider the stimuli of experiment 2, the monocular regions created by half occlusions (ie the random dots visible only by the left or the right eye), are always assigned to the background. Consequently the figure is slightly smaller than the region of background visible through a hole. We do not believe this factor to be of great consequence, because it is a difference between objects and holes that cannot explain the observed interaction, and because this difference was absent in the pictorial stimuli of Bertamini and Croucher (2003), nevertheless an investigation of size will test the generality of the reported interaction.

5.1 *Method*

Nine University of Liverpool students participated. We used two shapes (barrel versus hourglass) × two types of stimuli (figure versus hole). Stimuli and procedure were similar to those used in the RDS condition of experiment 1. The difference was the introduction of a new factor, the size of the shape. Each shape was scaled to three different sizes, corresponding to 4.5 deg, 6 deg, and 7.5 deg in height. This was a scaling of the whole shape, therefore the vertical offset between the vertices was scaled by the same amount as the rest of the figure.

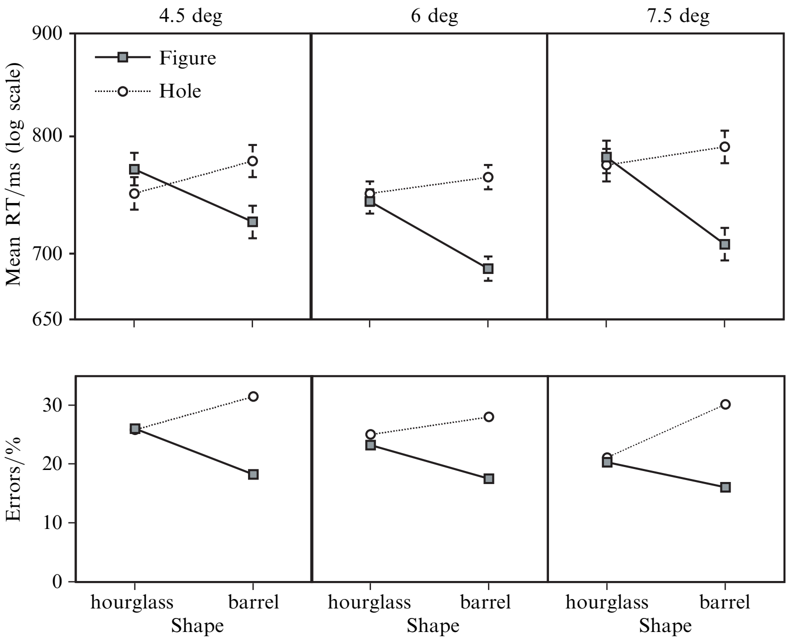

Figure 7. Data from experiment 4, for both RT and errors. RT data were analysed after a logarithmic transformation, and the scale is therefore logarithmic. The error bars are within-subjects standard errors of the mean.

5.2 *Results and discussion*
Mean reaction times and errors can be seen in figure 7. Following the same steps as for the previous analyses (1.6% of the data were excluded as outliers), we ran an ANOVA on transformed RT with shape, type, and size as factors, a $2 \times 2 \times 3$ within-subjects design. There was no effect of shape ($F_{1,8} = 3.36$), an effect of type ($F_{1,8} = 7.69$, $p = 0.024$), and an interaction between the two ($F_{1,8} = 32.67$, $p < 0.001$). Size was also significant ($F_{1,8} = 8.51$, $p = 0.003$) but it did not interact with any other factor. A similar ANOVA on the percentage of errors confirmed the significant interaction between shape and type ($F_{1,8} = 42.33$, $p < 0.001$), but not the effect of size ($F_{1,8} = 2.99$).

Experiment 4 replicated the interaction between shape and type found in previous experiments, and failed to confirm any influence of size on that interaction. In fact, even the significant main effect of size is uninteresting because the trend was not consistent in its direction (average RT for the three sizes were: 755, 736, and 763 ms). It is possible that other manipulations of size may have an effect, but from this experiment we can only conclude that the type by shape interaction is robust across a variation in the size of the hexagons.

6 General discussion
In four experiments we have found a consistent interaction in the time necessary to judge the position of vertices. This interaction can be seen as an advantage for vertices perceived as convex. As suggested by Bertamini (2001) this advantage may be the consequence of an early computation of part structure. Specifically, to parse a shape into parts is to assign a position to those parts. It is also possible that parts have orientations and not just positions but future experiments will have to test this aspect of the hypothesis.

In the experiments with stereograms the effect size was in the order of 50 ms (see figures 3, 5, 6, and 7). This is larger than Bertamini and Croucher (2003) found with stimuli in which the perception of a hole was generated by colour and texture (without disparity information; see figure 1). This is consistent with the fact that no ambiguity was present in the stereograms as to what was a figure and what was a hole (remember that fusion of the two images was necessary to perform the task).

The idea of an early computation of part structure is supported by a large body of evidence, reviewed in Singh and Hoffman (2001). For instance, there is evidence from visual search (eg Hulleman et al 2000; Xu and Singh 2002), symmetry detection (eg Baylis and Driver 1994; Bertamini et al 2002), shape matching (Braunstein et al 1989), and perception of transparency (Singh and Hoffman 1998).

It is also worth mentioning that Elder and Zucker (1993, 1994, 1998) have used shapes similar to the barrel and the hourglass. Although they did not discuss their results in terms of part structure, they found that a discrimination between the two (barrel and hourglass) was efficient only when these regions were unambiguously *closed*. They concluded that closure was the critical factor, but closure is also what makes the sign of the curvature unambiguous, so that their findings are consistent with a fundamental role of part structure mediated by contour – curvature information.

Since similar stimuli have been used before in the literature on attention, it is worth mentioning that Baylis and Driver (1993) did find slower responses with a change of figure – ground organisation for a barrel (from figure to space in between figures). The original work attributed the effect to the attentional advantage when comparing vertices within an object. Sign of curvature was a confound, as pointed out by Gibson (1994) but Baylis (1994) showed that attentional costs exist even when controlling for sign of curvature. Hulleman and Boselie (1997) also found that, when convex vertices are on separate objects, the task of comparing positions becomes harder. We accept the existence of attentional costs but our stimuli are designed to explore sign of curvature effects directly. In experiment 1, number of objects is constant, and in the other experiments it may predict a main effect of type, but not an interaction between type and shape (cf Tsal et al 2000). Gibson (1994) argued that the hourglass is more complex than the barrel and may be seen as being composed of two parts. However, if we take the presence of concavities as sufficient to define parts, then the object with an hourglass-shaped hole is more complex in this sense than an object with a barrel-shaped hole. Therefore, the difference in complexity cannot in itself explain the interaction that we have found.

In addition to the issue of part structure, the more specific hypothesis tested in the present paper is that positional information is more readily available for convex regions. Support has been found previously by Bertamini (2001), and Bertamini and Croucher (2003). Liu et al (1999) found an advantage using positional judgments for the hourglass shape. Prima facie this seems incompatible with our findings; however, in their task the position in depth of the top and bottom halves of the shape had to be compared. These are always convex, so the advantage found by Liu et al (1999) may be described as an advantage for convex parts separated by concavities compared to convex parts not separated by concavities. Another open question is what to predict for tasks that directly involve amodal contours, ie when the judgment is about the position of what is behind the occluder. An early investigation suggests that concave vertices are extrapolated to a larger degree than convex vertices, so as to minimise the occluded area (Gerbino and Fantoni 2002).

In summary, we used holes to study shape and, in particular, the encoding of part-structure based on contour curvature. Our predictions have been met: positional information for convex vertices is more readily available. Holes are the ideal stimuli for the investigation of effects of the sign of curvature, because the same region can change from a figure to a hole without altering the contours themselves (in terms of edge information). Moreover, in experiment 2 we have found effects of contour curvature for figures and holes defined exclusively by binocular disparity. In other words, binocular disparity allowed us to change a region from figure to hole without altering any other aspect of the configuration. Experiments 3 and 4 replicated the result and confirmed that the sign of curvature was the critical factor. In the final discussion, we have pointed to some links with other findings in the literature and we have more work underway that exploits the unique nature of holes.

References

Attneave F, 1954 "Some informational aspects of visual perception" *Psychological Review* **61** 183 – 193

Attneave F, 1974 "Multistability in perception" *Scientific American* **225**(6) 63 – 71

Barlow H B, Narasimhan R, Rosenfeld A, 1972 "Visual pattern analysis in machines and animals" *Science* **177** 567 – 574

Baylis G C, 1994 "Visual attention and objects: Two-object cost with equal convexity" *Journal of Experimental Psychology: Human Perception and Performance* **20** 208 – 212

Baylis G C, Driver J, 1993 "Visual attention and objects: evidence for hierarchical coding of location" *Journal of Experimental Psychology: Human Perception and Performance* **19** 451 – 470

Baylis G C, Driver J, 1994 "Parallel computation of symmetry but not repetition in single visual objects" *Visual Cognition* **1** 377 – 400

Bertamini M, 2001 "The importance of being convex: An advantage for convexity when judging position" *Perception* **30** 1295 – 1310

Bertamini M, Croucher C E, 2003 "The shape of holes" *Cognition* **87** 33 – 54

Bertamini M, Friedenberg J, Argyle L, 2002 "No within-object advantage for detection of rotational symmetry" *Acta Psychologica* **111** 59 – 81

Biederman I, 1987 "Recognition-by-components: A theory of human image understanding" *Psychological Review* **94** 115 – 147

Bozzi P, 1975 "Osservazioni su alcuni casi di trasparenza fenomenica realizzabili con figure a tratto", in *Studies in Perception: Festschrift for Fabio Metelli* Ed. G d'Arcais (Milan: Martelli-Giunti) pp 88 – 110

Braunstein M L, Hoffman D D, Saidpour A, 1989 "Parts of visual objects: an experimental test of the minima rule" *Perception* **18** 817–826
Bruno N, Bertamini M, Domini F, 1997 "Amodal completion of partly occluded surfaces: is there a mosaic stage?" *Journal of Experimental Psychology: Human Perception and Performance* **23** 1412–1426
Casati R, Varzi A C, 1994 *Holes and Other Superficialities* (Cambridge, MA: MIT Press)
Cavedon A, 1980 "Contorno e disparazione retinica come determinanti della localizzazione in profondità: le condizioni della percezione di un foro" Istituto di Psicologia Report 12, Università di Padova, Padua
Elder J, Zucker S, 1993 "The effect of contour closure on the rapid discrimination of two-dimensional shapes" *Vision Research* **33** 981–991
Elder J, Zucker S, 1994 "A measure of closure" *Vision Research* **34** 3361–3369
Elder J, Zucker S, 1998 "Evidence for boundary-specific grouping" *Vision Research* **38** 143–152
Fantoni C, Gerbino W, 2003 "Visual interpolation and unification factors: a field model" *Journal of Vision* **3** 281–303
Field D, Hayes A, Hess R, 1993 "Contour integration by the human visual system: Evidence for a local association field" *Vision Research* **33** 173–193
Foster D H, Gilson S J, 2002 "Recognizing novel three-dimensional objects by summing signals from parts and views" *Proceedings of the Royal Society of London, Series B* **269** 1939–1947
Gerbino W, Fantoni C, 2002 "Contour polarity and visual interpolation" *Perception* **31** Supplement, 152
Gibson B S, 1994 "Visual attention and objects: one versus two or convex versus concave?" *Journal of Experimental Psychology: Human Perception and Performance* **20** 203–207
Hoffman D D, Richards W, 1984 "Parts of recognition" *Cognition* **18** 65–96
Hulleman J, Boselie F, 1997 "Visual attention and objects: New tests of two-object cost" *Psychonomic Bulletin & Review* **4** 367–373
Hulleman J, te Winkel W, Boselie F, 2000 "Concavities as basic features in visual search: Evidence from search asymmetries" *Perception & Psychophysics* **62** 162–174
Julesz B, 1971 *Foundations of Cyclopean Perception* (Chicago, IL: University of Chicago Press)
Kanizsa G, 1979 *Organization in Vision* (New York: Praeger)
Kanizsa G, Gerbino W, 1976 "Convexity and symmetry in figure–ground organization", in *Vision and Artifact* Ed. M Henle (New York: Springer) pp 25–32
Kennedy J M, Domander R, 1985 "Shape and contour: the points of maximum change are least useful for recognition" *Perception* **14** 367–370
Koenderink J J, 1984 "What does the occluding contour tell us about solid shape?" *Perception* **13** 321–330
Koenderink J J, 1990 *Solid Shape* (Cambridge, MA: MIT Press)
Koffka K, 1935 *Principles of Gestalt Psychology* (New York: Harcourt, Brace)
Kristjánsson Á, Tse P U, 2001 "Curvature discontinuities are cues for rapid shape analysis" *Perception & Psychophysics* **63** 390–403
Liu Z, Jacobs D W, Basri R, 1999 "The role of convexity in perceptual completion: beyond good continuation" *Vision Research* **39** 4244–4257
Loftus G, Masson M, 1994 "Using confidence intervals in within-subject designs" *Psychonomic Bulletin & Review* **1** 476–490
Marr D, Nishihara H K, 1978 "Representation and recognition of the spatial organization of three-dimensional shapes" *Proceedings of the Royal Society of London* **200** 269–294
Nelson R, Palmer S E, 2001 "Of holes and wholes: The perception of surrounded regions" *Perception* **30** 1213–1226
Norman J F, Phillips F, Ross H E, 2001 "Information concentration along the boundary contours of naturally shaped solid objects" *Perception* **30** 1285–1294
Palmer S E, 1999 *Vision Science: Photons to Phenomenology* (Cambridge, MA: MIT Press)
Pelli D G, 1997 "the VideoToolbox software for visual psychophysics: Transforming numbers into movies" *Spatial Vision* **10** 437–442
Peterson M A, de Gelder B, Rapcsak S Z, Gerhardstein P C, Bachoud-Lévi A-C, 2000 "Object memory effects on figure assignment: conscious object recognition is not necessary or sufficient" *Vision Research* **40** 1549–1567
Rubin E, 1921 *Visuell wahrgenommene Figuren* (Kopenhagen: Glydenalske boghandel)
Singh M, Hoffman D D, 1998 "Part boundaries alter the perception of transparency" *Psychological Science* **9** 370–378

Singh M, Hoffman D D, 2001 "Part-based representations of visual shape and implications for visual cognition", in *From Fragments to Objects: Grouping and Segmentation in Vision* Eds T F Shipley, P J Kellman (Amsterdam: Elsevier) pp 401 – 459
Singh M, Seyranian G D, Hoffman D D, 2000 "Parsing silhouettes: the short-cut rule" *Perception & Psychophysics* **61** 636 – 660
Sutherland N S, 1968 "Outlines of a theory of visual pattern recognition in animals and man" *Proceedings of the Royal Society of London, Series B* **171** 297 – 317
Tsal Y, Lamy D, Ilan C, 2000 "The two-object cost is a space-based phenomenon" *Abstracts of the Psychonomic Society* **5** 33
Ulrich R, Miller J, 1993 "Information processing models generating lognormally distributed reaction times" *Journal of Mathematical Psychology* **37** 513 – 525
Xu Y, Singh M, 2002 "Early computation of part structure: Evidence from visual search" *Perception & Psychophysics* **64** 1039 – 1054

ISSN 0301-0066 (print) ISSN 1468-4233 (electronic)

PERCEPTION

VOLUME 33 2004

www.perceptionweb.com