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The importance of being convex: An advantage for convexity when judging position

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Abstract. Perception of contour polarity was investigated in five experiments in which observers had to judge the vertical position of a vertex. When the vertex was perceived as convex, the level of performance as measured by reaction time and errors was higher than when the same vertex was perceived as concave. I conclude that contour polarity affects how observers perceive shape, and in particular part structure, and that the position of a part is more readily available than the position of a boundary between parts.

1 The importance of being convex

The information available to the visual system includes the orientation of edges and, by extension, the curvature of the contours that are formed by these edges. Moreover, the visual scene is always organised into regions that form figures (as opposed to ground) defined by surfaces (as opposed to media). In this richer context of surfaces in space, contours are not isolated edges but correspond to the rims (visible boundaries) of the surfaces. The process of segmenting an image implies a distinction between the inside and the outside of regions which are respectively seen as figures and background. On the basis of which side is perceived as the inside, the curvature will have not only a magnitude but also a sign: positive for a convex region, and negative for a concave region. This paper is concerned with the processing of this information, ie curvature polarity, and the differences between convexity and concavity as revealed by different tasks.

Two important theoretical contributions have greatly increased the interest in studying how people perceive and use curvature polarity. First, Koenderink (1984) has shown that convex and concave regions of a contour arise from the projection in the image of convex and saddle regions of a smooth surface. That is, because of how objects self-occlude, contour polarity is informative about solid shape (surface curvature). Second, Hoffman and Richards (1984) have shown that, when arbitrary solid shapes meet and interpenetrate, they form concave creases. If one allows for some smoothing, the points along the crease are saddle points that can be seen in the image (ie any 2-D projection) as concavities. A crease is a concave discontinuity but, in the more general case of a smooth surface, this is a point where the negative curvature reaches a peak (a negative peak, and therefore a minimum of curvature). Hoffman and Richards (1984) consequently argue that the visual system should see shapes as composed of parts separated by minima of curvature. This part decomposition can be useful for the purpose of recognising a complex shape on the basis of its structural description (Biederman 1987; Marr and Nishihara 1978). Hoffman and Singh (1997) and Singh et al (1999) have also extended the theory to predict which parts will be seen as more salient, including the importance of the length of the 'cut' that separates two parts.

At the moment it is not known how or at what point the visual system turns information about edges, which can be computed locally, for instance on the basis of zero crossings (Marr 1982), into contours that have a signed curvature, and therefore depend on image segmentation and figure – ground organisation. Nevertheless, the psychophysical evidence about the importance of polarity is mounting, and its roots are in classic work by Bahnsen (1928) and Kanizsa and Gerbino (1976). Most of the empirical work that I will discuss here exploits the fact that, if convexities and concavities are important for how people see solid shapes, a figure–ground reversal will always have dramatic effects on what people see. For example, Rock (1983) found that people do not remember seeing a shape when that region is perceived as ground instead of figure. This could be interpreted as showing that the change of polarity changes the perceived shape (see also Attneave 1971). More recently, Driver and Baylis (1996) have used a visual-matching paradigm and found that it is very difficult to match two identical (ie congruent) contours when they are perceived as having different polarity. In simple terms, an indentation will not look like a protrusion even if the shape of the contour is identical. I want to emphasise the point that a task that can be performed on the basis of one-dimensional information about the edges becomes difficult because the perception of polarity makes the edges appear different. Driver and Baylis (1996) convincingly argue that assignment of polarity is fast and obligatory.

Recently Hulleman et al (1998) and Humphreys and Müller (2000), using the visual-search paradigm, found important differences between concave and convex contours in the speed and efficiency of visual search. It appears that concave edges are processed more efficiently, leading to shallower search functions. I will review these findings next and then I will review evidence that suggests, instead, that convex edges are processed faster, as measured by reaction time (Bertamini 2000; Bertamini and Friedenberg 2001; Gibson 1994). Finally, I will resolve this apparent contradiction on the basis of what information is made available to the system by polarity and by the related part decomposition of a shape.

2 Visual search

Elder and Zucker (1993, 1998) have studied closure and found that it has a significant effect on visual search. Only when contours formed a closed region did the difference between concave and convex stimuli (< > versus > <) lead to efficient search. This can be taken as indirect evidence of the importance of contour polarity as well as closure, because polarity is undefined without closure.

Hulleman et al (1998) have used various shapes in a visual-search task, and found that when a shape has a concavity the search becomes more efficient than when the shape is strictly convex. More specifically, a search asymmetry is present: searching for a concavity among convex shapes is faster and is affected less by set size than searching for a convex shape among shapes with concavities. In a series of experiments they ruled out possible confounds and argued that convexity is the factor that should be considered a basic feature. Perhaps the fact that concavity is important for defining the parts of an object (Hoffman and Richards 1984) dictates a special status for concavities and makes concavities more salient. Humphreys and Müller (2000) have performed similar experiments and confirmed the concave advantage and the search asymmetry. Furthermore, they have manipulated the figure–ground organisation of the stimuli by closing the contours differently. By changing figure–ground it is possible to reverse polarity without changing anything about the edges themselves. In other words, the task remains unchanged and the change in how contours are organised in figures and ground should be irrelevant if visual search is based on edges. However, because a reversal of figure–ground implies a reversal of polarity, one should expect also a complete reversal of the search asymmetry. This is what they found, and therefore it supports the idea that polarity is the critical factor. Humphreys and Müller's interpretation is similar to that of Hulleman et al (1998). They argue that concavities can be selected quickly, perhaps via the activation of specialised detectors.

3 Speeded responses about position

The literature on visual attention and objectness has almost by accident provided evidence about the relative processing speed of convex and concave vertices. Baylis and Driver (1993) used a paradigm in which two vertices on opposite sides of a figure had to be compared. The observer had to detect which vertex was lower. They found an advantage for the condition in which the vertices were perceived as part of a single object, as opposed to two separate objects. However, the figure – ground reversal necessary to change the one-object condition into a two-objects condition also turned convex vertices into concave vertices. This was pointed out by Gibson (1994) who found an interaction between objectness and polarity. Later, however, the single-object advantage was also reported with equal convexity (Baylis 1995).[(1)]

In figure 1, I have summarised the findings of two experiments in which convex and concave vertices were compared. The first experiment is by Gibson (1994) and manipulated objectness by an instruction to the observers. Either the red or the green region was seen as a figure, and consequently one or two objects were present. The figure – ground reversal meant that the convex and concave conditions reversed the polarity in the two-objects interpretation (labelled 'open' in figure 1). Therefore a convex advantage is shown by an interaction between objectness and polarity. The second experiment is by Bertamini and Friedenberg (2001) and replicates this interaction effect. The difference with respect to Gibson's experiment is in how the figure – ground organisation was effected. Bertamini and Friedenberg used closed contours in a way similar to the stimuli of Humphreys and Müller (2000). The interaction is still present, with a larger effect of objectness as might be expected. The same pattern was found in another experiment when observers were asked to judge whether the two vertices were symmetrical around the vertical axis [for a discussion, see Bertamini and Friedenberg (2001)].

It may seem contradictory that in a speeded-response task one finds a convex advantage (including a reversal of this advantage with figure – ground reversal), whereas in a visual-search task a concave advantage was found (including, again, a reversal of this advantage with figure – ground reversal) (Hulleman et al 1998; Humphreys and Müller 2000). If concavities are basic features, one would expect that performance should be high whatever the task. However, the relevance of the task points in an interesting direction; the results may depend on the task because of what information is made available by the polarity of the contours.

In this discussion I will assume, as does most of the literature, that the role of concave vertices is in the parsing of a shape [as proposed by Hoffman and Richards (1984)]. Moreover, parts have positions and perhaps are represented as having an axis of orientation [based on symmetry or elongation—Marr and Nishihara (1978)]. In general, this simply means that a shape that is perceived as composed of just one part will have one main orientation, whereas a shape perceived as composed of two parts will have two orientations that may or may not coincide [Biederman 1987; Hummel and Biederman 1992; Marr and Nishihara 1978; for a different view and a representation of shape based on superquadrics, see Pentland (1986)]. If this is correct we can look at the evidence again and see whether human performance may be consistent with the mediating effect of an obligatory part decomposition.

One potential source of confusion in the interpretation of the findings about polarity is the meaning of the words convex and concave when applied to contours and when

[(1)] Recently, Tsal et al (2000) have argued that the two-objects cost found by Baylis and Driver (1993) can be an effect of the size of the area attended to (instead of the number of objects). In their experiment, the two objects on the outside were joined, so that the central region was perceived as a hole. These findings are also consistent with an effect of curvature polarity, ie an advantage for comparing convex vertices.

applied to objects or closed shapes. It is possible to have local convexity and local concavity, but, with respect to a closed shape, curvature can be strictly positive but cannot be strictly negative. A strictly negative contour defines a hole, not an object [the study of perception of holes has only recently started, see Palmer (1999, pages 285 – 287)]. This is important, because in the visual-search experiments discussed above (Hulleman et al 1998; Humphreys and Müller 2000) the concave shape had also convexities, whereas the convex shape had no concavities. Therefore, if concavities create parts, the concave shape had multiple parts, whereas the convex shape had only one part. Even with the figure – ground reversal introduced by Humphreys and Müller (2000) the concave stimuli had more parts (four) than the corresponding convex stimuli (two). In visual search, these parts may play a central role, as the presence of extra parts turns the task into a search for a presence of these parts in one case, and a search for an absence in the other. The resulting search asymmetry in favour of a search for a presence is a well-known effect in visual search (eg a 'Q' pops out among 'O's but not vice versa), and it has been suggested that it results from the fact that there is no feature map defined by the absence of a feature (Treisman and Souther 1985). I believe this suggestion that parts are important in visual search is entirely consistent with the role of surfaces in visual search as demonstrated by He and Nakayama (1992) and Nakayama and Shimojo (1992).

This interpretation of the findings of Hulleman et al (1998), and Humphreys and Müller (2000) does not mean that concavity is not responsible for the search asymmetry, but it does suggest that the effect is mediated by the role that concavities have on part decomposition.

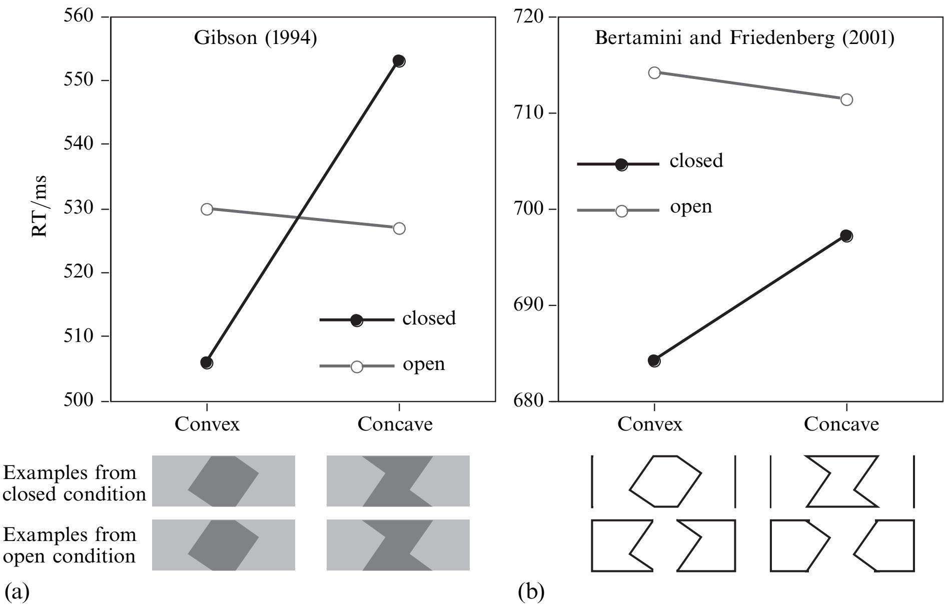

Figure 1. Summary of findings with the one-object/two-objects paradigm. (a) Mean reaction time replotted from Gibson (1994); in this experiment the figure – ground organisation was affected by the instructions to the observers to see either the red (dark grey) or the green (light grey) as the figure. The difference between closed and open conditions was therefore only in the instructions. (b) Replication of Gibson's experiment with closure used to affect figure – ground organisation (from Bertamini and Friedenberg 2001). In another experiment Bertamini and Friedenberg also found the same result when the task was to judge whether the two vertices were symmetrical. In all these experiments the area enclosed by the contours was the same for the convex and the concave conditions (examples are not meant to accurately reproduce the original stimuli). For simplicity, only response times (RTs) are shown in this figure, but error rates were consistent with this pattern.

I will now turn to the task of comparing the position of vertices. In this case, the number of parts may not be the important factor. It is true that one might expect an overall advantage when fewer objects, and presumably fewer parts, are present (Baylis and Driver 1993; Hulleman and Boselie 1998). In this sense, polarity and number of objects are confounded in the data presented in figure 1. However, when the task is to judge a position, I propose that the most important factor is whether there is *a part for that position to be of.* Figure 1 may already be interpreted in this way, but in this paper I set out to find new, unconfounded evidence for a convexity advantage for tasks that involve positional judgments using simpler stimuli and a minimum number of vertices.

4 Experiment 1: Positional information and convex and concave vertices

In this experiment, the task of the observer was to judge the vertical position of a vertex with respect to a white reference line. Because this task involves a judgment that has to be based on the perceived position of the vertex, I predict a difference based on whether the vertex is seen as a part (convex), or as a boundary between parts (concave).

The stimuli were based on the configuration illustrated in figure 2. A central region was divided into a red and a green section, and the boundary between the two had a vertex pointing either to the right or to the left. One of the coloured surfaces, red in the examples of figure 2, was extended to the left and to the right so that the smaller green region was perceived as the figure. Two white reference lines were present on either side, and the task was to judge whether the vertex in the middle was higher or lower (vertically) than the white line.

The hypothesis is that the task would be affected by the perceived part decomposition of the figure. In the case of a convex vertex, I assume that this convex region is perceived as a part, protruding from the rest of the figure. If so, observers can base their judgments on the position and/or orientation of this part. Contrast this situation with the case of a concave vertex. Although the edge that forms the vertex is identical to the convex case, the concave vertex is not seen as a part but rather as the boundary between two parts, one above and one below (because the position of the vertex was randomly chosen in the bottom or top part of the figure, it was not possible to perform the task by seeing which of the two parts was longer). The lack of a perceived part that corresponds to the concave vertex should make the task more difficult. It is important to note that this prediction is based on a hypothesis about how the visual system operates. There is no geometrical reason why the position and/or the orientation defined by a concave vertex should be harder to compute than the position and/or the orientation of a convex vertex.

In addition, participants were not instructed to see the whole figure as a surface or as an object; they could perform the task by concentrating only on the vertical line in the centre of their visual field, and judge the position of the vertex along this line. If they did so, no effect of polarity could be present because polarity cannot be defined with respect to a line (in fact, one would not know which condition to label as convex and which to label as concave). I expect this not to happen because, as discussed in section 1, polarity is obligatory for the human visual system (Driver and Baylis 1996).

4.1 *Method*

4.1.1 *Participants.* Ten students at the University of Liverpool participated. They were naïve with respect to the problem and the hypotheses until after the data were collected.

4.1.2 *Design and stimuli.* The factors were shape (convex versus concave), layout (whether the figure was on the left or on the right), and offset (higher versus lower than the white line) and position (whether the vertex was in the top or bottom half of the figure). They were factorially combined in a within-subjects design. The hypothesis is that shape will have an effect; the other factors are needed to create a task in which position has to be judged relative to a reference line. For example, the reason for two positions, one in the top half and one in the bottom half of the contour, is that this prevented observers from being able to judge the height of the vertex with respect to the fixation mark presented before the stimulus. Instead, the height of the vertex had to be compared to a white reference line and was higher or lower by 0.15 deg with equal probability. This factor (offset) and the layout (right or left presentation) were included in the analysis to look at possible spatial asymmetries.

Examples of the stimuli are illustrated in figure 2. They were presented on a monitor (resolution 1024 × 768 at 85 Hz) controlled by an Apple Macintosh computer. The height of the stimulus was approximately 3 deg. The actual position of the stimulus was randomly varied in each trial around the centre of the monitor (±0.6 deg in both dimensions) to discourage observers from using positional cues. This promotes a more holistic view of the display and avoids a strategy of focusing on position with respect to, say, the frame of the monitor.

4.1.3 *Procedure.* Each observer sat in a dimly illuminated room at a distance of approximately 57 cm from the monitor. The observers were given instructions and shown examples of the stimuli before the experiment started. They were instructed to press the 'z' key on the keyboard if the vertex was higher than the reference line and the '/' key if the vertex was lower. Once the session started, 24 trials formed a practice phase, and after this a message appeared asking the observer to start the experiment (by pressing the space bar). In the experiment, each participant performed 768 trials. For half of the participants the figure was green and the background red, and for the other half the figure was red and the background green. The trials were presented in rapid succession, but after every 128 trials a block ended and the observer was allowed time to rest. The start of subsequent blocks was self-paced. The computer recorded response times and controlled the presentation of the stimuli by means of the Video-Toolbox subroutines (Pelli 1997).

4.2 *Results and discussion*

The following steps were taken in the analyses for this and subsequent experiments. Responses that took longer than 3000 ms were discarded. Only trials with correct responses were used in the analysis of response time. The response time (RT) recorded in milliseconds was logarithmically transformed for two reasons: first, to normalise the distribution and meet the assumptions of ANOVA; second, because there are theoretical reasons to expect lognormal RT distributions (Ulrich and Miller 1993). A repeated-measures ANOVA on (transformed) RT for type of contour (convex versus concave) offset and layout confirmed that responses were faster for the convex condition ($F_{1,9} = 23.09$, $p < 0.001$); no other main effects or interactions were significant.

The means for RT and errors can be seen in figure 2. Overall, errors were made in 6.12% of the trials. Using the same design and the same factors as in the first ANOVA, I ran a second ANOVA on the percentage of errors but it did not reveal any significant difference.

The results confirmed the prediction that it is easier to judge the position of a convex vertex (on average the advantage was 33.37 ms for convex shapes). I believe this has to do with part decomposition in the sense that a perceived part has a position and a boundary between two parts does not. Looking at figure 2, in the concave condition the vertex is a boundary between two parts, in the convex condition the vertex is a part in itself.

According to the rules for parsing silhouettes proposed by Singh et al (1999), in both conditions the figure has a total of two parts, although their shape would be quite different. In the convex condition, one part consists of the convex vertex and the other

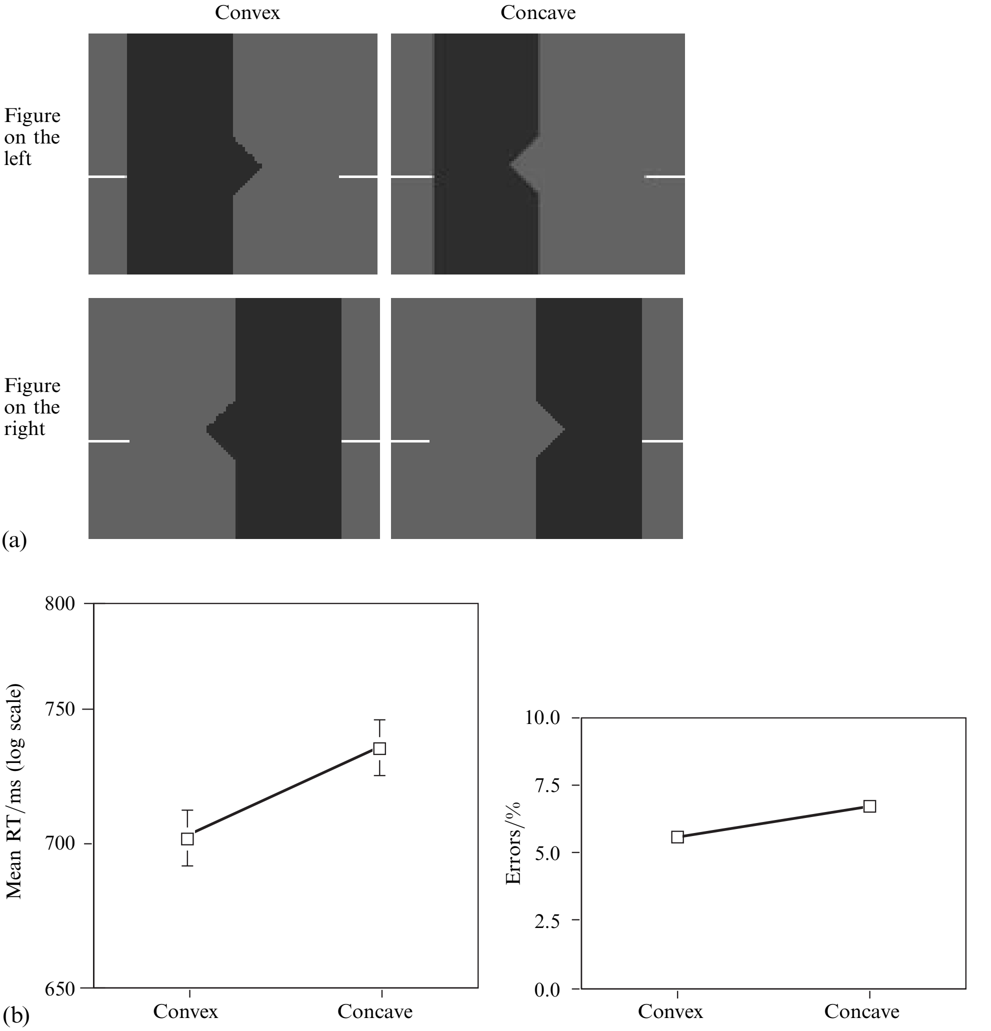

Figure 2. Stimuli and results from experiment 1. (a) Observers were asked to judge the position of the (central) vertex with respect to a reference white line. In these examples light grey = red and dark grey = green, so that the green region is seen as the figure. The colours were reversed for half of the participants. (b) Geometric means of reaction time and error rates plotted against the type of contour. Error bars are within-subjects standard errors for reaction time.

part is a rectangle; in the concave condition the two parts have similar shape and are separated by the concave vertex. Because the total number of parts is the same, this cannot be the reason for the difference in RT. Alternatively, it is possible that in the convex condition the figure is perceived as composed of only one part, but in this case the main axis of elongation is now ambiguous: possibly the main vertical axis and the horizontal axis through the convex vertex are equally salient. In either case, the presence of a major or even minor axis of elongation through the vertex can be the basis for performing the task. Conversely, in the concave condition, even if the whole region was not parsed into two parts but was seen as a single shape, there was no major or minor axis of elongation going through a concavity. In this sense the number of parts perceived is not the important factor; what is important is whether the vertex is seen as a convexity or merely as a boundary between convex parts.

5 Experiment 2: Control

Experiment 1 revealed an advantage for judging the position of a convex vertex. It was argued that the important factor was not how many objects or how many parts were perceived, but whether a part was perceived with a position or an axis of orientation that corresponded to the relevant vertex. A concave vertex (not seen as a part) would not have an orientation and its position is therefore not easily available. However, it is possible to argue that other factors may have played a role in experiment 1. For example, even though a single vertex was used, it is still possible to disagree about how many parts were perceived in the two conditions.

One possibility may be that in the convex condition a single part was perceived and in the concave condition two, leading to an advantage related to the single-object advantage reported in the literature (Baylis and Driver 1993; Gibson 1994). This is a problem that experiment 1 shares with the data presented in figure 1. Moreover, because of how the vertex was created, in the convex condition there were two concave vertices flanking the convex one, and in the concave condition there were two convex vertices flanking the concave one. Although it is unlikely, if observers were looking at these vertices instead of the central one, they may have still been able to perform the task, but my conclusion of a convex advantage would be unwarranted.

Experiment 2 was a control for experiment 1—it used different shapes but the task was unchanged. In one version (A) only one vertex was present. As can be seen in figure 3, not only the presence of flanking vertices was eliminated, but observers can probably agree on the number of parts perceived: one for the convex condition and two for the concave condition. In another version of the experiment (B) the position of the flanking vertices was varied in each trial so that they were at varying random distances from the reference line and therefore irrelevant to the task. More importantly, in this second version the overall shape changed so that the number of parts present was larger in the convex condition (three) than in the concave condition (two). Finally, a third version (C) tested the importance of edges between the central vertex and the reference line. An edge was always present at the boundary between the two coloured regions; in this condition there was the addition of a high-contrast line to make sure that edges were present both left and right. This made the display slightly more ambiguous, and the predicted effect of polarity relies solely on the role of colour, namely the fact that the uniform background still leads to the same figure–ground organisation.

Figure 3 shows the convex and concave condition with a green object on the left as an example. I predict that, notwithstanding the change in appearance, the convex advantage found in experiment 1 will be confirmed. This is because the critical factor is whether the observers are judging the position of a convex part as opposed to the position of a concavity.

5.1 *Method*

Everything in the method and procedure was identical to experiment 1 except for shape of the stimuli. Examples of the new stimuli can be seen in figure 3. Three groups of ten students participated as volunteers in the three versions of the experiment.

5.2 *Results and discussion*

I ran a mixed ANOVA on (transformed) RT for type of contour (convex versus concave, within-subjects) and type of stimuli (A, B, and C, between-subjects). The ANOVA confirmed that responses were faster for the convex condition ($F_{1,27} = 5.16$, $p = 0.031$) and there was no effect of type of stimuli ($F_{2,27} = 0.20$) nor an interaction ($F_{2,27} = 1.74$). The means can be seen in figure 3b, together with error rates. Overall the average error rate was 10.37%. An ANOVA on the percentage of errors using the same design did confirm an advantage for the convex condition ($F_{1,27} = 8.96$, $p = 0.006$) and no other effects or interactions.

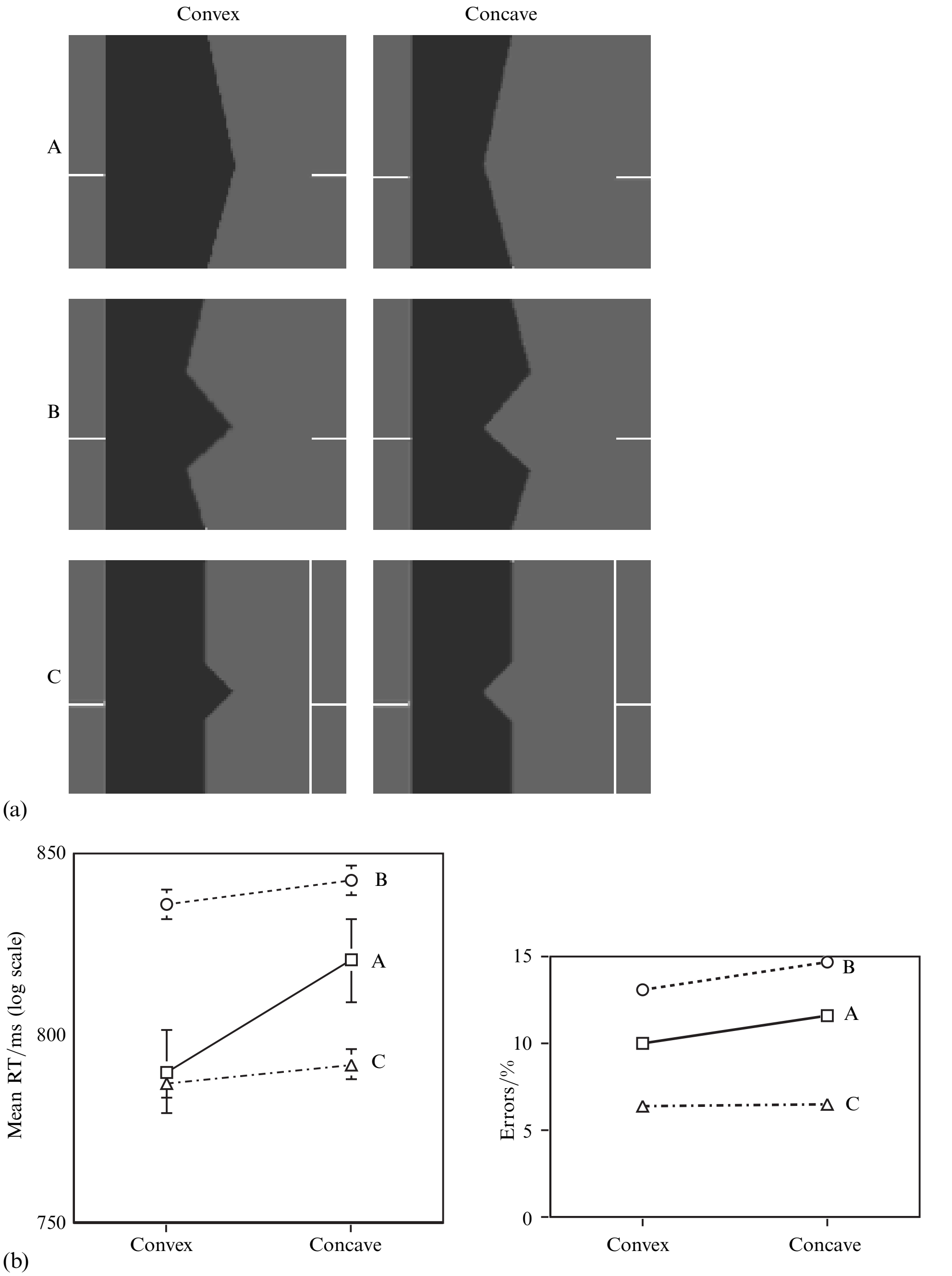

Figure 3. Stimuli and results from experiment 2. (a) In A only one vertex was present, in B the shape was changed so that the figure in the convex condition was composed of more parts (three) than the figure in the concave condition (two), and in C high-contrast edges were present on either side. For simplicity, only the condition in which the figure was on the left is shown here. (b) Geometric means of reaction time and error rate plotted against the type of contour. Error bars are within-subjects standard errors for reaction time.

Experiment 2 supports the view that the relevant factor is whether a vertex is perceived as convex or concave, irrespective of the differences in shape and number of parts introduced in the new stimuli.

6 Experiment 3: Colour instructions

Experiments 1 and 2 used colour and layout to affect figure–ground organisation and therefore polarity. Experiment 3 was designed to see whether the same effect can be found by simply asking participants to select as figure the region with a particular colour (for a similar manipulation see Baylis and Driver 1993). The advantage of this manipulation is that the stimulus presented remains identical (in the sense that it is impossible to classify convex and concave conditions by looking at the stimuli), and I predict an effect of polarity dependent on instructions alone.

6.1 *Method*

The method and procedure were identical to those of experiments 1 and 2 except for the changes described below. Examples of the new stimuli can be seen in figure 4. Either the red or the green region could be seen as figure and there were two sessions (640 trials each) of the experiment. In one session, observers were asked to see the

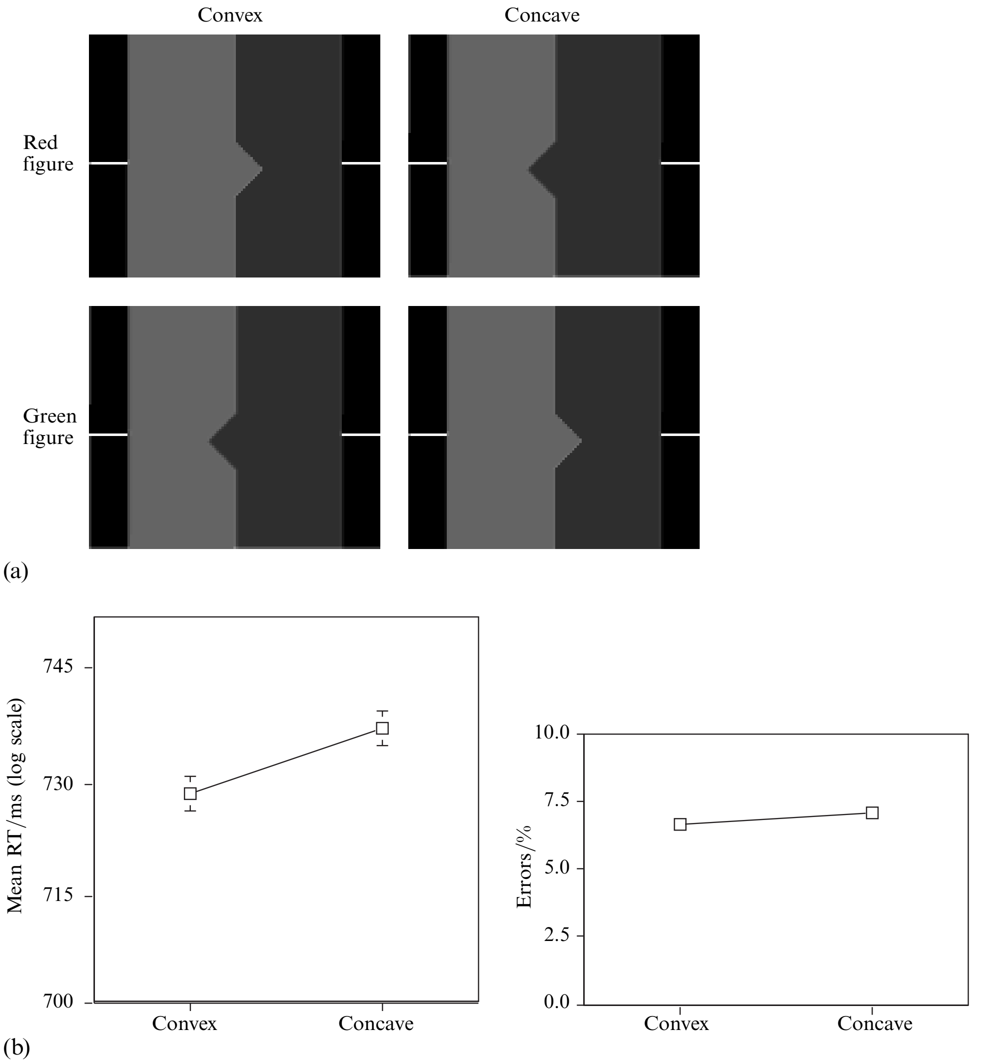

Figure 4. Stimuli and results from experiment 3. (a) The stimuli were the same in the convex and concave conditions but the instructions were different. Light grey = red, dark grey = green. (b) Geometric means of reaction time and error rate plotted against the type of contour. Error bars are within-subjects standard errors for reaction time.

red region as figure and in the other to see the green region as figure. This is a difficult task, and to help observers the following modifications were made: (i) the luminance of red and green was altered so that they were as similar as possible (approximately 31.5 cd m^{-2})—this avoided the problem that regions with higher contrast with the background tend to be seen as figures; (ii) one out of nine trials in the experiment presented only the red/green region compatible with the instructions, these trials were excluded from the analysis; (iii) each colour only appeared on one side, ie red on the left and green on the right. Ten students participated as volunteers in the experiment.

6.2 *Results and discussion*

A within-subjects ANOVA on (transformed) RT for type of contour (convex versus concave) and colour (red versus green) confirmed that responses were faster for the convex condition ($F_{1,9} = 6.69$, $p = 0.029$), and there was no effect of colour ($F_{1,9} = 1.10$) nor an interaction ($F_{1,9} = 0.76$). The means can be seen in figure 4b, together with error rates. Overall the average error rate was 6.98%. Although observers were more accurate for the convex condition, as predicted, an ANOVA on the percentage of errors did not confirm any significant effect or interaction.

Experiment 3 supports the finding that when a vertex is perceived as convex it is easier to judge its position than when the same vertex is seen as concave. This effect can be obtained by asking participants to subjectively try to see one region as figure.

7 Experiment 4: Fixed distance from reference line

Experiments 1, 2, and 3 used a display in which a central contour is flanked by two white reference lines. This makes the display symmetrical (ignoring figure–ground organisation) but perhaps participants were led to make the comparison more often on one side on the basis of figure–ground information. Even though the figure appeared with equal frequency on the left and on the right, if participants more often compared the position of the vertex to the line on the farther side (facing the object, so to speak), then this line was closer in the convex condition and this artifact may have contaminated the findings.

In experiment 4, I removed one of the two lines and left only the one on the farther side, as illustrated in figure 5. Moreover, I increased the size of the concave figure so as to position the intersection of the lines forming the vertex at the same distance from the comparison line in both conditions. Notice that by doing this, although the intersection points are now at a fixed distance from the reference line, in the concave condition the contours extend in the direction of the reference line and because of this they contribute to make the contours in this condition closer on average to the reference line. In other words, if the precise distance from the reference line is important, I have chosen a manipulation that stacks the odds against the hypothesis of a convex advantage. Nevertheless I predicted and found a significant advantage for the convex condition.

7.1 *Method*

The method and procedure were identical to experiment 1 except for the shape of the stimuli. Examples of the new stimuli can be seen in figure 5. Ten students participated as volunteers in the experiment.

7.2 *Results and discussion*

A one-way within-subjects ANOVA on (transformed) RT for type of contour (convex versus concave) confirmed that responses were faster for the convex condition ($F_{1,9} = 8.25$, $p = 0.018$). The means can be seen in figure 5b, together with error rates. Overall the average error rate was 6.33%. Although observers made less errors in the

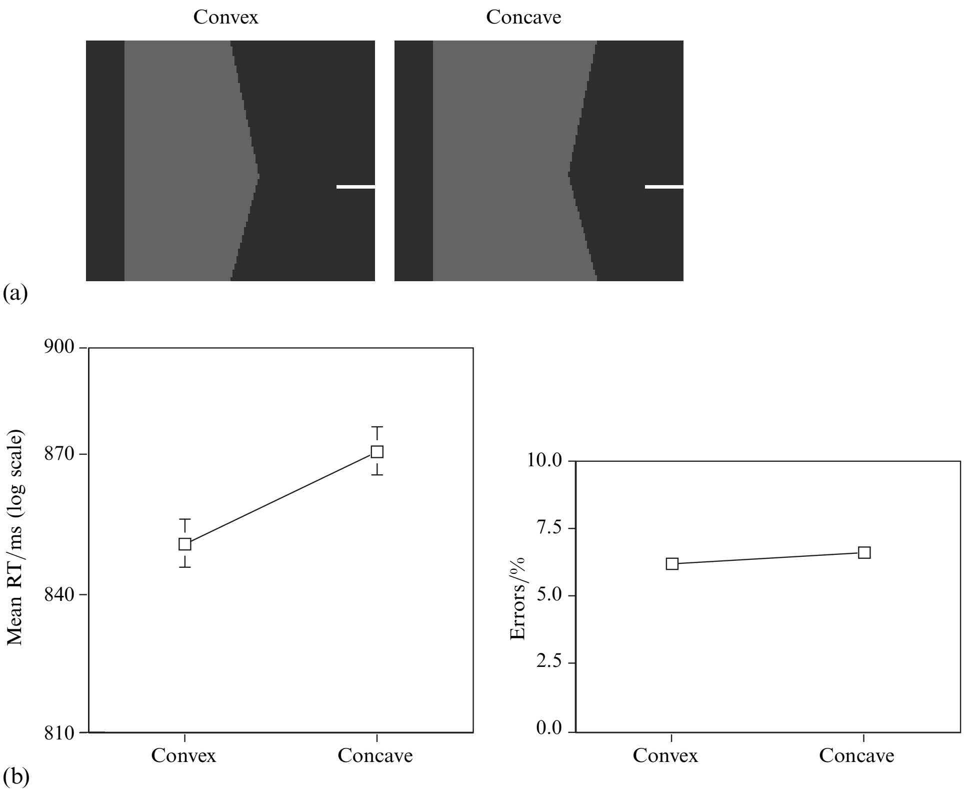

Figure 5. Stimuli and results from experiment 4. (a) Observers were asked to judge the position of the vertex with respect to a single reference white line. Light grey = red, dark grey = green. For simplicity only the condition in which the figure was on the left is shown here. (b) Geometric means of reaction time and error rate plotted against the type of contour. Error bars are within-subjects standard errors for reaction time.

convex condition as predicted, an ANOVA on the percentage of errors did not confirm any significant effect.

Experiment 4 confirmed that when a vertex is perceived as convex it is easier to judge its position than when the same vertex is seen as concave. This effect was present even when the distance between the intersection of the lines and the white reference line was fixed.

8 Experiment 5: Short presentation time

In the four experiments discussed so far, the task was to judge the vertical position of a vertex with respect to a reference line. The task in experiment 5 was arguably even simpler: observers had to judge the vertical position of the vertex with respect to a closed figure of which it was part. Figure 6 illustrates the stimuli and the procedure. Unlike the earlier experiments, this task involves a judgment about the position of a 'feature' (vertex) along the side of a single figure, eliminating the need for a reference line. The prediction, however, is again an advantage for convex vertices, because convex vertices are parts that have a position and observers can use this position and perhaps the axis of orientation of the part to perform the task. Another important aspect of experiment 5 is that the presentation of the stimulus lasted only 160 ms; therefore there was no time to explore or even simply move the eyes towards different positions of the figure.

8.1 *Method*

8.1.1 *Participants.* Twelve students at the University of Liverpool participated. They were naïve with respect to the problem and the hypotheses until after the data were collected.

8.1.2 *Design and stimuli.* Convex and concave shapes were used in a within-subjects design. Half of the time the shape was to the left and half of the time to the right of fixation. Stimuli were presented on a monitor (resolution 1024×768 at 85 Hz) controlled by an Apple Macintosh computer. The height of the stimulus was approximately 3 deg and the position of the vertex was offset from the centre by 0.15 deg. After a fixation mark was presented for 320 ms, the stimulus was presented for 160 ms and then it was followed by a mask. As can be seen in figure 6, the figure was a closed region drawn with black lines on a white background. The actual position of the fixation mark and the stimulus was randomly varied in each trial around the centre of the monitor (± 0.6 deg in both dimensions) to discourage observers from using positional cues.

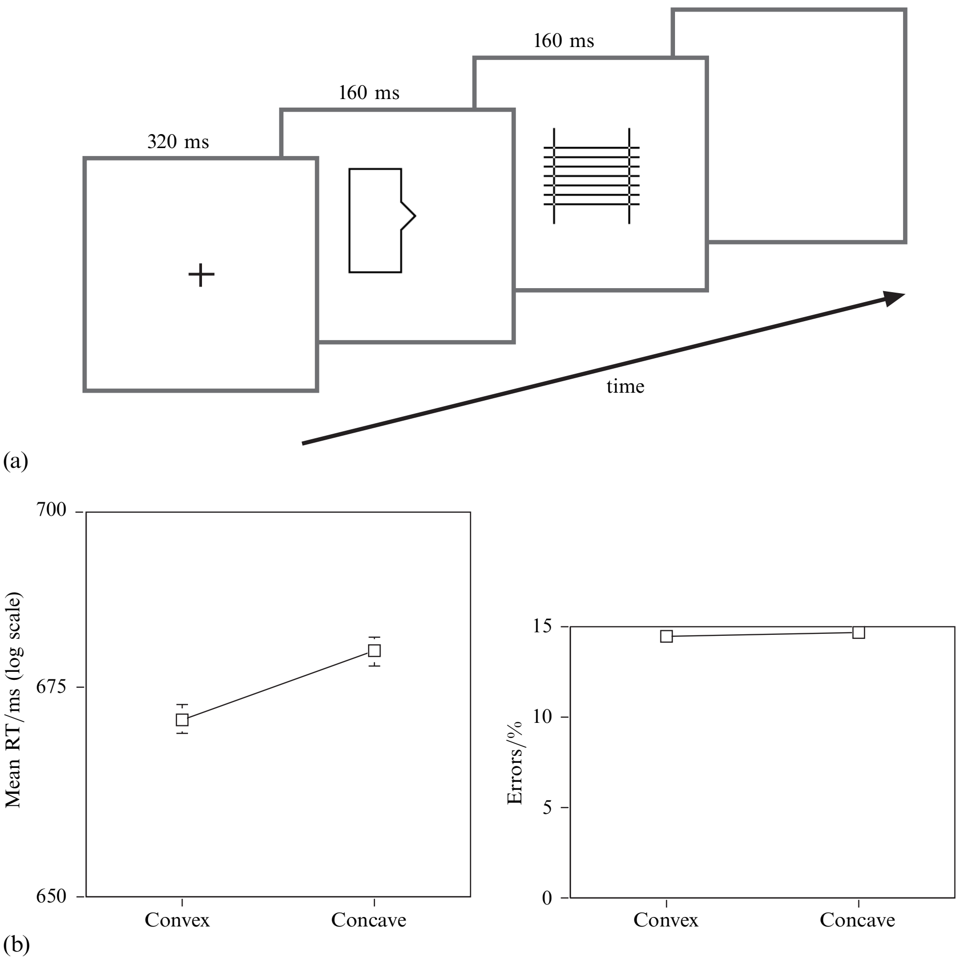

Figure 6. Procedure and results from experiment 5. (a) Every trial included a fixation mark, a stimulus, and a mask. The stimulus could face left or right and have either a concave or a convex vertex. (b) Geometric means of reaction time and error rate plotted against the type of contour. Error bars are within-subjects standard errors for reaction time.

8.1.3 *Procedure.* The procedure was similar to that of previous experiments. Observers were instructed to press the 'z' key on the keyboard if the vertex was in the top half of the figure and the '/' key if the vertex was in the lower half. 24 trials formed a practice phase, followed by 768 trials in the experiment. Every 128 trials a block ended and the observer was allowed time to rest; the start of subsequent blocks was self-paced.

8.2 *Results and discussion*
An ANOVA was performed on the logarithmically transformed response time, similarly to the previous experiments. An advantage for the convex condition was confirmed ($F_{1,11} = 11.46$, $p = 0.006$). As expected, given the short presentation time, the error rate was high, and on average there were 14.47% errors in the convex condition and 14.71% errors in the concave condition—this difference is as predicted. However, an ANOVA on the percentage of errors did not confirm any significant difference between conditions ($F_{1,11} = 0.06$).

Experiment 5 confirmed that when the task is to judge position, observers perform better when the vertex is perceived to be convex. As before, the task could have been performed in principle on the basis of information carried by the lines in the centre of the visual field, ignoring the context (closure). On this basis, convex and concave conditions are indistinguishable. The significant effect suggests that perception of contour polarity is fast and obligatory, and that it is easier to judge the position of convex regions.

The convex advantage in experiment 5 on average was 10.87 ms, which is smaller than in experiment 1 (33.37 ms) and in experiment 2 (14.70 ms); more individual variability was also observed. One reason may be that in experiment 5 some observers could have performed the task by seeing which of the two parts of the object was bigger or longer as opposed to where the vertex was located. This strategy was not available in the previous experiments, because the position of the vertex in the top or bottom part of the figure and the position of the vertex with respect to the reference line were uncorrelated.

9 Conclusion

I used a new task to compare performance for convex and concave vertices. In the visual-search literature it has been found recently that there is an advantage when searching for concave regions among convex shapes (ie the search for concavities among convex shapes was efficient whilst the search for convex shapes among shapes with concavities was not). This led to the hypothesis that the same edge was processed more efficiently when perceived as concave, perhaps because of specific detectors of concavities (Hulleman et al 1998; Humphreys and Müller 2000). Although I agree with the view that polarity is important and that the visual system extracts this information efficiently, I suggest that the visual-search data can be best understood in terms of the effect that concavities have on how observers perceive surface shape and in particular the effect of concavities on part decomposition. A strictly convex shape has only one part, a shape with concavities (and therefore also convexities) has more than one part; therefore the search can be for the presence of extra parts in the concave condition. This interpretation reconciles the visual-search data with the data showing that, when comparing *positions*, performance is best for convex shapes (Bertamini and Friedenberg 2001; Gibson 1994). In four experiments I have found a consistent convex advantage because the task always required the *position* of the convex or concave region to be processed.

Although part decompositions based on the differential geometry of contours (eg minima rule) and shape primitives (eg geons) are sometimes described as alternative solutions to perception of shape (Singh et al 1999), here I take the view that polarity and minima of curvature are important in defining boundaries, but that the parts created by such boundaries are represented and have properties such as position and orientation. Therefore, at least in this restricted sense, these parts are the building blocks of a structural description of shapes. Possibly the most exciting implication of the present findings is that perception of position on one hand, and representation of surfaces, including shape and volume primitives, on the other hand should be seen as closely related. In other words, contour polarity and surface layout are not secondary—rather they are basic properties available to the visual system for every spatial task, as argued for example by Nakayama et al [1995; for a recent theoretical argument for the primacy of surfaces see also Lappin and Craft (2000)].

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