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Detection of Convexity and Concavity in Context

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Sensitivity to shape changes was measured, in particular detection of convexity and concavity changes. The available data are contradictory. The author used a change detection task and simple polygons to systematically manipulate convexity/concavity. Performance was high for detecting a change of sign (a new concave vertex along a convex contour or a new convex vertex along a concave contour). Other things being equal, there was no evidence of an advantage for detecting a new concavity compared with a new convexity, for detecting a change of angle to a concave vertex compared with a convex vertex, for detecting a change within a concave region compared with a change within a convex region, or for an interaction between convexity and concavity and changes affecting or not affecting a vertex. The author concludes that change detection is affected by changes of sign of curvature (leading to changes in part structure). However, contrary to previous proposals, there is no special role for negative curvature or minima of curvature in guiding attention.

Keywords: visual perception, shape, signal detection, object representation

Convexity and concavity information has been long recognized as important for how humans perceive shape (e.g., in Alhazen's *Optics,* around 1030, and in modern times by Attneave, 1954). It is also generally accepted that observers may gain information about Gaussian curvature from curvature along a contour (Koenderink, 1984; Richards, Koenderink, & Hoffman, 1987) and that concavities play a central role in perceived part structure (Hoffman & Richards, 1984; Singh & Hoffman, 2001).

Recently, using a detection task, researchers have found that changes in contours are more easily detected if they involve a concavity rather than a convexity (Barenholtz, Cohen, Feldman, & Singh, 2003; Cohen, Barenholtz, Singh, & Feldman, 2005). This concavity advantage seems to be consistent with an advantage in detection of concavities using the visual search paradigm (Hulleman, te Winkel, & Boselie, 2000; Humphreys & Müller, 2000; Wolfe & Bennett, 1997). The speculation is that, because concavities have a central role in describing shape, "fast selection of concave edges, perhaps via the activation of specialized detectors, may thus serve a useful computational purpose" (Humphreys & Müller, 2000, p. 197). In their review of attributes that guide the deployment of attention, Wolfe and Horowitz (2004) cite curvature as a likely attribute with a possible preference for concavity and make reference to the work by Barenholtz et al. (2003).

A few different hypotheses can be formulated about when attention is guided towards concavity. The critical factor may be whether a contour has concave curvature. Alternatively, attention may be directed towards concave regions once a change of curvature takes place, for instance because a new minima is introduced. Another possibility is that attention is directed not towards concavities in general but only towards minima (peaks of negative curvature). All these possibilities are tested in this article.

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There is, however, another difficulty with the idea that attention is guided towards concavities. Some tasks, discussed in more details below, point to an advantage in processing convex information or information located at convexities. In this article, I argue that the changes always need to be seen in their context; for instance, a new concavity may be salient only when it is introduced in an object that was mainly convex before the change. On this basis, I reanalyze the critical factors for change detection and conclude that (a) changes in sign of curvature along the contour are always easier to detect compared with changes that do not involve a change of sign; and (b) other things being equal, there is no evidence that changes involving concavities are more salient than changes involving convexities. This second conclusion is more problematic given that it is based on null findings, but two things need to be considered. First, I argue that the existing evidence for the saliency of concavities only supports the saliency of changes of sign. Second, in this article I present data from five experiments, and I propose different criteria to test for a concavity advantage. For instance, it may be reasonable to argue that only concave changes involving vertices should be salient (relative to convex vertices) because such points are critical for part parsing (Experiment 5). None of these multiple tests confirmed that changes involving concavities are more salient than changes involving convexities.

Detection of Shape Changes

The paradigm introduced by Barenholtz et al. (2003) used a two-intervals forced choice task (cf. Phillips, 1974). A polygon is presented and in the second interval its shape may change slightly. A similar design and similar stimuli have subsequently been used by Bertamini and Farrant (2005); Cohen et al. (2005); and Vandekerckhove, Panis, and Wagemans (2005, 2007).

The original study used closed polygons and introduced shape changes by adding (or removing) a new vertex in the middle of a straight edge (Barenholtz et al., 2003), as illustrated in Figure 1.

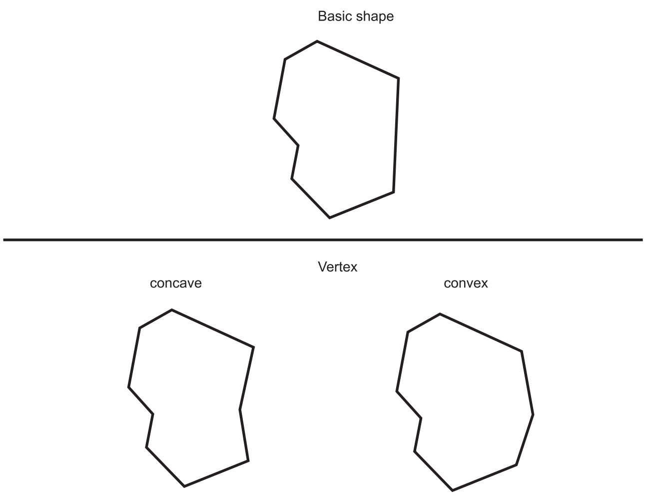

Figure 1. The basic shape used by Barenholtz et al. (2003) was a filled polygon with a number of vertices that varied between 9 and 12. Of these 0, 1, or 2 were concave vertices and the other were convex. The change to be detected was the introduction (or removal) of a new vertex located along a straight edge of the basic shape. The key comparison was between conditions in which such vertex was concave and conditions in which it was convex.

The new vertex could be either convex or concave. There was a large difference in performance: Percentage correct for concave and convex changes was 70.83% and 36.94%, respectively.

Three problems exist with the interpretation of the higher performance in the case of a concave vertex. First, as Barenholtz et al. (2003) mentioned, it is possible that observers are better at detecting concavities per se, but it is equally possible that observers are more sensitive to changes of sign (i.e., a change from convexity to concavity), perhaps because a change of sign affects part structure. Note that in the basic shape, the straight edge is a convex region of the object,[1] so only in the case of a concave vertex the sign changes (making the design asymmetrical in this respect). A new concavity is likely to split an object into subcomponents, or parts, because concavities play a central role in part parsing (Hoffman & Richards, 1984).

Second, a new concave vertex tends to be located nearer the center of the object and nearer fixation, and a new convex vertex tends to be located farther away. Fixation is important because of the eccentricity of the vertex, but independently of fixation the center of an object is also likely to provide a useful frame of reference for judgments about position as found, for instance, by Wang and Burbeck (1998). Barenholtz et al. argue against the role of the location of the vertex on the grounds that a concavity advantage was present (and of similar magnitude) even for small displacements of the vertex.

Third, the polygons used had a variable number of vertices but on average had a larger number of convex vertices than concave vertices. Therefore, in the convexity condition the new convex vertex was added along a contour containing already several convex vertices, but in the concavity condition the new concave vertex was added along a contour that contained few if any such vertices (maximum two).

Cohen et al. (2005) modified the stimuli and confirmed a concavity advantage. In their Experiment 1, instead of adding new vertices, they changed existing vertices. That is, the location of a convex/concave vertex changed either inwards or outwards with respect to the center of the polygon. The main advantage of this manipulation is that, if the object is parsed at concavities, no new object structure is introduced because only the position of already existing vertices is affected. Cohen et al. (2005) discussed the remaining limitations of this experiment, which are related to the three issues listed above. The polygons had a larger number of convex compared with concave vertices, and the angle of the convex and concave vertices was not matched. This problem stems from the fact that for closed polygons the total convex turning angle must be greater than the total concave turning angle (otherwise closure would not be achieved). Therefore, number and turning angle of convex and concave vertices cannot be equal (although an equal number of convex and concave vertices are possible with unequal angles, as in a star shape).

To address these problems Cohen et al. (2005) ran a second experiment in which a circle was divided into halves by a zigzag line. The resulting half-circle has a curved outside and a line in the center containing convex and concave vertices. By assigning closure either to the left or to the right half of the original circle, researchers can insure that convexities and concavities are perfectly matched. This experiment confirmed a concavity advantage, although the size of the effect was much reduced. Percentage correct was 63.96% for concavity and 56.53% for convexity.

One possibility is that several factors are important in change detection. For example, a pure concavity advantage may exist but the effect may be small, and in the original work by Barenholtz et al. (2003) it was combined with other effects such as the change of sign of curvature (e.g., when a convexity turns into a concavity). Unfortunately, small effects are more subject to the problems discussed above, such as the role of fixation or of frames of reference. Moreover, the argument against a role of fixation on the basis that the magnitude of the effect was similar for different displacements is weakened, as most of the magnitude may have been related to the effect of change of sign.

In their studies, Bertamini and Farrant (2005) presented stimuli using random dot stereograms (RDSs). Stereograms ensure unambiguous figure-ground segmentation and the absence of any color or luminance differences between the foreground and background surfaces. In the first experiment, Bertamini and Farrant made the prediction that if there is a concavity advantage, such advantage for inwards changes should become an advantage for outwards changes when the polygon is perceived as a hole (because the

[1] Strictly speaking, a straight contour has zero curvature, so within a very small sampling window it is not possible to assign a curvature sign. Yet if the window is large enough to include a vertex, both vertices flanking the straight edge are convex (see Figure 1). Another way of thinking about this is to think of a smoothed version of the polygon, in which case this straight region between two convex maxima (M+) would have convex curvature and a convex minimum (m+). Here and later in the article I use the standard terminology for curvature singularities; these are inflections (I), positive maxima (M+), positive minima (m+), negative maxima (M−), and negative minima (m−). Note that absolute curvature reaches a peak at M+ and m−, which can therefore be related closely to the vertices of a polygon and can also be referred to as extrema.

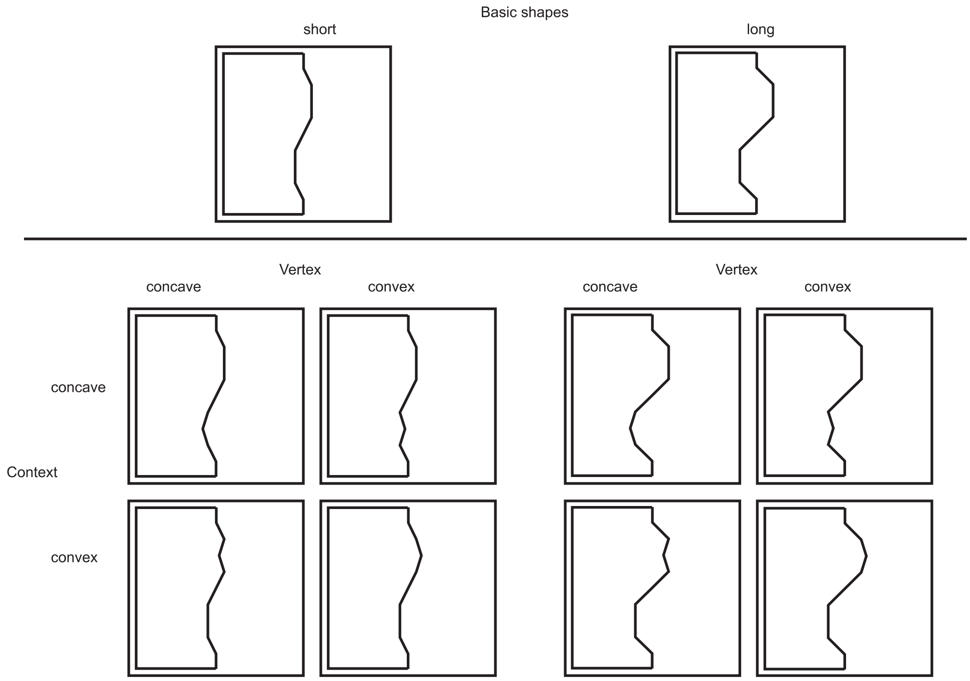

Figure 2. Stimuli for Experiment 1. The actual stimuli were random dot stereograms, but the regions with different depth are shown here with polygons. The two basic shapes are shown at the top. The shapes differ only in the extent of the parts (short or long). The bottom figure shows the variables type of vertex and context. The square background was always at zero disparity, and the figure had a disparity of 72 arcsec. In one version of the experiment, there was also an occluding square frame with a disparity of 108 arcsec; only the version without frame is shown here. In this figure stimuli are located on the left side of the square background, but they were also presented on the right side with equal probability. Also in this figure the convex context is always above the concave context, but the opposite orientation was presented with equal probability.

polygonal region perceived as a hole is a ground region).[2] This would rule out fixation as an explanation for an inwards advantage. Detection was higher for inwards than for outwards changes in the case of figures, but there was no significant difference in the case of holes. This leaves open the possibility that a small convexity advantage exists but was working against the effect of distance from fixation in the case of holes.

Most relevant for this article is Bertamini and Farrant's (2005) Experiment 2. Similarly to the second experiment in Cohen et al. (2005), the change took place along a vertical contour, which was one side of a larger surface.[3] It is important that the basic contour had an equal number of convex and concave vertices with equal angles. The central contour was seen within a rectangular occluding frame. In other words the contour was a depth step between two otherwise identical surfaces. This means that the overall shape of the objects is irrelevant (because it is unknown), and observers had to focus only on the central contour. When a shape change was present, it was equally likely to be in one of two locations, which I refer to as contexts, one above and one below fixation (see Figure 2). In the convex context the change is located between two convex vertices, and in the concave context the change is located between two concave vertices.

The design of this experiment implied that, in addition to comparing the detection of a new convex/concave vertex, it was possible to compare the detection within a convex/concave context and the detection when a change of sign is present or absent. Bertamini and Farrant (2005) found that only the latter factor was significant: Performance was higher for changes of sign along the contour, independently of whether this meant a new concave vertex between convex vertices or vice versa. They concluded that perceived structural shape is the most likely underlying explanatory factor.

Vandekerckhove et al. (2005) also reported a concavity advantage using closed polygons similar to those employed by Cohen et al. (2005). It is interesting that they also attempted a comparison of the effects when a change of sign was present or absent. Although performance was higher when a change of sign was present, this difference was not significant, and they concluded that both factors are probably of similar magnitude. However, the same problems discussed above exist with respect to the interpretation of their findings, namely the fact that a concave change was a change towards the inside of the object and the fact that unequal numbers of convex and concave vertices were present.

[2] There is a debate on whether holes are a special case of ground that can have quasi-figural properties. For more on this, see Bertamini (2006), Bertamini and Hulleman (2006), and Nelson and Palmer (2001).

[3] Although I describe them sequentially, the studies by Bertamini and Farrant (2005) and by Cohen et al. (2005) were conducted and published at the same time.

Search Asymmetry

The problems of interpretation discussed in the change detection studies also existed in the studies that have compared convexity and concavity using the visual search paradigm and in particular the search asymmetry criterion (Hulleman et al., 2000; Humphreys & Müller, 2000; Wolfe & Bennett, 1997). In these studies, the convex target was strictly convex, but what was referred to as a concave target had both convex and concave regions (for a discussion of the asymmetry of design in search asymmetry studies, see also Rosenholtz, 2001). To illustrate, imagine that you are searching for a shape with a single concave cusp (the so-called concave stimulus) among shapes without concavities and with a single convex cusp (convex stimuli); this search is easier than when target and distractor are swapped (Hulleman et al., 2000). Note that the concave stimulus is not strictly concave; it has a complex structure in which convexities and concavities alternate. In other words, along its contour there is a change of sign of curvature that is likely to affect perceived part structure. No such change of sign is present in the convex stimulus because in this case the stimulus is strictly convex.

Recently, Bertamini and Lawson (2006) conducted a series of visual search studies on this issue and compared strictly convex and strictly concave stimuli. In terms of contour curvature, if a circle is a strictly convex stimulus, then a circular hole is a strictly concave stimulus. Bertamini and Lawson used objects and holes and concluded that the most likely explanation for the existing data is in terms of perceived part structure rather than sign of curvature. In other words, it is not concavity per se that guides attention in visual search.

Convexity Advantages

There is another reason to be skeptical about the conclusion that changes involving concavities are more salient per se, that is, the idea of a processing advantage for concavities over convexities. In the literature on effects of convexity and concavity, there are a few examples where observers are better at processing shape information relative to or located at convexities. For instance, in a series of studies, Bertamini and collaborators (Bertamini, 2001; Bertamini & Croucher, 2003; Bertamini & Farrant, 2006; Bertamini & Mosca, 2004) found that observers are faster at judging relative position of vertices for vertices perceived as convex. Another interesting finding is the fact that when comparing a pair of small probes located along a contour, observers are better when both probes are located along a convex contour rather than a concave contour (Barenholtz & Feldman, 2003). In both cases (positional judgments and probe comparison), the key factor seems to be the indirect effect that convexity has on the perception of parts so that, for example, neither effect is retained when snake-like contours are used (Barenholtz & Feldman, 2003; Bertamini & Farrant, 2006).

These tasks are different from a change detection task; nevertheless, it seems strange that observers can direct their attention to convexities effectively when processing position or comparing small probes but display a disadvantage when detecting whether a convex vertex has changed slightly, as this is also a change localized on a convex region. Conversely, if the effect of sign of curvature is mediated by its effect on part parsing, all these findings are consistent with a single theoretical view: Parts are computed early and obligatorily and are hierarchically represented, so that positional information about parts is easily accessed and probes confined within a part are easily compared. Because of this, changes of sign such as the introduction of a new concavity are salient as they alter the hierarchy within the structural representation of shape. Changes that do not change sign along a contour are much less salient whether they affect convexities or concavities.

Models of Shape Segmentation

The argument about part structure and change detection outlined here is not specific to one model of shape description. It is compatible with a family of models in which parts are not predefined (cf. Marr & Nishihara, 1978); instead, geometric rules are used to find the parts in the image.

I have already mentioned the seminal work by Hoffman and Richards (1984) and the proposal that minima are fundamental for parsing. Subsequent work by Singh, Seyranian, and Hoffman (1999); Singh and Hoffman (2001); Siddiqi, Tresness, and Kimia (1996); Rosin (2000); and others have developed this theory by introducing more precise rules. In Siddiqi et al.'s (1996) model, necks are produced when a maximally inscribed circle is also a local minimum of the diameter. Siddiqi, Kimia, Tannenbaum, and Zucker (2001) have used necks and other curve singularities to distinguish between parts and protrusions. In this article I do not use this distinction; instead, I use the general term part for a shape subunit which, by definition, is explicitly represented by the visual system. Bertamini and Farrant (2005) have introduced the term *bracketing hypothesis* to suggest that some parsing always takes place when a convexity is bracketed by concavities. I return to this idea in the final discussion.

Recently, de Winter and Wagemans (2005) have reviewed the literature and attempted an integrative study. They note that a few ideas are common in most models in the literature. First, most models include minima as possible segmentation points for parts. Second, a short part line is preferred to a longer one. Third, global factors such as symmetry axes may interact with local curvature information. On the basis of the empirical data, they concluded that all of the previously proposed rules have some support in their results (i.e., minima of curvature, proximity, collinearity, symmetry, and elongation) in conjunction with top-down cognitive influences.

Summary of Experiments

In this article, results from five change detection experiments are reported. Experiment 1 used RDSs and confirmed the importance of a change of sign. It also confirmed that this result is general whether the region is partly occluded or not, a change that has great importance for some models of shape parsing because it affects internal symmetry. Because of the use of RDS, the stimuli used were large with large shape changes, similar to those used by Bertamini and Farrant (2005).

Experiments 2, 3, 4, and 5 used luminance-defined contours and brief presentations, a procedure similar to that in Barenholtz et al. (2003) and Cohen et al. (2005). In Experiment 2, the change to detect was the appearance of a new vertex (or disappearance of an old one), whereas in Experiments 3 and 4 the angle of existing vertices was changed. This is important because a change of existing vertices should not alter the overall part structure. Experiment 3 was therefore a direct test of the difference in detection for convex and concave vertices; in addition, it also tested the importance of overall shape complexity. Experiment 4 introduced participants' knowledge about where the changes were possible (either to a convex or a concave vertex) but confirmed a lack of difference in performance for convexity and concavity.

Experiment 5 tested for an interaction between type of change (a change in number of vertices or a size change that did not change the vertices) and sign of curvature (convex or concave). The idea was to explore whether convex and concave vertices behave similarly when contrasted with other convex and concave changes. The results of Experiment 5 support the view that extrema of curvature (negative minima and positive maxima) are salient as a consequence of having high curvature, but they behave similarly whether curvature is positive or negative.

In summary, in contrast with the clear evidence of the importance of change of sign, there was no advantage, using multiple criteria, for concavity per se.

Experiment 1: Detection of Change in RDS

This experiment is similar to Experiment 2 in Bertamini and Farrant (2005). Observers viewed two RDSs in succession, as described in Figure 3. The shapes within the stereograms were either identical or one was a slightly altered version of the other, and observers reported whether they were the same or different. Bertamini and Farrant (2005) used a rectangular frame surrounding a bipartite stimulus. Only a vertical contour was visible, and the figural (nearer) side was specified by binocular disparity. The current experiment introduces three changes. First, the frame was either present or absent. Second, a new variable was introduced: the extent to which the contour moved from left to right in the basic configuration (see Figure 2). Third, power was increased by increasing the number of participants (from 12 to 20).

Note that the basic shape has an equal number of convex and concave vertices, and that the figural side of the contour can be either to the left or to the right. Because the basic contour moves towards the inside and the outside of the figure, the change of shape can be located in one or the other of these two regions (convex or concave context).

The combination of type of vertex (convex and concave) and context (between convex or concave vertices) generates four conditions. Higher d' values are expected for conditions in which the sequence of convexities and concavities changes, and I, therefore, predict an interaction between type of vertex and context.

A concavity advantage may be detected in at least three different ways: (a) Changes involving concave vertices should be easier to detect (main effect of type of vertex), (b) Any kind of change within a concave context should be easier to detect (main effect of context), and (c) Within the trials in which there was no change of sign, the concave change should be easier to detect (concave vertex within concave context $>$ convex vertex within convex context). This design therefore allows multiple ways in which to test the concavity advantage.

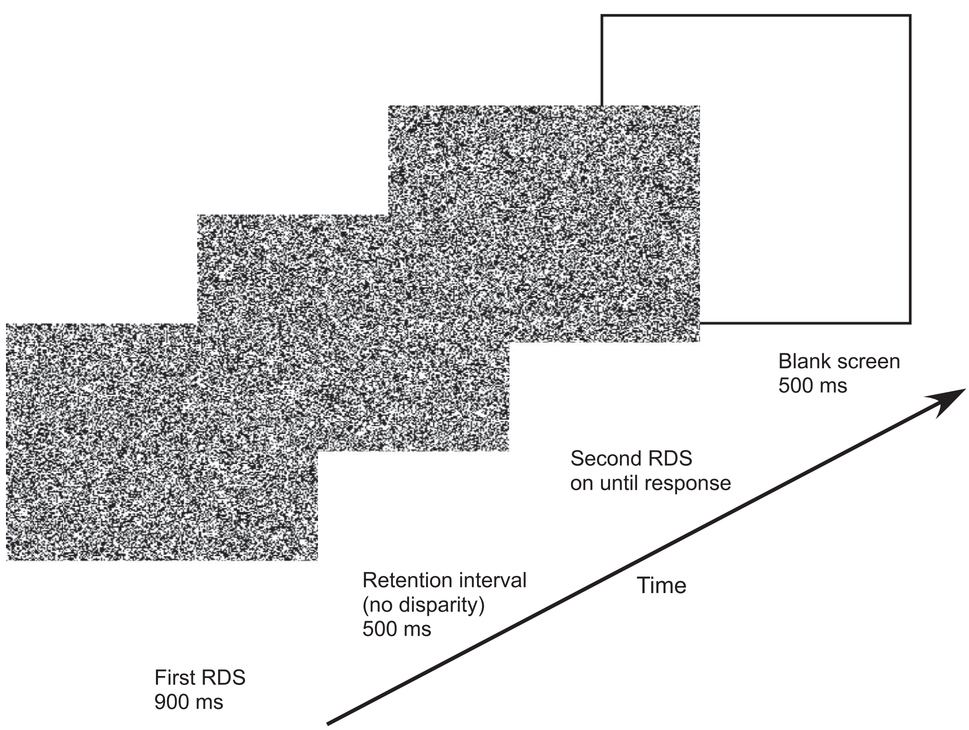

Figure 3. In Experiment 1, observers saw one stimulus in the first interval and had to judge whether the shape had changed or had remained the same in the second interval. The random dot background presented during the retention interval was different from that in the first and second intervals, thus providing an effective mask. RDS = random dot stereogram.

Method

Participants. Twenty students at the University of Liverpool participated. They were screened for stereoacuity using the TNO stereotest. Acuity ranged between 15 and 120 arcsec.

Stimuli and procedure. For each trial, stimuli were generated by a Macintosh computer and presented on a Sony F500T9 monitor with a resolution of 1280 × 1024 pixels at 120 Hz. Two stereo images were presented with the use of a NuVision infrared emitter and stereoscopic glasses. Because left and right images were interleaved, effective vertical resolution and refresh rate were halved (512 pixels at 60 Hz).

Stimuli are illustrated in Figure 2. There was a basic shape and a central contour with seven straight edges; the contour turned either to the left and then to the right or vice versa. Independently of whether it turned left or right first, the figural side could be either to the left or to the right. In one condition, the two surfaces (foreground and background) were seen through a square aperture; in another condition, the foreground region was visible. Figure 2 shows only the condition without the occluding frame. The side of the square region was 120 mm. The horizontal displacement of the vertex in the change trials was 4 mm.

Observers sat in a dark and quiet room at approximately 57 cm from the monitor. They were instructed about the possible changes and about their location. The practice was divided into two halves of 18 trials. In the first half, the figure (with crossed disparity and therefore perceived in front) was presented not as a random dot surface but as a solid red surface to make sure observers knew what type of shapes to look for. In the second half of the practice, the stimuli were RDSs. Throughout the practice when the participant made an incorrect response, after a warning beep the stimuli were presented again but without the mask between first and second interval so that the change (or absence of a change) was clearly visible.

For trials in which there was no change, the same set of shapes from the change trials were presented. In only half of the no-change trials, the first interval had the basic shape, just as in the change trials. This ensured that the shape presented in the first interval provided no information as to whether this was a change or a no-change trial.

When the experiment proper started, each observer performed 384 trials in rapid succession (see Figure 3). After every 64 trials a block ended, and the observer was allowed time to rest. The start of subsequent blocks was self-paced.

In summary, the complete set of stimuli was the factorial combination of the following factors: change from first to second interval (same or different shapes), appearance (change introduced in the second interval, or removed in the second interval), location (foreground on the left or on the right), orientation (convex context above concave context or vice versa), vertex (convex or concave), context (change located between convex or concave vertices), extent (short or long), and occluding frame (present or absent). All factors except the last one were interleaved; the stimuli with or without occluding frame were instead used in two versions of the experiment.

Results and Discussion

For each observer, hit rates and false alarm rates were computed, and d' values were derived. Next, I carried out a mixed analysis of variance (ANOVA) on d' values. The factors were vertex (convex or concave), context (between convex or concave vertices), extent (short or long), and frame (present or absent).

Mean values are plotted in Figure 4. There was a main effect for context, $F(1, 18) = 20.72$, $p < .001$, partial $\eta^2 = 0.54$: Performance was better for changes in the convex context. As predicted, there was a significant interaction between vertex and context, $F(1, 18) = 89.64$, $p < .001$, partial $\eta^2 = 0.83$: Performance was better when there was a change of sign. There were no other significant main effects or interactions.

As discussed in the introduction, a concavity advantage could be detected in one of three ways: (a) a main effect of type of vertex, (b) a main effect of context, and (c) a difference in a direct comparison between convex/concave changes when there was no change of sign. There was no main effect of type of vertex. The main effect of context was found, but it revealed a convexity advantage rather than a concavity advantage. With respect to (c), a paired t test confirmed an advantage for convex changes, $t(19) = 4.82$, $p < .001$. However, note that because of the significant effect of context, the convexity advantage from the t test could have been an artifact of the context effect because the convex change takes place in the convex context.

In summary, I found no evidence of a concavity advantage, but I found evidence for the convexity advantage that was only marginally significant in Bertamini and Farrant (2005). This may be due to increased power. Neither the presence of a frame nor the left/right extent of the convexities and concavities played a significant role.

Experiment 2: Detection of Change in Luminance-Defined Displays

Experiment 1 replicated the results of Bertamini and Farrant (2005), with the additional indication of an advantage for detecting

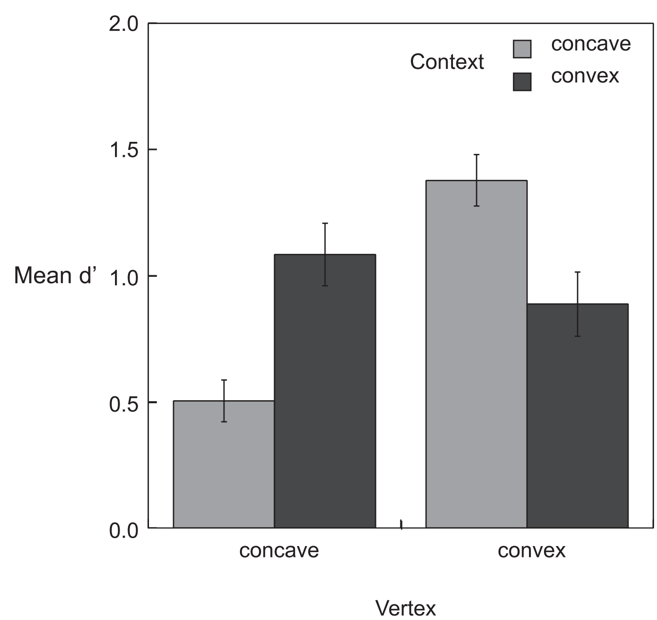

Figure 4. Data from Experiment 1. Sensitivity (d') is shown as a function for type of vertex and separately for the two contexts. Error bars are standard errors of the mean.

changes within a convex context, which is located on the outside of the object. Next, I asked the question whether these results were due to the use of RDSs. Although I argued that clear advantages exist for their use, one problem with using RDSs is that relatively large changes and long presentation times are necessary to perform the task. In Experiment 2, therefore, I changed the stimuli into high contrast contours. If the advantage for the convex context in Experiment 1 was a scanning bias, then it should be eliminated in Experiment 2 because now the shapes are smaller and are only presented for 266 ms and then masked.

In addition to the type of vertex and context factors, I introduced two sizes for the basic shapes, as illustrated in Figure 5. The idea was to test the hypothesis that even when the change in the contour is the same, if the change is nearer the center of the object (and its outside edge), this may provide an advantage. This would clearly be important in interpreting the published data because concave changes have always been located nearer the inside of the object (see, e.g., Experiment 2 in Cohen et al., 2005).

I expected that the advantage for the condition in which the sign changes would be replicated. I therefore expected again a significant interaction between type of vertex and context.

Method

Participants. Eighteen students at the University of Liverpool participated.

Stimuli and procedure. Equipment and procedure were similar to those of Experiment 1, except that stimuli were line drawings and not surfaces defined by disparity. The stimuli are illustrated in Figure 5. The side of the square region was 70 mm. The horizontal displacement of the vertex in the change trials was 2 mm.

Observers were instructed about the possible changes and about their location, and they performed two practice sessions before the start of the experiment. Throughout the practice, there was a beep after an incorrect response, and the stimuli were presented again but without the mask so that the change (or absence of a change) was clearly visible. Each observer responded to 384 trials in rapid succession. After every 64 trials a block ended, and the observer was allowed time to rest.

The sequence of events is described in Figure 6. On each trial the first stimulus was presented for 266 ms and then masked by a display of random squares. The second stimulus was also presented for 266 ms and then masked.

The complete set of stimuli was the factorial combination of the following factors: change from first to second interval (same or different shapes), appearance (change introduced in the second interval, or removed in the second interval), location (on the left or on the right), orientation (convex region above concave region or vice versa), vertex (convex or concave), context (between convex or concave vertices), and size (narrow or wide).

Results and Discussion

For each observer, hit rates and false alarm rates were computed, and d' values were derived. Next, I carried out a repeated measures ANOVA on d' values. The factors were vertex (convex or concave), context (between convex or concave vertices), and size (short or long).

There were no significant main effects, although there was a nonsignificant trend in favor of narrow objects, $F(1, 17) = 3.99$, $p = .062$, partial $\eta^2 = 0.19$. As predicted, there was a significant interaction between vertex and context, $F(1, 17) = 31.22$,

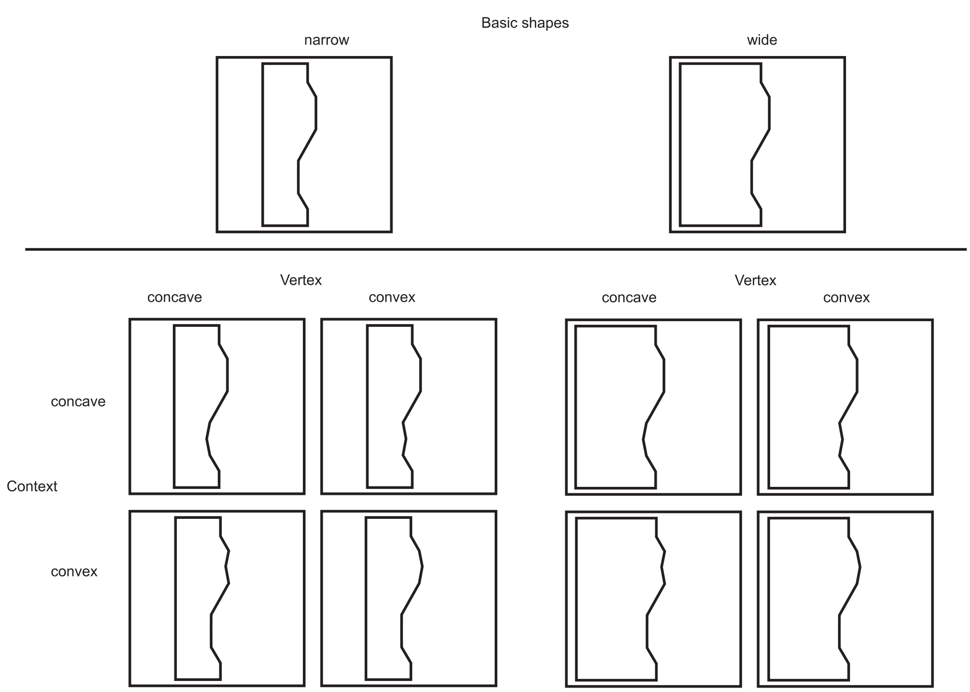

Figure 5. Stimuli for Experiment 2. The actual stimuli were contour outlines on a light green square background. The two basic shapes are shown at the top; they differed only in the size of the closed region (narrow or wide). The bottom figure illustrates the critical variables type of vertex and context.

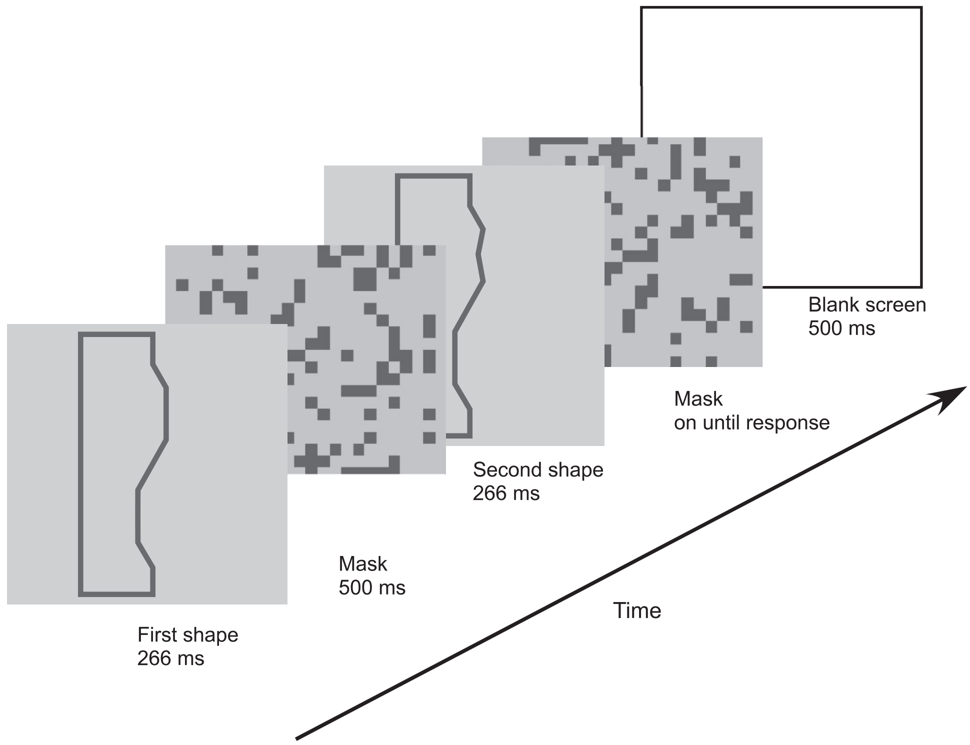

Figure 6. In Experiments 2 and 3, observers saw one stimulus in the first interval and had to judge whether the shape had changed or had remained the same in the second interval. The mask was generated by a series of squares randomly distributed and with the same color as the contours of the shapes.

$p < .001$, partial $\eta^2 = 0.65$; performance was higher when there was a change of sign, as shown in Figure 7. There was also a significant interaction between context and size, $F(1, 17) = 6.70$, $p = .019$, partial $\eta^2 = 0.28$. This interaction is shown in Figure 7. Size did not make a difference when the change was in the convex context, which is located towards the outside of the object. However, performance was higher for the narrow stimuli in the concave context. This supports the hypothesis that changes near the center of the objects are slightly easier to detect, probably because the center (or the straight edge shown on the left in Figure 5) provides a useful reference.

The advantage for the convex context found in Experiment 1 was not confirmed with brief presentations, suggesting that it may have been a scanning bias. There was no evidence for a concavity advantage from any of the three tests discussed in the introduction. With respect to the direct comparison between convex/concave

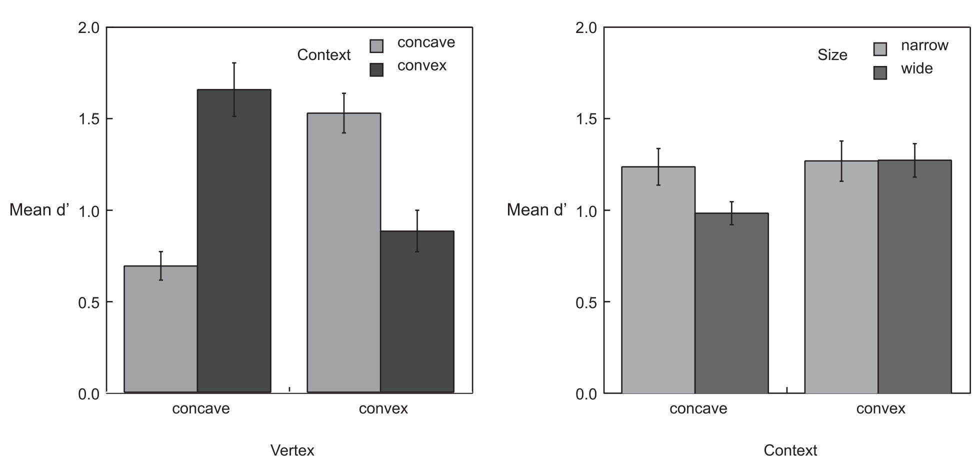

Figure 7. Data from Experiment 2. Left: Sensitivity (d') is shown as a function of type of vertex and separately for the two contexts. Right: Sensitivity (d') is shown as a function of context and separately for the two levels of size. Error bars are standard errors of the mean.

changes when there was no change of sign, a paired *t* test did not confirm any significant difference, $t(17) = 1.93$, *ns*.

Although the description of the stimuli for Experiments 1 and 2 (Figures 2 and 5) may appear similar, the stimuli differed in many respects: Experiment 1 used RDSs, larger stimuli, and larger changes. Presentation time was also shorter in Experiment 2. It is, therefore, interesting that the results are remarkably similar (compare Figures 4 and 7). Neither experiment provided any evidence in favor of a concavity advantage, whereas both experiments supported the importance of a change of sign.

Experiment 3: Detection of Change for Vertices Already Present

The change used in Experiments 1 and 2 was the introduction or the removal of a vertex. In such conditions, performance was higher for changes of sign. Perhaps a better comparison between convexity and concavity requires changes to the angle of already existing vertices (Cohen et al., 2005). If no change of sign is ever present, smaller effects could be detected as they would not be overshadowed by the larger effect of a change of sign. I adopted this strategy in Experiment 3, using high contrast contours similar to those used in Experiment 2.

In addition to the type of vertex and context factors, I introduced two types of objects, as illustrated in Figure 8. The idea was to separate the horizontal location with respect to the center of the object (the factor context in Experiments 1 and 2) from the type of vertex. Typically the concave vertex has to be located near the inside, and this may constitute an important confound, but in Experiment 3 the complex object of Figure 8 has a concave vertex located near the outside.

The two types of objects differ in the total number of changes of sign and therefore their perceived complexity. Thus, a main effect of type of object could depend on complexity. This is interesting as the advantage found in Experiments 1 and 2 for changes of sign may relate to complexity. I do not believe that this is the real explanation, as there is no obvious reason why people should find the task easier in the case of more complex shapes, but Experiment 3 tested this possibility. In addition, an interaction between type of object and type of vertex would support the importance of the location: inside or outside with respect to the center of the object.

Related to the difference in complexity is a difference in angles. When introducing a new vertex in the middle of a straight edge, inevitably the angles of the two flanking vertices also change. As can be seen in Figure 2, when there is no change of sign, the angles involved are large (close to 180°). When there is a change of sign, the angles involved are small. Although it is unlikely that this difference alone could explain the advantage for the conditions in which there was a change of sign, Experiment 3 also provided evidence towards the importance of such factor. As can be seen in Figure 8, the complex shapes have vertices with smaller angles; therefore, if this makes the task easier, one would predict better performance for complex shapes over simple shapes.

Method

Participants. Twelve students at the University of Liverpool participated.

Stimuli and procedure. Equipment and procedure were similar to those of Experiment 2. The stimuli are illustrated in Figure 8. The side of the square region was 70 mm. The horizontal displacement of the vertex in the change trials was 2 mm. After practice, each observer responded to 384 trials in rapid succession. After every 64 trials a block ended, and the observer was allowed time to rest.

The complete set of stimuli was the factorial combination of the following factors: change from first to second interval (same or different shapes), appearance (change introduced in the second interval or removed in the second interval), location (on the left or on the right), orientation (convex region above concave region or vice versa), vertex (convex or concave), and basic shape, which I refer to as structure (simple or complex).

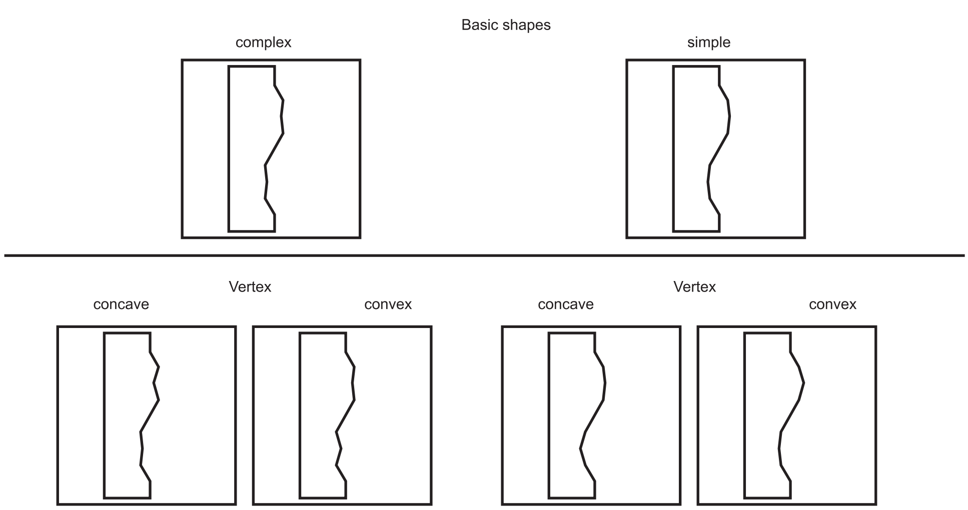

Figure 8. Stimuli for Experiment 3. The actual stimuli were contour outlines on a light green square background. The two basic shapes are shown at the top (simple and complex). The bottom figure illustrates the variables type of vertex and context.

Results and Discussion

For each observer, hit rates and false alarm rates were computed, and d' values were derived. Next, I carried out a repeated measures ANOVA on d' values. The factors were vertex (convex or concave) and structure (simple or complex).

Mean values are plotted in Figure 9. There was a significant main effect of structure, $F(1, 11) = 102.71$, $p < .001$, partial $\eta^2 = 0.90$: Performance was better for the simpler stimuli. There was no other significant main effect or interaction.

The absence of an effect of vertex suggests that there is no difference between detection of concavities and convexities per se. The higher performance for simple shapes is interesting as it means that the previously found effect of change of sign may have been due to a change in complexity but not to the greater average complexity of the stimuli (over the two intervals) or to the average smaller angles of the stimuli.

Finally, the absence of an interaction between vertex and structure suggests that, other things being equal, there is no advantage for changes located in a region towards the inside of the object (with respect to its center) compared with changes located in a region towards the outside of the object. This is not entirely consistent with the results of Experiment 2, but Experiment 3 used only the narrow stimuli, and therefore there is not a direct comparison between narrow and wide stimuli.

Experiment 4: Blocked Design

The stimuli used in Experiment 4 are similar to the simple objects of Experiment 3. The main difference is the fact that convex and concave changes were separated into different blocks. Although this may seem a small change, it means that the observers are aware of the location of the possible change: either the convex or the concave region of the object. It is interesting to see how useful such knowledge is. In addition, a more powerful analysis of the participants' responses is made available by this modification in the procedure. In all the studies discussed in the introduction on change detection, as well as in Experiments 1, 2, and 3, observers must detect a change when present, but changes involving convexities or concavities were interleaved. From hit and false alarms rates d' values can be computed, hit rates can be separated for trials in which a convex or a concave change was present, but false alarm rates are shared. This is because it is impossible for the experimenter to separate false alarms to convex changes from false alarms to concave changes, as false alarms come from trials in which no change was present in the stimuli. Experiment 4 is, in a sense, a combination of two experiments; it is, therefore, possible to correctly assign false alarm rates because detection of convex changes and detection of concave changes come from two separate tasks.

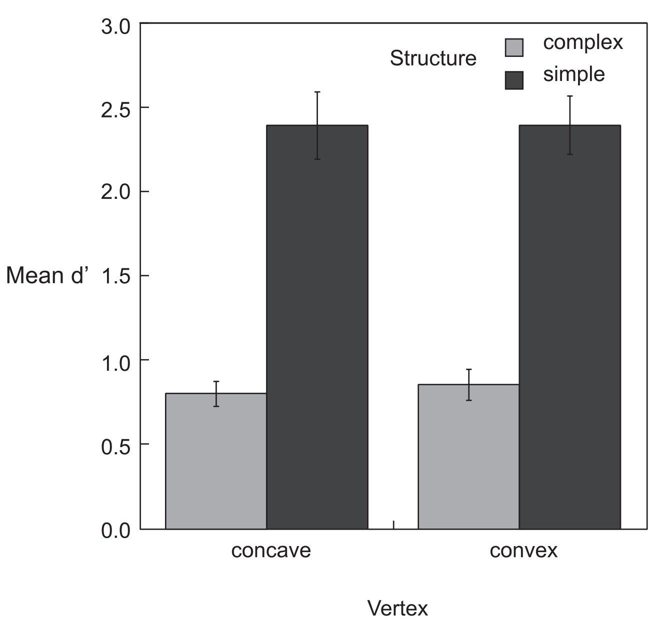

Figure 9. Data from Experiment 3. Sensitivity (d') is shown as a function of type of vertex and separately for the two levels of structure. Error bars are standard errors of the mean.

One inevitable consequence of instructing participants about what change is possible within a block is the fact that performance is likely to improve. I made a few minor changes to the stimuli to make sure that the task was challenging, so as to avoid a ceiling effect. Presentation time was reduced to 233 ms, the displacement of the vertex was reduced to 1.5 mm, and more variability in the extension of the basic vertices was introduced by setting this to two possible values, slightly longer and slightly shorter than the stimuli in Figure 8.

Method

Participants. Twelve students at the University of Liverpool participated.

Stimuli and procedure. Equipment and procedure were similar to those of Experiment 3. The horizontal displacement of the vertex in the change trials was 1.5 mm. After practice, each observer responded to 192 trials in rapid succession in each of two sessions (384 total trials). After every 64 trials a block ended, and the observer was allowed time to rest. For half of the participants the convexity detection session was followed by the concavity detection session, and for the other half the order was reversed.

The complete set of stimuli was the factorial combination of the following factors: change from first to second interval (same or different shapes), appearance (change introduced in the second interval or removed in the second interval), location (on the left or on the right), orientation (convex region above concave region or vice versa), vertex (convex or concave), and angle (two values of the vertices in the basic shapes). The two angles corresponded to two values for the offset of the vertices from the vertical line; these values were either 1 mm or 2 mm. As in all previous experiments, the basic shapes were used to generate the stimuli, but the extra displacement of the vertex by 1.5 mm was introduced also in half of the trials in which there was no change between intervals. Because of this, it was impossible for the observers to learn the basic shapes and then select the "no change" response to these stimuli. The use of two angles in the basic shapes simply increased the variability in the stimuli presented.

Results and Discussion

For each observer, hit rates and false alarm rates were computed, and d' values were derived. Next, I carried out a repeated measures ANOVA on d' values. The within-subjects factors were vertex (convex or concave) and angle, and the between-subjects factor was the order of blocks.

Mean values are plotted in Figure 10. There was no main effect of vertex, $F(1, 10) = 0.92$, *ns*, partial $\eta^2 = 0.08$; no effect of order, $F(1, 10) = 0.72$, *ns*, partial $\eta^2 = 0.07$; and a marginal effect of angle, $F(1, 10) = 5.86$, $p = .036$, partial $\eta^2 = 0.37$. This means that the task was slightly easier for the sharper vertices, but this result is of little theoretical interest, especially since this factor did not interact with any other factor. With respect to the effect of vertex, not only was there no advantage for concave vertices, but the direction of the difference was actually for higher sensitivity for convex vertices as can be seen in Figure 10. This is entirely consistent with results from Experiments 1, 2, and 3 (see Figures 4, 7, and 9).

Experiment 5: Changes Involving and Not Involving Extrema

The changes studied in Barenholtz et al. (2003), in Bertamini and Farrant (2005), and in Experiments 1 and 2 involved introducing or removing vertices. By contrast, the changes studied in Cohen et al. (2005) and in Experiments 3 and 4 did not alter the number of vertices but only the angles. A new manipulation in Experiment 5 changed neither the number of vertices nor the angles. As illustrated in Figure 11, it is possible to change the length and position of edges while keeping the angles of the vertices the same. This is useful for completeness, but the more interesting goal of Experiment 5 was to test a new hypothesis that I outline here.

In the literature, the importance of concavity is generally discussed in relation to Hoffman and Richards' (1984) "minima rule." Negative minima (the location along a concavity where curvature has a peak) clearly play a central role in perceived part structure, and empirical evidence supports this theory (e.g., Braunstein, Hoffman, & Saidpour, 1989; de Winter & Wagemans, 2005).

It is therefore possible to formulate the hypothesis that attention should be directed not to concavities in general but rather towards minima (m−). The evidence from Experiments 1–4 does not support this hypothesis, but a more direct test would be to compare concave and convex extrema (m− and M+) not against each other but in relation to concave and convex changes that do not affect the curvature extrema. Vertices are a convenient way of manipulating extrema. There may a difference between events in which a vertex is or is not affected, and there may also be a difference between changes to convex and concave regions of the contour, but will there be an interaction between the two? This interaction could provide evidence for a special status of concave vertices and, therefore, minima. It should be stressed, however, that this is a test of the special status of minima in guiding attention, not in affecting perceived structure. In other words, the minima rule in itself does not predict such interaction because it makes a claim about a role of minima in parsing, not in guiding attention.

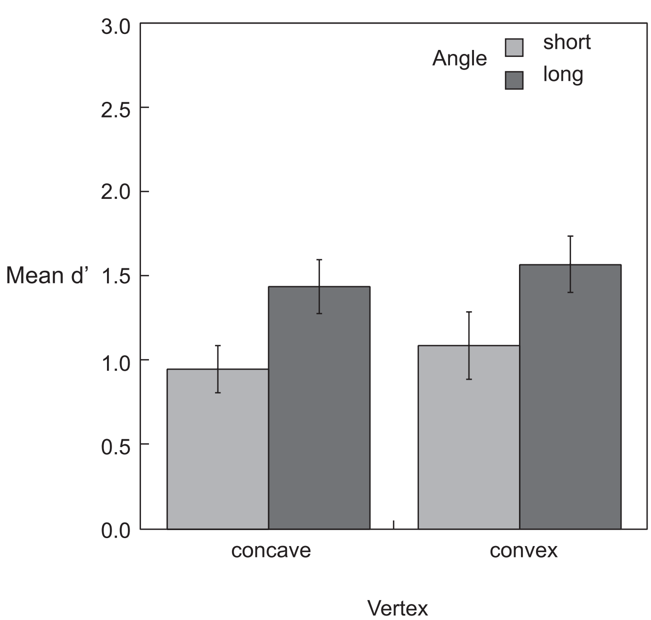

Figure 10. Data from Experiment 4. Sensitivity (d') is shown as a function of type of vertex and separately for the two levels of angle. Error bars are standard errors of the mean.

Method

Participants. Sixteen students at the University of Liverpool participated.

Stimuli and procedure. Equipment and procedure were similar to those of Experiment 4. After practice, each observer responded to 192 trials in rapid succession in each of two sessions (384 total trials). After every 64 trials a block ended, and the observer was allowed time to rest. The stimuli are illustrated in Figure 11. Note how the shape changes size and shape in the top row without the vertices being affected.

For half of the participants, a session in which the task was the detection of a convexity change was followed by a session in which the task was the detection of a concavity change, and for the other half the order was reversed.

The complete set of stimuli was the factorial combination of the following factors: change from first to second interval (same or different shapes), appearance (change introduced in the second interval, or removed in the second interval), location (on the left or on the right), orientation (convex region above concave region or vice versa), curvature sign (convex or concave), and type of change (either no change to any vertex, or a vertex appears/disappears). These last two factors are specific to Experiment 5; they allow a comparison of trials in which the change affected the vertices and others in which the change did not affect the vertices.

Results and Discussion

For each observer, hit rates and false alarm rates were computed, and d' values were derived. Next, I carried out a repeated measures ANOVA on d' values. The within-subjects factors were curvature sign (convex or concave) and type of change, and the between-subjects factor was the order of blocks.

Mean values are plotted in Figure 12. There was no main effect of curvature sign, $F(1, 14) = 0.53$, *ns*, partial $\eta^2 = 0.04$; no effect of order, $F(1, 14) = 0.76$, *ns*, partial $\eta^2 = 0.01$, and an effect of type of change, $F(1, 14) = 122.62$, $p < .001$, partial $\eta^2 = 0.89$. This means that the task was easier for the condition in which there

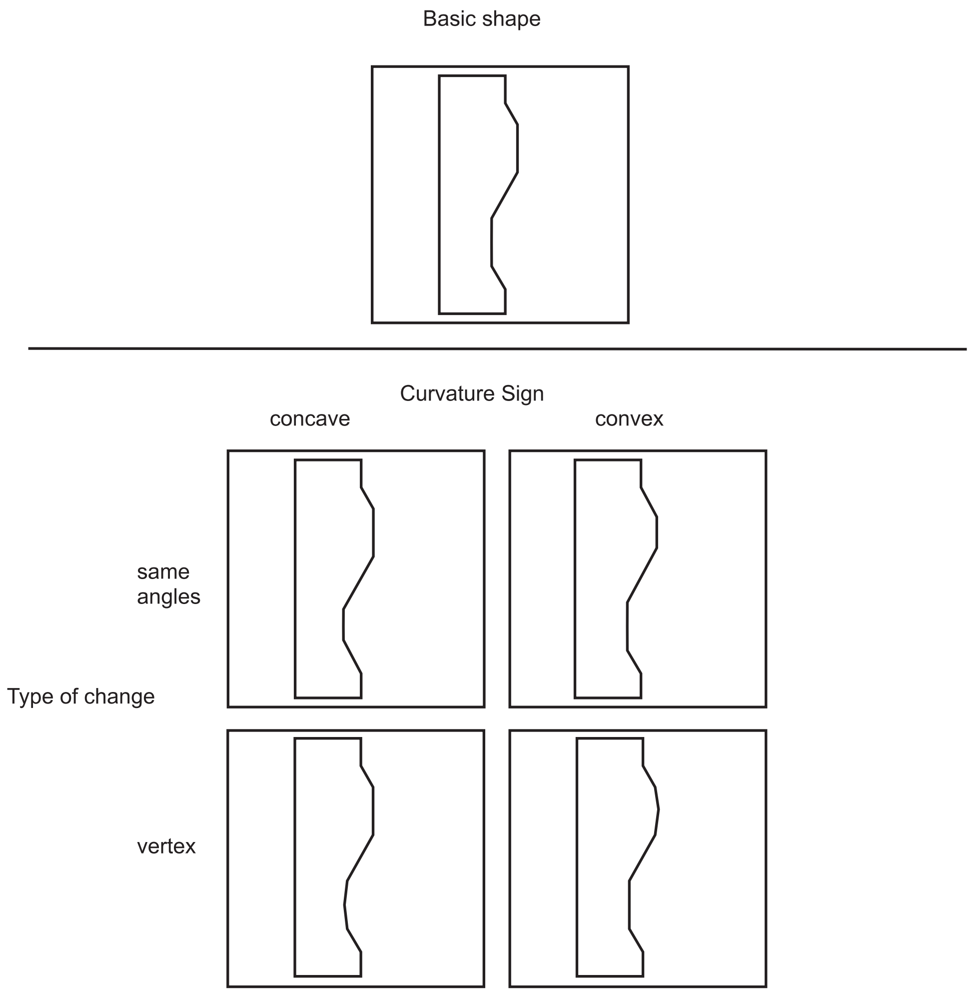

Figure 11. Stimuli for Experiment 5. The actual stimuli were contour outlines on a light green square background. The basic shape is shown at the top. The bottom figure illustrates the variables curvature sign and type of change. Curvature sign refers to whether the change was within a concave or a convex region. The first type of change did not alter the number or the angle of the vertices, whereas the second type changed the number of vertices.

was a change affecting the vertices. This difference, however, should be treated with caution as the two situations are qualitatively different and not directly comparable. With respect to the effect of curvature sign, not only was there no advantage for concavity, but the direction of the difference was for higher sensitivity for convexity, as can be seen in Figure 12. This is consistent with the findings for the variable vertex in the previous experiments. The most important aspect of Experiment 5 is the (lack of) interaction between curvature sign and vertices, $F(1, 14) = 1.65$, *ns*, partial $\eta^2 = 0.11$.

General Discussion

I compared sensitivity with changes that involved convexities or concavities along a contour, trying to separate the effects of type of contour (convex/concave) and type of vertex (convex/concave) from other effects such as a change of sign of curvature (a change from convex to concave or vice versa). In five experiments, I found evidence that sensitivity to change of shape is higher when a change of sign is present (Experiments 1 and 2), but I never found any evidence of a concavity advantage, either in terms of changes within a concave region or in terms of an advantage for changes to concave vertices. In Experiments 1 and 2, a new vertex was introduced, whereas in Experiments 3 and 4 the angle of existing vertices was changed. In both cases there was no advantage for changes involving concavities, nor was there an advantage for changes taking place within a concave context.

In Experiment 5, the appearance/disappearance of a vertex was intermixed with changes that did not alter any of the angles of the vertices. This was done so as to explore the additional importance of a change to a concave vertex or a convex vertex in relation to the overall performance for convex/concave changes that did not affect the vertices. In other words, independently of the overall difference between convexity and concavity, if concave vertices have a special status that derives not from being vertices but

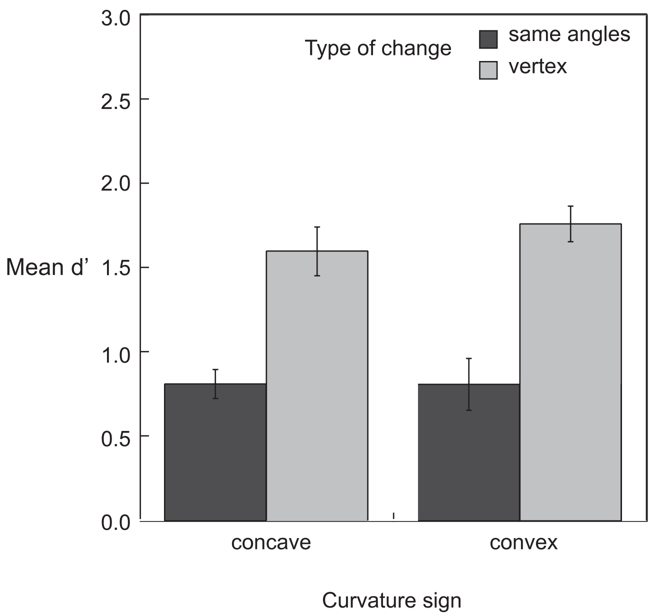

Figure 12. Data from Experiment 5. Sensitivity (d') is shown as a function of curvature sign and separately for the conditions of type of change. Error bars are standard errors of the mean.

specifically from being curvature minima, then one would expect an interaction between the type of change and type of curvature: Concave vertices should be uniquely salient. This interaction was not present in the results.

The pattern of results was remarkably consistent. For instance, the stimuli used in Experiments 1 and 2 differed in many aspects: In one case contours were defined by disparity and in the other by luminance, the overall size, and the size of the possible changes, and the presentation times were all different. Despite these differences, in both Figures 4 and 7, there was a strong interaction between type of vertex and context, and in the conditions where no change of sign was present there was a tendency to better performance for convex vertices. Although the lack of an advantage for concavity is a null finding, the consistent pattern across five different experiments and the different ways in which a concavity advantage was tested leaves little space for doubt.

In addition, although participants were asked only to respond as accurately as possible without trying to respond quickly, response time was recorded by the computer for all experiments. The analysis of reaction time revealed a pattern consistent with d' values in each experiment.

In summary, these results contradict the proposal that concavities are inherently more salient. The detection of a convex vertex (or of a change of angle for a convex vertex) can be more salient than the detection of a concave vertex (or of a change of angle for a concave vertex), depending on the context (i.e., there is an interaction between type of vertex and context). In other words, the introduction or removal of a convex vertex in the context of a concavity is much more salient than in the context of a convexity. The same is true, *mutatis mutandis,* for a concave vertex.

Other Empirical Findings

In the literature there are several cases of an advantage for convexity over concavity. The tasks include positional judgments (Bertamini & Croucher, 2003), the local comparison of probes (Barenholtz & Feldman, 2003), figure-ground segmentation (Bertamini & Lawson, in press), perceived metric depth (Burge, Peterson, & Palmer, 2005), and symmetry detection (Hulleman & Olivers, 2007). It is possible that these effects all originate from the status of convexities as perceived parts. In terms of change detection, I did not find an advantage for convexities. However, given that a trend in that direction seems to be a common feature in the results of different experiments, this possibility could be followed up in the future.

Some cases of an advantage for concavities exist in the literature. The general role of concavities as part boundary is not controversial and is well supported by empirical evidence. This is in no way at odds with the evidence about convexity mentioned above. But a few articles have also suggested that attention is directed towards concavities (Barenholtz et al., 2003; Cohen et al., 2005; Hulleman et al, 2000). This would be a problem, because if attention were to be guided towards concavities, then one must predict a concavity advantage also in the tasks mentioned above, for instance, when judging position. A closer look at the evidence suggests that when a concavity advantage has been reported, the design of the experiment was not symmetrical, as discussed in the introduction. For instance, a larger number of convexities than concavities were present in the stimuli in the first experiment by Cohen et al. (2005). The second experiment in Cohen et al. is more similar to the stimuli I have used. I believe that the small concavity advantage present in that experiment was probably due to the fact that concavities tend to co-occur with changes in the distance from the outside of the object (for the role of necks in part structure, see Siddiqi et al., 1996). Although this indirect effect should be present also in my stimuli, the changes in the neck region used in Cohen et al. are considerably larger than mine (compare for instance Figure 5 in Cohen et al. with my Figure 8). Moreover, support for this explanation comes from the difference between narrow and wide objects in my own Experiment 2 (confined to the concave context, where a neck is present).

Taken together, therefore, the available results support the idea that convexities and concavities play different roles in shape perception and, in particular, in parsing. The evidence, however, does not support the hypothesis that attention is guided towards concavities.

Perceived Part Structure

I interpret the current results in terms of perceived part structure: Sensitivity was higher when the sign of curvature along the contour changed, presumably because changes of sign affect perceived part structure. Specifically, a new concave vertex in a convex region splits that region into two parts, and a new convex vertex in a concave region introduces a new part that was not previously present.

In terms of the existing literature, Keane, Hayward, and Burke (2003) found evidence of good detection of changes of part structure for three dimensional objects, although in their study the changes did not alter the total number of parts. Also consistent with the importance of parts is the finding that differences in the number of parts are more readily discriminated than differences in metric properties (Foster & Gilson, 2002).

As discussed in the introduction, there are strong arguments in favor of the idea that contour curvature, and the related properties of medial axes, should affect perceived structural shape (Siddiqi et al., 1996; Singh et al., 1999). There is evidence that parts are processed early and obligatorily (e.g., Xu & Singh, 2002), and there is also evidence that part boundaries constrain the deployment of attention (e.g., Vecera, Behrmann, & McGoldrick, 2000).

The behavioral evidence for early processing of contour curvature information is also consistent with emerging neurophysiological evidence. There is a central role for convexities and concavities in how the visual system represents shape, starting with the simple properties of V4 neurons (Pasupathy & Connor, 2002) and later by a sparser and more explicit coding in inferotemporal regions (Brincat & Connor, 2006). It is likely that perceived parts play a role in the effects of figure-ground (Kourtzi & Kanwisher, 2001), because figure-ground reversals change contour curvature. In summary, there is converging evidence reinforcing the idea that contour curvature affects shape representation very early and before object identification.

There is general agreement that concavities are important for parsing shape (e.g., Koenderink, 1990). However, the process of parsing carried out by the visual system is complex, and there is a difference in emphasis between theories that stress the existence of volume primitives and theories that stress rule-based parsing (for a review, see Singh & Hoffman, 2001). Within the second approach, de Winter and Wagemans (2005) have recently explored the relative strength of many factors involved in parsing and concluded that all of the previously proposed rules have some support in their results. They also proposed a framework in which cognitive and visual influences are combined. It appears, therefore, that the parsing process is affected by multiple rules not easily captured in a simple algorithm. With respect to minima, they did find that these were the most frequent locations for a part cut. However, although negative singularities were in general more important than positive ones, and negative minima (m−) more important than negative maxima (M−), they also found that positive maxima (M+) were more important than positive minima (m+). There was therefore no interaction between curvature sign and curvature magnitude (as both m− and M+ have high curvature). Another interesting aspect in de Winter and Wagemans's paper (2005) was the relative rarity of negative maxima (M−) in silhouettes of natural objects.[4]

To stress the importance of a change of sign, Bertamini and Farrant (2005) have introduced the term *bracketing hypothesis*. By this they meant that, although the sequence of convexities and concavities has powerful effects on shape representation, in themselves convexities and concavities do not attract differential processing by the visual system or different attentional resources. This goes against a suggestion in the literature based on change detection studies (Barenholtz et al., 2003; Cohen et al, 2005) and visual search studies (Hulleman et al., 2000; Humphreys & Müller, 2000). However, as discussed above, in these studies there were changes of sign along the contour of some stimuli or other confounding factors.

The bracketing idea is consistent with Hoffman and Singh's (1997) proposed salience factors: size of the part relative to the whole object; degree of protrusion; and strength of the part boundaries. A part obtained by segmenting at minima that do not bracket a convexity would fail such criteria (no protrusion). The original salience factors (Hoffman & Singh, 1997) included degree of protrusion, but Singh et al. (1999) found that observers did not have a preference for either shorter or longer parts, whereas factors such as relative area and cut length were important. Therefore, protrusion may be an all-or-none criterion, equivalent to the idea of bracketing. The importance of the convexity of the resulting parts is also central to Rosin's model (2000). He proposed a specific formula to quantify the convexity of the partitioned region, which can therefore be seen as a measure of salience for a candidate part.

Note that putting the emphasis on changes of sign of curvature implies also that emphasis is taken away from the role of extrema. Clearly negative minima are often chosen as part boundaries (e.g., de Winter & Wagemans, 2005), but there is a difference between considering minima as salient locations because of high curvature or considering them as stimuli having a special status that attracts differential processing. If what matters is degree of curvature, then for a given minimum parsing should depend also on the turning angle (Singh & Hoffman, 2001), and Singh and Hoffman (1998) found evidence of the importance of the turning angle. Another special case to illustrate the role of extrema is when negative minima (m−) and maxima (M−) follow each other along a contour, for instance in the case of an elliptical hole. Would these extrema have a significant role to play in determining part structure? If they do not, then extrema are perhaps not as important as previously hypothesized. Although the studies presented in this article do not address this issue directly, in Experiments 1 and 2 a change involving a convex maximum (vertex) along a convex contour (context) was compared with a change involving a concave minimum (vertex) along a concave contour (context); here one might have expected a difference if the visual system treats positive maxima (M+) and negative minima (m−) as fundamentally different, with a unique role played by a negative minimum. Experiment 5 used a different strategy to test for the same idea of a special role of negative minima. Overall, the results do not support the special attentional status of negative minima.

In summary, there is agreement that contour curvature is important for perception of shape, and that concavities in particular are important for an early and obligatory process of parsing. Consistent with this idea, I have found that when there is a change in the way convexity and concavity alternate along a contour, this event is highly salient. But there is no need for the visual system to differently allocate resources to regions of contour based on the sign of curvature alone. A case could be made for directing attention to negative minima (m−) to a greater extent than to positive maxima (M+), even when magnitude of curvature is matched, but no evidence is available to support this hypothesis. Therefore, I conclude that sign per se is not a factor that guides

[4] Richards et al. (1987) have proposed a classification of shape in terms of the sequence of curvature extrema. There are a total of five primitive elemental shapes, called codons. Although, as discussed, there is already good empirical support for the importance of curvature in describing shape, more work is necessary on the degree of sophistication of the visual system. For instance, given a horseshoe shape, how much will it matter if the concavity has one, two, or three minima? These are different codon sequences that may be treated similarly in many visual tasks.

attention, rather convexity and concavity effects are always mediated by their role in perceived part structure.

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