Perception, 2006, volume 35, pages 1679 – 1692

DOI:10.1068/p5534

The perceived structural shape of thin (wire-like) objects is different from that of silhouettes

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Received 7 October 2005, in revised form 23 February 2006

Abstract. Observers are faster at judging the position of convex vertices compared to concave vertices. This is believed to be due to an explicit representation of position for visual parts. The best evidence comes from comparing the same contours perceived as either figures or holes, because this is a pure figure – ground reversal (Bertamini and Croucher, 2003 *Cognition* **87** 33 – 54; Bertamini and Mosca, 2004 *Perception* **33** 35 – 48). Specifically, an interaction is present between type of object (object or hole) and shape. One assumption is that the contour of a silhouette is perceived as the rim of a solid object. It follows that a different pattern should be found for thin (wire-like) objects compared to silhouettes. We confirm this difference in three experiments. We argue that this is due to the perceived parts when contours can be interpreted as self-occlusion rims.

1 Introduction

A closed contour in the plane defines a region with a given shape, for instance a square or something more complex like the shape of a giraffe, but there are reasons why not all closed contours are the same. Closed contours perceived as a figure or as a hole have been studied before; in this paper we focus on a new type of stimulus, a thin wire-like object. To anticipate our conclusion, thin objects can be shown to behave in a way that is qualitatively different from a silhouette with the same outline. We explain this effect in terms of how silhouettes are linked to solid shapes.

1.1 *Previous work on positional judgments*

When observers judge the position of a vertex, they are faster at responding when vertices are perceived as convex. Bertamini (2001; Bertamini and Croucher 2003) suggested that, when a shape is parsed into parts based on contour curvature, it is easier to judge the location of convexities because they are perceived as parts.

Contours are important for perceived solid shape. If 2-D contours are the projection of surface rims (the location where a surface self-occludes), then an important relationship exists between the sign of curvature of contours and the Gaussian curvature of the surface (Hoffman and Richards 1984; Koenderink 1984). In short, convex contours (positive curvature) are projections of the rims of convex surfaces, and concave contours (negative curvature) of the rims of saddle surfaces. Surfaces with concave curvature, like the inside of a football, do not have rims (they do not self-occlude). Because of this it makes sense to perceive convexities along a contour as defining parts, and concavities as defining the boundary between different parts. One can think of examples of saddle curvature in the real world: the middle section of a peanut, or the joining of the neck and torso of a human body. Both can be considered examples of boundaries between parts.[1] Note that this argument is about how 2-D contours are perceived, but the logic relies on the assumption that we live in (and perceive) a world of solid shapes.

[1] This is true as a general statement but not as a strict rule; a bent pipe may have a saddle that does not segment the pipe into parts. What remains true is that a concavity projected by a rim signals the presence of a saddle on the surface (Koenderink 1984); part-structure depends on a number of other factors (for a recent review, see De Winter and Wagemans 2005).

A quote from Koenderink (1990) may help to clarify the importance of convexity: "In general the surfaces of things growing or blown up from the inside tend to possess positive Gaussian curvature. [...] the sculpture of many cultures reveals this very clearly. Very often the negatively curved parts are reduced to narrow V-shaped grooves between the bulging ovoid parts. An extreme example is the famous 'Venus of Willendorf' from paleolithic origin (ca 11000 BC). Clearly this fact that we all seem to know from introspection is not a short-lived cultural whim" (Koenderink 1990, page 251). For a similar point about convexities as parts see Leyton (1992).

In talking about convexity and concavity we make the assumption that a contour location has an unambiguous sign of curvature. For this to be the case, one side of the contour must be coded as figure and the other as ground. A figure – ground reversal would change convexity into concavity and vice versa. It is well known that contours tend to bound only the figure and not the ground side (Rubin 1921; Koffka 1935; Kanizsa 1979). This is often referred to as unidirectional border ownership (Nakayama et al 1989). However, whether unidirectional border ownership applies to any contour is debated. Kennedy (1974) and Peterson (2003) have suggested that a contour does not necessarily mark the boundary between figure and ground. One example in Kennedy (1974) shows lines seen as thin objects, wire-like, and therefore not separating a figure from a ground. We were inspired by this example, but line drawings are inherently ambiguous, so we decided to study instead very thin objects floating above a background. In the present paper (experiments 1 and 2) we test contours that are defined and perceived as thin objects.

We report three experiments on the speed to judge the position of vertices. The paradigm is that used by Bertamini and Mosca (2004). Observers judge which of a pair of vertices belonging to irregular hexagons is higher vertically. When the hexagon has all convex vertices (barrel) the responses are faster than when the relevant vertices are concave (hourglass), even though when the area is the same the vertices are farther apart for the barrel (see figure 1). However, a figure – ground reversal of these regions changes the pattern of responses. We impose a figure – ground reversal (a different depth stratification) by means of binocular disparity within random-dot stereograms (RDSs). When perceived as ground, the barrel and the hourglass regions are holes in the background [for more on holes as ideal stimuli to study figure – ground relations see Bertamini (2006), and, for different view, see Palmer (1999)].

Although originally inspired by Kennedy's book (1974), our research question is not directly related to Kennedy's point. First of all, we consciously chose not to work in the context of pictorial stimuli; we always specify depth unambiguously (using stereograms). Second, our contours do not exist as luminance edges, but only as surface edges (they do not exist unless the stereograms are fused). We want to find further support for our hypothesis that the advantage to respond to convex vertices is due to the role that convex vertices have in defining visual parts (Bertamini 2001). We reasoned that this applies to silhouettes, because their contours can be interpreted as the rim of a solid shape, but not to thin wire-like objects. We discuss this in more detail in the next section.

1.2 *Summary of experiments*

Experiment 1 is the central experiment for this paper. It introduces a new kind of stimulus, a thin surface that appears almost like a wire as far as this is possible to achieve within RDSs. It is important to clarify that the use of RDSs is critical for this test. A thin line that is coplanar with the background, as in a line drawing, is inherently ambiguous: it could be a thin object or it could be the border of a surface. A thin line that floats in front of the background is not ambiguous in this sense, but, if it were defined by a luminance edge, observers would not need to fuse the stereograms to select the correct answer. In our stimuli we can be confident that the lines are perceived as thin objects because the contours are defined only by disparity and therefore are only visible when the stereograms are fused, making depth information available to the observer.

Let us consider three hypotheses.

(a) The contour of a thin object defines a shape just as clearly as an occluding contour. It seems intuitively appealing to believe that a shaped wire (eg shaped like a fish) is fundamentally the same as the silhouette of the object. Both carry intrinsic shape information in that they are stable and non-accidental shapes. If so, the results for the thin object and the object conditions will be the same, with an advantage for the barrel condition over the hourglass condition.

(b) The outside shape of a surface-with-hole may be irrelevant. If what is important is the presence of a hole through which we see a farther surface, then results for the thin-object condition and the hole condition will be the same, with an advantage for the hourglass condition over the barrel condition. This seems the least plausible scenario, but we list it here for completeness.

(c) We believe that neither of the two previous hypotheses is correct. Our theoretical position is that responses are faster when observers are judging the position of perceived parts (Bertamini and Croucher 2003). The elbow-like vertices of a thin object are identical, with respect to part-structure, whether they belong to a barrel or to an hourglass shape; therefore we predict no difference between these two conditions.

One could phrase this idea differently: positional information is available for convexities, therefore the critical aspect is whether a convexity is present. For thin objects, a convexity is present both for vertices pointing inwards and for vertices pointing outwards. The fact that a concavity is also present at the same time and approximately in the same location makes no difference; convexities lead to faster responses but there is no reason why concavities should slow down responses.

Note that relative speed of responses to barrel and hourglass shapes may shift for a number of reasons; therefore it is more important to look at these differences in terms of an interaction between these shapes and the type of stimuli. In light of this, hypothesis (c) predicts a significant interaction between shape (barrel and hourglass) and type (thin object and object), and at the same time a significant interaction between shape and type (thin object and hole). This we would take as evidence that the thin objects behave neither as objects nor as holes (in relation to shape). Clearly, hypotheses (a) and (b) predict only one of these interactions to be significant because they predict that the thin object would behave (with respect to shape) like the object or like the hole, respectively.

Experiment 2 is similar to experiment 1: the only difference is that stimuli are split to form two separate objects, two separate holes, or two thin objects. The results from experiment 2 broadly replicate the findings of experiment 1. We conclude that the number of objects and holes in the display is not an important factor. Similarly, whether the vertices to be compared belong to the same object or different objects is not important for this effect.

Experiment 3 is another control. We placed rectangular holes inside the shapes (and rectangular objects inside the holes) so that these new objects are similar (at least topologically) to the thin objects. However, the rectangular hole (and the rectangular object) does not carry any information relevant for the task (it has no left and right vertices) and therefore we expect experiment 3 to replicate the interaction found by Bertamini and Mosca (2004). This adds evidence that the critical factor is whether the relevant vertices are perceived as convex or concave. In other words, experiment 3 shows that stimuli with holes can behave as stimuli without holes, as long as the critical information (that is, the vertices to be compared) is not carried by the contour defining the hole region.

2 Experiment 1: Thin objects

This study is closely related to those in Bertamini and Mosca (2004). Two shapes were presented, which we call the barrel and the hourglass (see figure 1). The task is to judge whether the vertex on the right or the vertex on the left is lower. As in Bertamini and Mosca (2004) we presented the shapes as either objects or holes in the background. We believe that the reason for the interaction is the sign of contour curvature of the relevant vertices. In addition to object and holes, experiment 1 introduces a new type of stimulus. Therefore the three conditions are object, hole, and thin object. As discussed in the introduction, we can make three hypotheses with respect to the interaction between type and shape: (a) thin objects will behave as objects; (b) thin objects will behave as holes; (c) thin objects will not behave as either objects or holes.

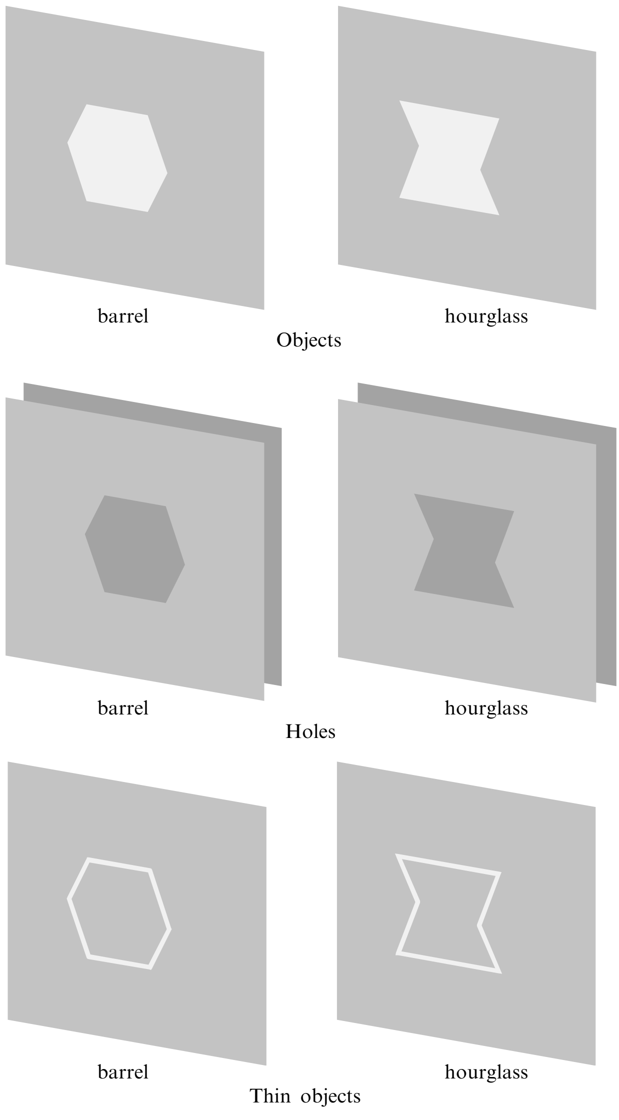


Figure 1. Stimuli used in experiment 1. The diagram illustrates the cyclopean view by using different shades of gray (darker is farther and the middle gray is the zero-disparity plane). The actual stimuli were random-dot stereograms. Moreover, in the experiment the square background was exactly twice as large in width and height compared to the one shown here. There are three types of objects, referred to as object, hole, and thin object.

Our prediction is that hypothesis (c) will be confirmed. This prediction is based on the idea that in the case of the thin objects the vertices (elbow-shaped) pointing either inwards or outwards (for barrel and hourglass, respectively) do not confer a different part-structure.[(2)]

2.1 *Method*

2.1.1 *Participants.* Sixteen observers participated. They all had normal or corrected vision and they were screened for stereoacuity with the TNO stereotest (stereoacuity ranged between 15 and 120 s of arc).

2.1.2 *Design and procedure.* The factor shape had two levels: barrel and hourglass. The factor type had three levels: object, hole, and thin object (see figure 1).

Stimuli were generated on a Macintosh G4 computer, and presented on a Sony F500T9 monitor (1280 by 1024 pixels, 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 by using the Videotoolbox functions (Pelli 1997).

A square area of background (16 cm of side) was always present on the screen, but the random-dot pattern changed at every trial. Both the barrel and the hourglass were 3 cm tall and were matched in area. The vertical offset between the vertices on the left and the right side was fixed at 0.4 cm. 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 one of two keys on a gamepad to perform the discrimination task. Stimuli were slightly shorter and wider than those in Bertamini and Mosca (2004) to minimise overall response differences between barrel and hourglass.

Each observer sat in a dimly illuminated room at a distance of approximately 57 cm from the monitor. After completing 28 practice trials the observers were asked whether they had questions or needed more practice. The practice was followed by three blocks of 216 trials each. Participants had to wear stereoscopic glasses throughout the experiment and were encouraged to take breaks at the end of each block if necessary. Figure 1 shows diagrams in which different gray levels specify different depth planes to illustrate the cyclopean view of the stimuli.

2.2 *Results and discussion*

The following steps were taken in the analyses for this and subsequent experiments. Only trials with correct responses were used in the analysis of response times (RTs). The RTs were logarithmically transformed to normalise the distribution and meet the ANOVA assumptions. We ran a repeated-measures ANOVA with shape (barrel and hourglass) and type (object, hole, and thin object) as factors. There was no significant effect of shape ($F_{1,15} = 0.29$, $p = 0.599$), a significant effect of type ($F_{2,30} = 8.23$, $p < 0.001$), and a significant interaction between the two ($F_{2,30} = 20.23$, $p < 0.001$).

To know whether the thin-object condition behaved more like the object condition or the hole condition in relation to the variable shape we employed within-subjects contrasts.

[(2)] We suspect that parts are always present for the thin objects, but it is also possible that parts are never present (because an L-shape location with a concave cusp can describe a boundary between two parts). For the purpose of this paper what is important is that we have the same structure for barrel and hourglass. One might try to resolve the issue by predicting faster responses in general for thin objects compared to all other stimuli if they are perceived as parts, or slower responses in general if they are not perceived as parts. However, we prefer to focus on the comparison of barrel and hourglass within each type of object, ie the interaction between shape and type. Absolute level of performance for any type of object is inevitably contaminated by many factors. For instance, a thin object has a much smaller surface than an object, and therefore fewer disparity-carrying dots; this reduced information could counter the advantage of parts.

The 2×2 interaction between shape (barrel and hourglass) and type (object and thin object) was significant ($F_{1,15} = 25.39$, $p < 0.001$). The 2×2 interaction between shape (barrel and hourglass) and type (hole and thin object) was also significant ($F_{1,15} = 5.04$, $p = 0.040$). These two effects were predicted on the grounds that thin objects are different both from objects and from holes.

The means for RTs and errors can be seen in figure 2. Overall, the average error rate was 6.2%. Although errors were rare (and parametric analysis of such data problematic), a repeated-measures ANOVA on percentage of error showed that type was not significant ($F_{2,30} = 2.45$, $p = 0.105$), shape was significant ($F_{1,15} = 7.63$, $p = 0.015$), there were more errors for hourglass than for barrel, and there was a significant interaction between shape and type ($F_{2,30} = 8.91$, $p < 0.001$).

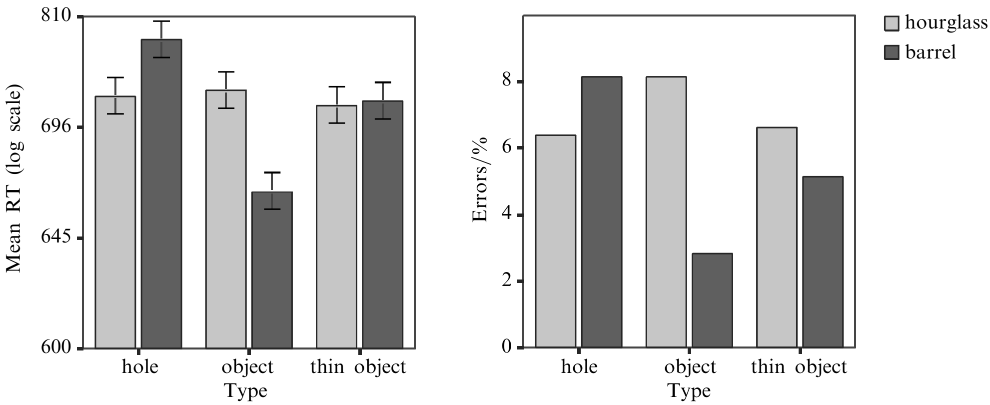
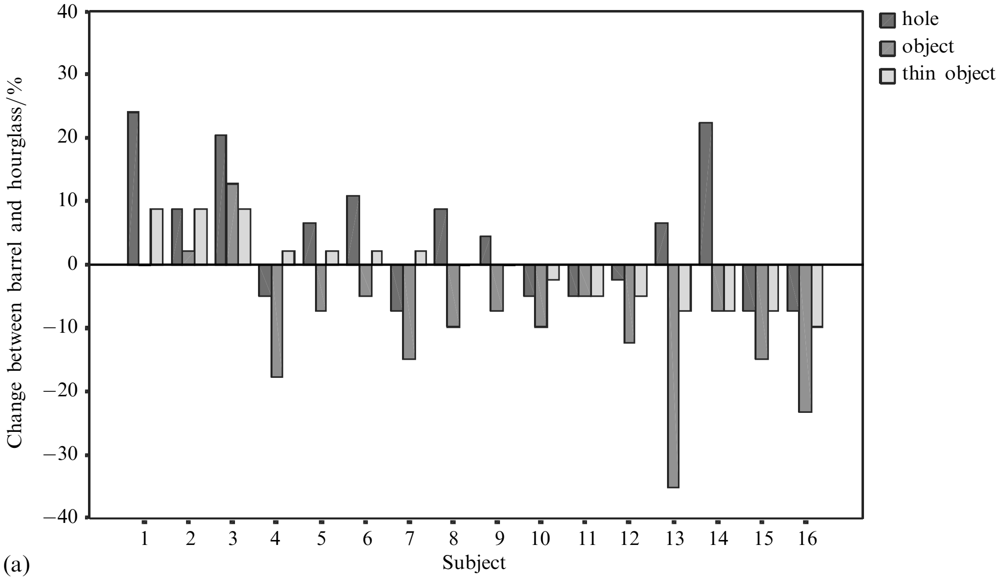


Figure 2. Results from experiment 1. The bar graphs show RTs and errors for the interaction between type and shape. Error bars are within-subjects SEMs.

The 2×2 interaction between shape and type (object and thin object) was significant ($F_{1,15} = 5.10$, $p < 0.039$). The 2×2 interaction between shape and type (hole and thin object) was also significant ($F_{1,15} = 5.40$, $p = 0.035$). Perhaps more importantly, there was no indication of a speed – accuracy tradeoff because the pattern in figure 2 is the same for RTs and for errors.

In interpreting the results it is important to compare the pattern for all three types of objects. We know that the RT difference for shape can vary from one experiment to the next, so that the most important test is the interaction between shape and type of object. If we just look at objects and holes first, the interaction between shape and type of object was strong, and the means cross over in the graph of figure 2 (both for RTs and for errors). These trials were interleaved with a new condition (thin object), and the question is whether the thin object behaves like an object, a hole, or neither. The graph and the contrasts on mean differences suggest that the thin-object condition behaved differently from both object and hole conditions, and that for the thin object there was no difference between barrel and hourglass. We believe that this is because there are always parts to be judged for the thin object. At this stage other possible explanations need to be discussed. An obvious possibility is that the thin object is perceived some times as an object (focusing on the outside) and some times as a hole (focusing on the inside). We cannot rule this out completely at present, but we think it is unlikely and we have two pieces of evidence against it.

First, we reasoned that, if thin objects can be perceived as either objects or holes, for some observers they would be treated more like objects and for others more like holes. In other words, some observers may have decided to focus on the outside and some on the inside. We looked at the mean difference (barrel – hourglass) separately for all observers, and we plotted absolute differences for the three types of objects in figure 3.



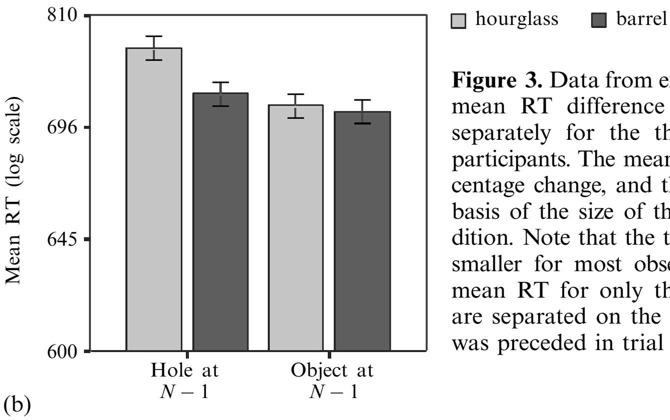


Figure 3. Data from experiment 1. Bar graphs (a) show mean RT difference between barrel and hourglass separately for the three levels of type and for all participants. The mean difference is expressed as a percentage change, and the participants are sorted on the basis of the size of the change in the thin-object condition. Note that the thin-object values are consistently smaller for most observers. Bar graphs (b) show the mean RT for only thin-object trials. However, trials are separated on the basis of whether the thin object was preceded in trial $N-1$ by an object or a hole.

The key question is whether the difference for the thin objects was large but with opposite sign for different observers. The graph shows that the percentage difference between barrel and hourglass varies from participant to participant, but the range of values is similar for objects and holes, and consistently smaller for the thin objects.[3]

Second, we reasoned that, if a thin object is always ambiguous and can be seen as either an object or a hole, then it should be possible to prime one or the other percept (for a recent example of priming a figure–ground reversal see Hulleman et al 2005). If so, there should be a difference between trials when the thin object was preceded by an object and trials when a thin object was preceded by a hole. We extracted these trials from the data set, and we ran an analysis on only the thin-object trials, but we

[3] It is worth pointing out that the percentage difference is a good way to describe a difference between log values. We have transformed RTs because of the positive skew of the RT distribution. But when we take the difference between log values (for barrel and hourglass) this number may not be easily understood. Fortunately, a difference between log values is the log of a ratio, so $\log(RT_1) - \log(RT_2) = \log(RT_1/RT_2)$, and if we subtract from 1 the back transformation of this value we get the change (as a proportion) between RT_1 and RT_2, which we chose to multiply by 100 and report as a percentage. Moreover, for small log differences (< 0.1) this transformation is approximately linear, meaning that if we had plotted the log differences the pattern would have been very similar (Hopkins 2000).

labelled as object the thin-object hourglass/barrel preceded by an object hourglass/barrel, and as hole the thin-object hourglass/barrel preceded by a hole hourglass/barrel. The four means can be see in figure 3. The idea was that an interaction should be present if the way thin objects are perceived depends critically on what was seen before. There were no significant main effects or interactions, although there was a trend for faster responses when the stimulus at $N-1$ was an object, both for hourglass and for barrel ($F_{1,15} = 2.11$, $p = 0.167$). This suggests that the lack of difference between hourglass and barrel for thin objects (figure 2) was not the result of averaging trials in which thin objects were perceived as objects and trials in which they were perceived as holes.

In conclusion, the results for the thin-object stimuli were midway between those for hole and object stimuli. On balance, it seems that the difference between barrel and hourglass was not present for these stimuli, and that this lack of difference was not the result of bistability. This result is what was predicted on the basis that parts are available for thin objects whether they are shaped like a barrel or an hourglass.

3 Experiment 2: Vertices belonging to separate objects

In experiment 2 we wanted to replicate and extend the finding of experiment 1. The new experiment has the same design as experiment 1 and provides a control. We believe that the critical factor to produce a difference between barrel and hourglass is the perceived part-structure. Therefore, the number of objects presented and the fact that vertices (parts) to be compared may not belong to the same object should not be important factors. In experiment 2 the hexagonal region (object, hole, or thin object) is split vertically into two halves (see figure 4). We predict an interaction between type of object and shape, and we predict that, as in experiment 1, the data for the thin-object stimuli will show no difference between barrel and hourglass conditions.

3.1 *Method*

The method and procedure were identical to those in experiment 1 except for the shape of the stimuli (see figure 4). Sixteen students at the University of Liverpool participated. They were screened for stereoacuity with the TNO stereotest (mean stereoacuity varied between 15 and 120 s of arc).

3.2 *Results and discussion*

As for experiment 1, we analysed transformed RTs for trials with correct responses. We ran a repeated-measures ANOVA with shape (barrel and hourglass) and type (figure, hole, and wire) as factors. There was a significant effect of shape ($F_{1,15} = 7.90$, $p = 0.013$), a significant effect of type ($F_{2,30} = 29.77$, $p < 0.001$), and a significant interaction between the two ($F_{2,30} = 35.24$, $p < 0.001$). The means for RTs and errors can be seen in figure 5.

To know whether the thin-object condition behaved more like the object or the hole condition in relation to the variable shape, we employed within-subjects contrasts. The 2×2 interaction between shape (barrel and hourglass) and type (object and thin object) was significant ($F_{1,15} = 36.28$, $p < 0.001$). The 2×2 interaction between shape (barrel and hourglass) and type (hole and thin object) was not significant ($F_{1,15} = 0.07$, $p = 0.791$). On this analysis we can therefore say that, in relation to shape, the thin object behaves differently from the object but not from the hole.[4]

[4] In experiment 1, a direct test on the difference between barrel and hourglass for the thin-object condition confirmed that the means were not different from each other ($t_{15} = -0.48$, $p = 0.634$). In experiment 2, a direct test confirmed no significant difference between barrel and hourglass in the thin-object condition ($t_{15} = -0.71$, $p = 0.484$) as well as the hole condition ($t_{15} = -0.88$, $p = 0.391$). However, for errors, only the difference between barrel and hourglass for the thin-object condition was not significant ($t_{15} = -0.48$, $p = 0.634$). We report these tests only in a footnote because, as explained in the introduction, we believe that it is more important to base our conclusions on the interaction between type and shape.

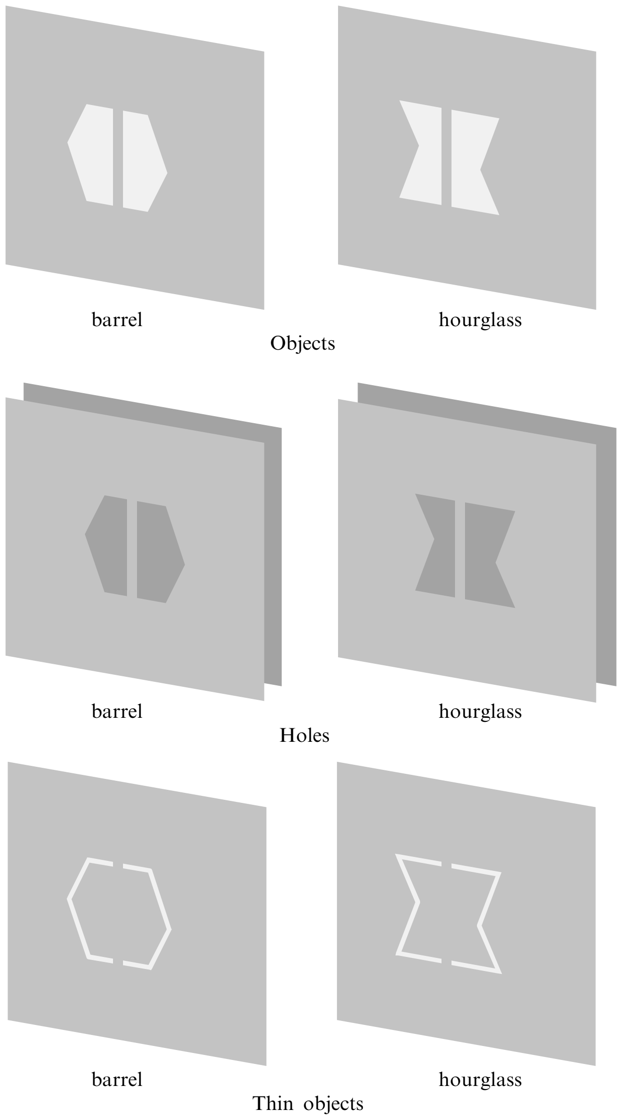


Figure 4. Stimuli used in experiment 2. The actual stimuli were random-dot stereograms. The three types of objects—object, hole, and thin object—are the same as in experiment 1 but are separated into two halves.

A repeated-measures ANOVA on percentage of errors showed significant effects of type ($F_{2,30} = 7.13$, $p = 0.003$), shape ($F_{1,15} = 17.07$, $p < 0.001$), and a significant interaction between type and shape ($F_{2,30} = 11.74$, $p < 0.001$). Figure 5 shows that, although the RT pattern is similar for holes and thin objects, for errors these patterns may differ. To test this possibility we performed the same contrast analysis on errors. The 2×2 interaction between shape (barrel and hourglass) and type (object and thin object) was significant ($F_{1,15} = 6.68$, $p = 0.021$). The 2×2 interaction between shape (barrel and hourglass) and type (hole and thin object) was also significant ($F_{1,15} = 7.44$, $p = 0.016$). This means that, in terms of accuracy, the thin objects behaved differently from both the objects and the holes (with respect to shape).

Arguably the most important effect is the difference between thin objects and objects, because this makes the outline of thin objects qualitatively different from the contours of

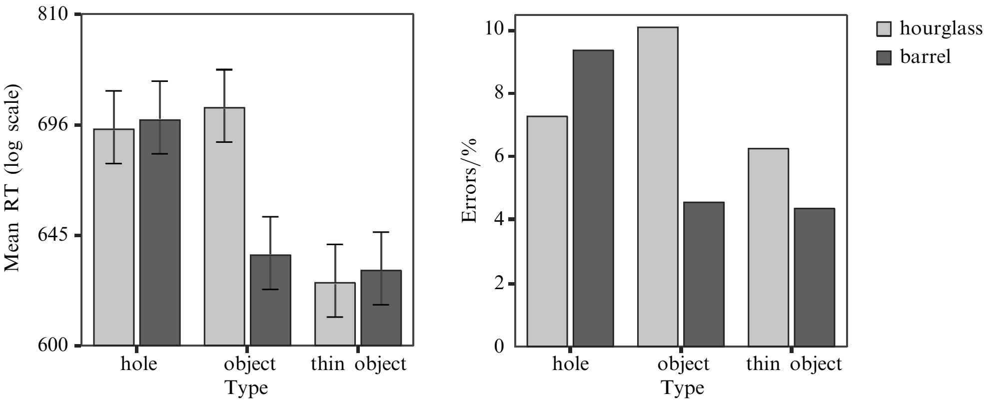


Figure 5. Results from experiment 2. Bar graphs show RTs and errors for the interaction between type and shape. Error bars are within-subjects SEMs.

a silhouette, as we predicted in the introduction. Both experiment 1 and experiment 2 confirmed this finding. In addition, thin objects seem to differ also from holes; the within-subjects contrast was not significant in experiment 2 for RTs, but was significant when errors were analysed. A comparison between experiments 1 and 2 shows that in experiment 2 there was a shift towards a general advantage for barrel over hourglass (a main effect for shape). We will come back to this issue after the analysis of experiment 3.

4 Experiment 3: Figures with holes and holes with figures

Experiment 3 is another control. As in Bertamini and Mosca (2004), we presented shapes as either objects or holes in the background. We believe that the reason for the interaction is the sign of contour curvature of the relevant vertices, not any other difference between objects and holes. Therefore, this experiment introduced a condition in which the objects were always presented with a rectangular hole in them and the holes were presented with a rectangular object inside. Consider the hexagonal object with a rectangular hole. From a topological point of view this stimulus is identical to the rectangular object with hexagonal hole used in the first experiment in Bertamini and Mosca (2004). Yet, the relevant vertices are concave in one case (Bertamini and Mosca 2004) and convex in the new stimuli. We predict that it is not the presence of a hole in itself that is important, but the change in ownership of the contours when there is a figure – ground change.

4.1 *Method*

4.1.1 *Participants.* Twelve students at the University of Liverpool participated. They were screened for stereoacuity with the TNO stereotest (mean stereoacuity varied between 15 and 120 s of arc).

4.1.2 *Stimuli and procedure.* The procedure was identical to that of experiments 1 and 2. We used two shapes (barrel and hourglass) and two types of stimuli (objects and holes). One condition of the experiment was a straight replication of the basic finding in Bertamini and Mosca (2004), whilst in the new condition the objects always had a rectangular hole in the centre, and the holes had a rectangular object in the centre.

Figure 6 illustrates the stimuli. Once the session started, 24 trials formed a practice phase and were not analysed, after which each observer performed four blocks of 120 trials.

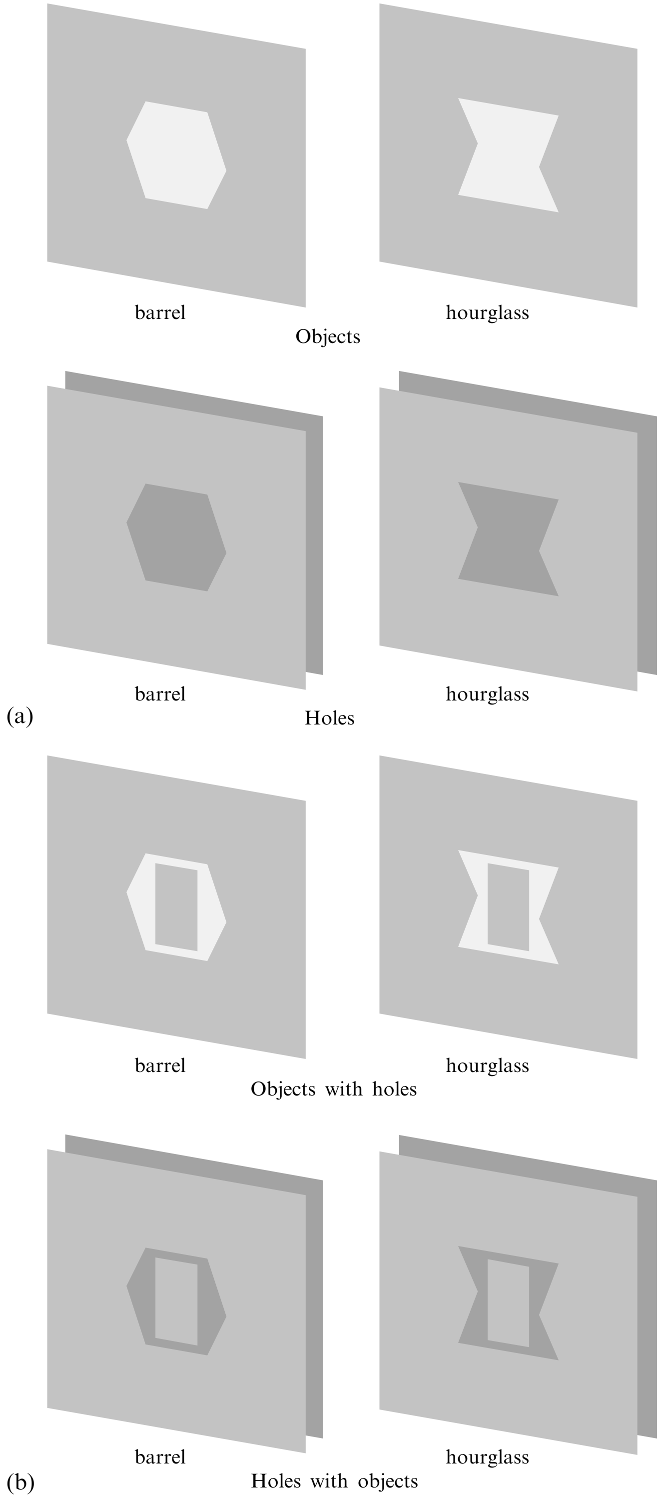


Figure 6. Stimuli used in experiment 3. The actual stimuli were random-dot stereograms. (a) Basic condition: there are two shapes, referred to as barrel and hourglass, and two types of objects, referred to as object and hole. (b) Modified condition: a rectangular hole has been added to the object condition, and a rectangular object to the hole condition.

4.2 *Results and discussion*

We analysed transformed RTs for trials with correct responses. A repeated-measures ANOVA on (transformed) RTs for shape (barrel and hourglass), type of object (object and hole), and condition (uniform regions and regions with new central hole/figure) confirmed a significant effect of shape (responses were faster for the barrel shape: $F_{1,11} = 11.01$, $p < 0.007$), a significant effect of type (responses were faster for the object: $F_{1,11} = 26.83$, $p < 0.001$), and a significant effect of condition (responses were faster when there was no inner rectangle: $F_{1,11} = 11.76$, $p < 0.006$). There was also a significant interaction between shape and type ($F_{1,11} = 24.90$, $p < 0.001$). No other interaction was significant.

The means for RTs and errors can be seen in figure 7. Overall, errors were made in 8.4% of the trials, without any indication of a speed–accuracy tradeoff. An ANOVA on errors with the same design as the analysis of RTs confirmed a significant effect of type ($F_{1,11} = 15.02$, $p = 0.003$), and a significant interaction between type and shape ($F_{1,11} = 5.35$, $p = 0.041$), but no other effects or interactions.

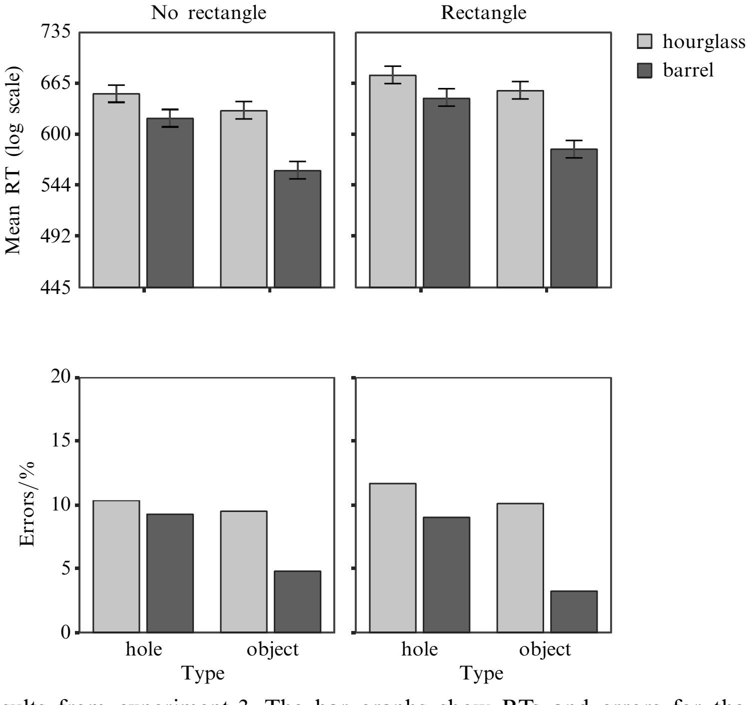


Figure 7. Results from experiment 3. The bar graphs show RTs and errors for the interaction between type and shape. Error bars are within-subjects SEMs.

The results confirmed the prediction that there is an interaction between shape and type: for objects the responses to the barrel were faster than to the hourglass ($t_{11} = -5.491$, $p < 0.001$), but this difference was absent for holes ($t_{11} = 1.58$, $p = 0.141$). Importantly, the interaction between shape and type does not depend on the presence of extra rectangular holes/objects within the stimuli. We take this as further support for the hypothesis that the reason for the interaction is the convexity and concavity of the vertices that need to be judged. In other words, with respect to the interaction there is nothing unique about seeing a hole, other than what is implied by the different ownership of the contours.

5 Effect of shape in experiments 2 and 3

Unlike experiment 1, experiments 2 and 3 revealed a main effect of shape, meaning that responses to the barrel were generally faster than the responses to the hourglass. This effect complicated the interpretation of the results, as it meant that the basic interaction between type (hole and object conditions) and shape (barrel and hourglass) was a cross-over interaction in experiment 1, was a weaker cross-over in experiment 2, and was not a cross-over in experiment 3. Nevertheless, the interaction was always significant, and we suspected therefore that a factor absent in experiment 1 may have hindered responses to the hourglass relative to the barrel in the other two experiments. This is likely to be the presence of new contours inside the region as can be seen in figures 4 and 6. The location of these contours is fixed, but as a consequence they are closer to the vertices of the hourglass than to the vertices of the barrel, and they may cause more interference in the former case. This would also explain the faster responses to the thin-object condition of experiment 2 relative to the other conditions, because no edges were present for such stimuli (see figure 4). This issue is not critical with respect to the main focus of the paper. However, we want to briefly mention that we have found more evidence to support this interpretation. We repeated experiment 2 but extended the thin objects so that the contours closed into two separate objects (with new vertical thin parts). This new control experiment replicated all the findings of experiment 2, but responses to the thin-object condition were now more similar to those in the other two conditions.

6 Conclusion

In experiment 1 we introduced a new type of stimulus (a thin object) for which we predicted that similar part-structure will be perceived in the case of a barrel as well as in the case of an hourglass configuration.

The thin-object condition was inspired by an example in Kennedy (1974) in which he discusses a line drawing and suggests that a thin line may be perceived as not belonging to either figure or ground. In a sense, the thin line is an object in itself. We made sure our thin lines were objects with the use of RDSs. Kennedy's demonstration is interesting with respect to the debate on whether border ownership is obligatory, but this aspect of the problem is not central to the present paper. Instead, we are interested in what happens to perceived part-structure for thin objects. Part-structure is closely related to convexity and concavity coding, which in turn depends on figure–ground coding, but it should not be reduced to that. Parts may be perceived on the basis of a combination of factors, including symmetry, protrusion, familiarity, and others (eg Siddiqi et al 1996; Singh et al 1999; De Winter and Wagemans 2005). In the past we have used irregular hexagons to manipulate convexity and concavity, and we found that positional judgments about vertices of a barrel-shaped or hourglass-shaped region depended on figure–ground coding (objects versus holes). The thin objects in our stimuli are interesting because they may be expected to be as good a specimen of the object category as the filled objects. However, we predicted that, because the L-shaped region is identical in terms of convexity/concavity whether it points inward or outward, the difference between barrel and hourglass should be relatively weak. Results from experiments 1 and 2 support this hypothesis.

This result is surprising because it is intuitively appealing to think that the perceived part-structure of a thin, wire-like, object is the same as the perceived part-structure of a silhouette (with the same outline). However, perceived part-structure depends on the changes of sign along the contour (convexities and concavities) and their relation to Gaussian curvature of 3-D surfaces. For a silhouette it is reasonable to expect that the contour is the projection of the rim of a surface, but for a thin object this is not the case.

Elbow-shapes have been discussed before in the literature and there is some evidence that people perceive an elbow as the boundary between two parts (Singh et al 1999). We cannot say for sure from the available data whether our participants saw the elbows of the thin objects as parts or as boundaries. This is an interesting topic for future work: it seems to us that elbows are boundaries in a sense, if nothing else because the regions on either side differ significantly in orientation, but in another sense the elbows are parts in themselves. This is also suggested by the fact that most languages have a word for the elbow and people think of it as a part of the human body.

In experiment 3 we have shown that the interaction between shape and type of object (objects and holes) is not affected by the presence of irrelevant holes and objects. By irrelevant we means that the contours of these new entities did not carry any information useful for the task. Therefore, we have replicated and strengthened the idea put forward in Bertamini and Croucher (2003) and Bertamini and Mosca (2004) that this interaction is caused by the fact that the convexity and concavity coding of the relevant vertices is reversed by a change from objects to holes. Our theoretical account is that what is critical is the perceived part-structure, and convexity and concavity affect part-structure.

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

PERCEPTION
VOLUME 35 2006

www.perceptionweb.com