Concavities as basic features in visual search: Evidence from search asymmetries

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Concave cusps and negative curvature minima play an important role in many theories of visual shape perception. Cusps and minima are taken to be part boundaries, used to segment an object into parts. Because of their important role in determining object structure and because there is some evidence that object structure is processed in parallel, it might be expected that concave cusps and negative curvature minima are processed preferentially. We tested this conjecture in several visual search experiments. Visual search for a target with a concave cusp among totally convex distractors yields nearly flat slopes (< 10 msec/item) for both present and absent trials. Reversing the roles of the target and the distractor results in inefficient search. The same asymmetry is found when the concave cusp is replaced by other types of concavity. We conclude, therefore, that concavities can serve as basic features in visual search experiments. This conclusion implies that the unit of selection in a visual search task is an object, rather than a location.

Concave cusps and negative curvature minima play an important role in theories of visual shape perception. Especially those theories that belong to the structural description variety (e.g., Biederman, 1987; Cooper, Schacter, Ballesteros, & Moore, 1992; Marr & Nishihara, 1978) depend heavily on them. They use concave cusps and negative curvature minima to find the borders between parts and, subsequently, describe a visual scene in terms of parts and the relationships between them (Winston, 1975).

The rationale for the use of concave cusps to find the structure of an object has been given by Hoffman and Richards (1984). They described transversality regularity: When two arbitrarily shaped surfaces are made to interpenetrate, they always meet in a contour of concave discontinuity of their tangent planes. So, when an object has to be segmented into its constituent parts, as is proposed by structural description theories, concave discontinuities are natural places to split the contour. This idea has been formulated by Hoffman and Richards in their minima rule: Divide a surface into parts along contours of concave discontinuity. Hoffman and Richards subsequently generalized their partitioning rule to include negative curvature minima, which they considered smoothed cusps.

There is some evidence that objects and object structures are processed in parallel by the visual system. For instance, Baylis and Driver (1994) reported reaction times for the detection of symmetry that were independent of

the number of part boundaries present in the stimulus. According to Baylis and Driver (1994), this outcome implied that a global shape description in terms of component parts was derived in parallel. This result was obtained with a single object presented at the fixation point, but evidence obtained from visual search tasks also shows that object structure is processed very rapidly. Rensink and Enns (1995) used Müller-Lyer (ML) stimuli. They found that the total configuration of the ML stimuli influenced search. The component lines, on the other hand, did not influence the search rates. Wolfe, Friedman-Hill, and Bilsky (1994) reported that search for a target that is defined by a conjunction of colors is much easier when there is a part-whole relationship (*red house with yellow windows*) than when there is a part-part relationship (*red house and yellow house*). However, there are also limits to the fast processing of object structure. Brown, Weissstein, and May (1992) failed to find evidence that simple volumetric shapes are processed preattentively. In their experiments, they did find pop-out, probably caused by differences in two-dimensional features of the geonlike objects (Biederman, 1987). But in four cases, different geons with an identical orientation were not discriminable preattentively. Wolfe and Bennett (1997) also reported several experiments in which differences in object structure did not produce pop-out (e.g., a chicken among shapes with rearranged chicken parts).

So, given that some aspects of object structure are processed in parallel, and given that concave cusps and negative curvature minima play an important role in determining object structure, it might be expected that concave cusps and negative curvature minima are processed preferentially by the visual system (i.e., are features).

Search asymmetries have been proposed as a means by which to determine whether a certain image property is a feature (Treisman & Souther, 1985). Taking feature in-

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Figure 1. Examples of the stimuli used in previous experiments. A–B: the stimuli used by Wolfe and Bennett (1997). C–D: the stimuli used by Elder and Zucker (1993).

tegration theory (Treisman & Gelade, 1980) as a starting point, Treisman and Souther suggested that pop-out will occur for both target-present and target-absent trials, when the target in a visual search task contains a distinctive feature. They suggested that the relevant feature map can be checked for the presence and the absence of activity. Consequently, search will be fast. If, on the other hand, the distractors possess the distinctive feature and the target does not, the relevant feature detector cannot be used, because it will always be very active, both in the present and in the absent trials. If there is no other distinctive feature in the latter case, slow search will result. So, there is a search asymmetry: When the target contains the distinctive feature, search will be fast, and when the distractors contain the distinctive feature, search will be slow.

Search asymmetries have a similar interpretation in attentional engagement theory (Duncan & Humphreys, 1989, 1992), an alternative to feature integration theory. According to Duncan and Humphreys, visual search has three components: a parallel description stage, a selection stage at which the input descriptions are matched against an internal template, and a stage at which selected descriptions enter visual short-term memory. The matching in the selection stage is influenced by the ease of classification and perceptual grouping. Duncan and Humphreys (1992) suggested that the internal template might be instantiated by enabled connections between feature maps and a master map. So, in attentional engagement theory, search asymmetries indicate differences in the availability of feature maps (necessary to specify the attentional template) too, along with differences in the extent to which perceptual grouping is possible between the elements in the display.

Despite the interest in the preattentive processing of object structure, there has been very little research directed at establishing the featural status of curvature minima and cusps. To our knowledge, there are only two relevant studies (Elder & Zucker, 1993; Wolfe & Bennett, 1997). Both of them concern concave cusps.

Wolfe and Bennett (1997) reported an asymmetry between search for a target with a concave cusp among totally convex distractors and search for a totally convex

target among distractors with a concave cusp (shown in Figures 1A and 1B). Search for the target with a concave cusp was very fast (9.6 and 3.4 msec/item for present and absent trials, respectively), whereas search for the totally convex target was much slower (28.9 msec/item for present trials and 39.6 msec/item for absent trials). These results suggest that a concave cusp is indeed a feature.¹

However, the results of the second relevant study, reported by Elder and Zucker (1993), cast doubts on this conclusion. Elder and Zucker performed an experiment, in which participants had to search for a biconcave target (Figure 1C) among totally convex distractors (Figure 1D). Their results do not suggest that search for a concave target is effortless (12 msec/item for present trials and 48 msec/item for absent trials). Wolfe's (1998) combined criterion for feature search is not met. Neither are the slopes shallow, nor is the slope ratio between absent and present trials smaller than 2.0.

The results of the two studies thus differ markedly: Whereas Wolfe and Bennett (1997) find a pop-out of concave targets, Elder and Zucker (1993) do not. This discrepancy might be explained in several ways. A first explanation is that the concavities of the stimulus used in the experiment by Elder and Zucker were simply not conspicuous enough and, therefore, did not result in pop-out. The concave cusp in the stimulus used by Wolfe and Bennett is perceptually much more salient (Hoffman & Singh, 1997; Stevens & Brookes, 1988). If this explanation holds, concave cusps are features after all. However, a second explanation is that it is simply the presence of any cusp that is effortlessly detected in the experiment of Wolfe and Bennett. Note that the concave cusp is the only cusp present in their shapes. The inefficient search found by Elder and Zucker corroborates this explanation. In their experiment, both target and distractor possess cusps (concave as well as convex). Consequently, it is not possible to search for a cusp to perform the detection task.

In sum, the featural status of concave cusps has not been established yet, because it has not been ascertained that it is necessary for a cusp to be concave to yield an asymmetry. The question of whether a cusp has to be concave to yield efficient search not only has implications for theories of shape perception. Recently, Goldsmith (1998) presented results that suggested that the unit of selection in a visual search task is an object, rather than a location. If search for a concave cusp differs from search for a convex cusp, this would be a corroboration of the results of Goldsmith. After all, the distinction between convex and concave is only possible when there is a figure and a ground.

We ran a series of experiments, to answer three related questions. First, do concave cusps have a featural status? Second, if so, is this featural status restricted to concave cusps, or do all kinds of concavities support pop-out? Third, if all kinds of concavities support pop-out, do concave cusps yet possess features that other concavities lack? The first question was answered by Experiments 1–2B. In Experiment 1, we tested whether there is a search asymmetry between searches for a shape that possesses a con-

Figure 2. Examples of the stimuli used in the present experiments. A–B: the stimuli used in Experiment 1. C–D: the stimuli used in Experiment 2A. E–F: the stimuli used in Experiment 2B. G–H: the stimuli used in Experiment 3. I–J: the stimuli used in Experiment 5.

cave cusp among shapes that possess a convex cusp and vice versa. To exclude alternative explanations of the results of Experiment 1, we designed Experiments 2A and 2B. We addressed the second question in Experiments 3 and 4, where we tested whether we also find a search asymmetry when the cusps of Experiment 1 are replaced by circular arcs or negative curvature minima. Finally, in Experiment 5, we tried to answer the third question, by pitting a shape with a circular concavity against a shape with a concave cusp.

The stimuli used in Experiment 1 are depicted in Figures 2A and 2B. Both stimuli had equal area, equal width, and equal height. Both area and size have been suggested to be features (Rubin & Kanwisher, 1985; Treisman & Gelade, 1980), and we therefore controlled for them. The main difference between our stimuli and those of Wolfe and Bennett (1997) is that, in our experiment, the totally convex shape also has a cusp. There were two differences from the stimuli of Elder and Zucker (1993). First, the concave cusp was more conspicuous. Second, both target and distractor had one cusp only.

If participants search only for the mere presence of any cusp, a search for both the convex and the concave shapes as a target would be inefficient, because both shapes possess a cusp. Consequently, contrary to Wolfe and Bennett (1997), no search asymmetry would be found. On the other hand, if we find a search asymmetry, this would be strong evidence for the featural status of concave cusps. In all our experiments, we used the combined criterion for feature search, suggested by Wolfe (1998). There should be shallow slopes when the target is present and shallow slopes when the target is absent. The slope ratio between absent and present trials should be significantly less than two.

EXPERIMENT 1

Method

Participants. Twelve participants (4 men and 8 women), all undergraduates at the University of Nijmegen, took part in this experiment. All had normal or corrected acuity by self-report. They received course credit for their participation.

Apparatus and Materials. The experiment was conducted on a 486 PC with a 15-in. SVGA (800 × 600) monitor. The displays consisted of a 6 × 6 grid, centered on the screen. Each element of the grid had a size of 2.4° × 1.9°. The objects were positioned at the center of an element. Target objects appeared in each of the four quadrants of the grid at each possible distance from the center. Distractor objects were positioned randomly on the grid. The orientation of an object was chosen randomly from 16 possibilities. The objects were solid white on a black background. Objects had one of two shapes: a shape with a concavity (Figure 2A) or a totally convex shape (Figure 2B). Both had a height of 2.1° and a width of 1.35° and had equal areas. The concavity of the concave shape was a triangle with a base size of 0.76° and a height of 0.38°. The same triangle reappeared as the convex cusp on the top of the convex shape. Smooth curves were fitted to the triangle, to ensure that the apex was the only cusp in a shape (Hulleman & Boselie, 1997). We used display sizes of 1, 6, and 12 items.

Design. There were three within-subjects factors in the experiment: target type (convex shape or concave shape), display size (1, 6, or 12), and presence (target present or absent).

Procedure. The participants sat in a normally lit room. They were instructed by a screen on which the target and the distractor were shown. They were told to search quickly and accurately for the target between the distractors, but they were not told which aspects of the stimuli they should use.

The experiment consisted of four blocks: a training block for the first target (36 trials); then, the experimental block for the first target (288 correct trials); subsequently, a training block for the second target (36 trials); and finally, the experimental block for the second target (288 correct trials). The target of the first experimental block was the distractor of the second, and vice versa. Error trials in the experimental blocks were repeated in chronological order at the end of the block, as were trials in which the reaction time was larger than 2,000 msec. There were breaks at the end of each block and at the end of the third quarter of the experimental blocks. Half of the participants were presented the convex shape as a target in the first experimental block, half the concave shape. The participants answered by pressing the button of a button-box. Half of the participants had to use their preferred hand to signal the presence of a target, the other half the nonpreferred hand. There were four combinations of target sequence and hand mapping. Three participants were randomly assigned to each combination.

Figure 3. Experiment 1: Mean reaction times and search slopes (above) and proportion of errors (below). The error bars represent standard errors; the lines represent linear best fits. The results for concave targets are indicated by a circle; the results for convex targets by a triangle. Filled symbols, present trials; open symbols, absent trials.

Stimulus presentation ran as follows: There was a high tone (1500 Hz) for 55 msec; then, the display was presented until response. The display was followed by a black screen for 1,500 msec, after which a new sequence started. In case of an incorrect response, there was a low noise burst of 600 Hz for 200 msec.

Analysis. There were 576 correct trials available for each participant. Of these, 288 were trials with a convex target, and 288 were trials with a concave target. These trials were used in the reaction time analysis. For each participant, there was a varying number of incorrect trials. Those trials were included in the accuracy analysis. Trials that exceeded the time limit of 2,000 msec were not used in either analysis.

Results

The results are shown in Figure 3. As can be seen from the reaction time data in Figure 3, the difference between the slopes of present and absent trials was larger when the participants had to search for the convex target than when they had to search for the concave target. This was shown by the significant three-way interaction between target type, display size, and presence [$F(2,10) = 10.63$, $p < .003$] in a repeated measures multivariate analysis of variance (MANOVA) on the reaction time data. The two target types were analyzed in separate two-way (display size $\times$ presence) MANOVAs. When the participants searched for a concave target, the slope for the present

condition did not differ from the slope for the absent condition [$F(2,10) = 2.48$, n.s.], although the slopes did differ from zero [$F(2,10) = 50.17$, $p < .001$], and the reaction times were slower in the absent condition than in the present condition [$F(1,11) = 5.18$, $p < .044$]. When the participants searched for a convex target, the slope for the present condition was smaller than the slope for the absent condition [$F(2,10) = 11.87$, $p < .002$].

For small display sizes, there were no more errors in the present displays than in the absent displays. For the largest display size, however, there were more errors when the target was present than when the target was absent [$F(2,10) = 10.98$, $p < .003$]. Furthermore, there were more errors for the largest display size when the target was convex [$F(2,10) = 4.80$, $p < .035$].

Discussion

There was a clear asymmetry between the search for the concave target and the search for the convex target (see Figure 3). Whereas the search for the concave target yielded very efficient search (5.5 and 7.9 msec/item for present and absent trials, respectively), the search for a convex target was inefficient (23.3 msec/item for present and 36.8 msec/item for absent trials). These results replicate those of Wolfe and Bennett (1997). However, this time

we have excluded the possibility that *any* cusp was the feature used by the participants, by incorporating a convex cusp in the distractors. Nevertheless, it is too early to conclude that concave cusps are features. Finding a search asymmetry is not the same as identifying the feature that accounts for it. Any difference between the target and the distractor could be responsible for the asymmetry, and in our shapes, there were other differences than just the cusps.

For instance, it could be argued that it was not the presence or absence of a concave cusp but, rather, the difference in complexity between the target and the distractor that was responsible for the asymmetry. Search for a target that was more complex than the distractors would be efficient, whereas search for a target less complex would be inefficient. In the work of Scharroo, Stalmeier, and Boselie (1994), there is some support for such a claim. They found that the detectability of a target increases when the complexity of the distractors decreases. The issue of complexity is rather complicated, however. The complexity of shapes has been quantified in various ways, and the difference in complexity between the target and the distractor therefore depends on the quantification, because the complexity metrics do not always agree. For instance, according to the complexity metric introduced by Garner (1970), both shapes in Experiment 1 were equally complex. Consequently, according to the Garner metric, the results in Experiment 1 cannot be due to differences in complexity. However, according to Attneave's metric (1957), the convex shape was less complex than the concave shape. Attneave has shown that a larger number of independent turns entails a higher judged complexity of shapes. When the convex cusp is replaced by a concave one, the number of independent turns increases. So, according to the Attneave metric, there was a difference in complexity between the shapes, which could have been responsible for the results in Experiment 1. The more complex concave shape was found more easily than the less complex convex shape. Although the complexity metrics do not agree, and even though shapes containing a concavity are perhaps necessarily more complex than purely convex ones, we decided to investigate whether the search asymmetry found in Experiment 1 would be sensitive to a manipulation of the complexity of the target and distractor shapes. Such a sensitivity would strongly suggest that it was not the concave cusp but, rather, the difference in complexity introduced by the concave cusp that was responsible for the search asymmetry.

We designed the two new shapes depicted in Figures 2C and 2D. Now, the concave shape is bilaterally symmetric, whereas the convex shape is asymmetric. Attneave (1957) showed that the introduction of symmetry reduces the judged complexity of shapes. In this pair of shapes, the difference in complexity according to the Attneave metric is much smaller than that in Experiment 1. Moreover, according to the complexity metric introduced by Garner (1970), the concave shape is now the least complex of the two. If the search asymmetry in Experiment 1 is sensitive to manipulation of complexity, we should now observe a

substantial change in the results. The search rates for the concave target (Figure 2C) should increase, whereas the search rates for the convex target (Figure 2D) should decrease.

EXPERIMENT 2A

Method

Participants. Twelve participants (6 men and 6 women), all undergraduates at the University of Nijmegen, took part in this experiment. All had normal or corrected acuity by self-report. They received either course credit or a small payment for their participation.

Apparatus and Materials. The experiment was the same as Experiment 1 in every respect, except for the shapes used. The concave shape was perfectly symmetric (see Figure 2C); the convex shape (Figure 2D) was asymmetric. The shapes had a height of 2.2° and a width of 1.6°. The size of the concavity was the same as that in Experiment 1.

Results

The results are shown in Figure 4. As in Experiment 1, we see that the difference in slope between absent and present trials was larger for the convex targets than for the concave targets. This was confirmed by a significant three-way interaction between target type, display size, and presence in a MANOVA on the reaction time data [$F(2,10) = 7.14, p < .012$]. An analysis of the concave target condition with a two-way (display size $\times$ presence) MANOVA showed that the slopes for the present condition and the absent condition did not differ [$F(2,10) = 1.2, n.s.$]. The slopes did, however, differ from zero [$F(2,10) = 53.22, p < .001$], and the reaction times in the absent condition were slower than the reaction times in the present condition [$F(1,11) = 5.47, p < .039$]. A similar analysis of the convex target condition showed that the slope for the present condition was smaller than the slope for the absent condition [$F(2,10) = 8.57, p < .007$].

In the accuracy data, we see that the proportion of errors was approximately constant across display size for the concave targets but that there were many errors for the largest display size when there was a convex target present. This was supported by a significant three-way interaction between target type, display size, and presence [$F(2,10) = 7.06, p < .012$], the absence of any effects when the concave targets were analyzed separately, and a significant interaction between display size and presence in a separate analysis of the convex targets [$F(2,10) = 7.88, p < .009$].

Discussion

Again, there was a clear asymmetry between the search for a concave target and the search for a convex one. As can be seen from Figure 4, the slopes for the search for a concave target were again under 10 msec/item (7.4 and 8.3 msec/item for present and absent trials, respectively). The search for a convex target was much slower (24.8 msec/item for present and 43.3 msec/item for absent trials). Although the search rates for the concave targets were a little higher than those in Experiment 1, this

Figure 4. Experiment 2A: Mean reaction times and search slopes (upper panel) and proportion errors (lower panel). The error bars represent standard errors; the lines represent linear best fits. The results for concave targets are indicated by a circle; the results for convex targets by a triangle. Filled symbols, present trials; open symbols, absent trials.

was offset by an increase in accuracy. For all the largest display sizes (see Figures 3 and 4), the proportion of errors was lower in Experiment 2. This indicates that it was not so much the change in complexity but, rather, a tradeoff between speed and accuracy that was responsible for the small difference in the search rates for concave targets between Experiments 1 and 2A. The search rates for the convex targets did not support any sensitivity for complexity either, because they increased rather than decreased. Nevertheless, it is still too early to conclude that it is the presence of a concave cusp that is responsible for the search asymmetry.

Note, again, that the shapes in Experiment 2A differed in other properties than just concavity. The concave shapes now contained an axis of symmetry, whereas the convex shapes did not. Is it possible that a change in slopes owing to the manipulation of complexity was masked by this difference in symmetry? We think not. Recently, Olivers and van der Helm (1998) showed that it is very difficult to search for bilateral symmetry. In several experiments, in which participants had to search for a bilaterally symmetric target, they did not find any pop-out. In fact, Olivers and van der Helm never found any search rates below 30 msec/item for symmetric targets. However, in the data

of Olivers and van der Helm, there is a tendency for search slopes to become more shallow as the complexity of the stimuli decreases.

To find out whether the participants possibly used the symmetry in Experiment 2A, we ran a control experiment. In this experiment, the first shape (Figure 2E) was identical to the concave shape used in Experiment 2A, but this time, the asymmetric second shape (Figure 2F) possessed a concave cusp too. So, if it was symmetry that the participants used in Experiment 2A, we would expect another search asymmetry in Experiment 2B. However, if it was the concave cusp that was used in Experiment 2A, we would expect inefficient searches in Experiment 2B, because both shapes possessed one.

EXPERIMENT 2B

Method

Participants. Twelve participants (4 men and 8 women), all undergraduates at the University of Nijmegen, took part in this experiment. All had normal or corrected acuity by self-report. They received either course credit or a small payment for their participation.

Apparatus and Materials. The experiment was in every respect the same as Experiment 1, except for the stimuli. In this experiment there were two concave shapes. The symmetric shape (Figure 2E)

Figure 5. Experiment 2B: Mean reaction times and search slopes (upper panel) and proportion of errors (lower panel). The error bars represent standard errors; the lines represent linear best fits. The results for symmetric targets are indicated by a circle; the results for asymmetric targets by a triangle. Filled symbols, present trials; open symbols, absent trials.

was the same as that used in Experiment 2A; the asymmetric shape (Figure 2F) was newly designed for this experiment. Both shapes had the same width, height, and area.

Results

The results are shown in Figure 5. This time, there was no difference between the target types; the symmetric and the asymmetric targets behaved almost identically. A three-way (target type $\times$ display size $\times$ presence) repeated measures MANOVA of the reaction time data showed no significant effect involving target type (all p s $> .05$). Target-present trials had a smaller slope than target-absent trials, as was shown by a significant two-way interaction between display size and presence [$F(2,10) = 17.77, p < .001$].

In the accuracy data, there was an effect of target type. The difference between present and absent trials was smaller for the asymmetric targets than for the symmetric targets. This was confirmed by a significant three-way interaction between target type, display size, and presence in a MANOVA [$F(2,10) = 5.65, p < .023$]. A separate analysis of the symmetric targets showed that the difference in number of errors between present and absent trials increased with increasing display size [$F(2,10) =$

45.829, $p < .001$]. Furthermore, there were many more errors in the present condition than in the absent condition [$F(1,11) = 101.414, p < .001$]. A similar picture emerged for the asymmetric targets: an increasing difference in number of errors between present and absent trials with increasing display size [$F(2,10) = 22.689, p < .001$] and many more errors for present trials [$F(1,11) = 62.144, p < .001$].

Discussion

This time, we did not find a search asymmetry. Moreover, we did not find any sign of effortless search either. Search for a symmetric as well as for an asymmetric target was highly inefficient (symmetric target: present trials, 49.7 msec/item, absent trials, 76.0 msec/item; asymmetric target: present trials, 50.9 msec/item, absent trials, 69.7 msec/item). The error proportions were comparable with those in the previous experiments for the first display size, but they became very large for the two other display sizes. These high error proportions were caused by the 2,000-msec criterion for reaction times, which forced the participants to answer before they had completely searched the display. The task was rather difficult, but this was not caused by the confusability between the target and the dis-

Figure 6. Experiment 3: Mean reaction times and search slopes (upper panel) and proportion of errors (lower panel). The error bars represent standard errors; the lines represent linear best fits. The results for concave targets are indicated by a circle; the results for convex targets by a triangle. Filled symbols, present trials; open symbols, absent trials.

tractor. If this had been the case, we would have expected a large amount of errors for the smallest display size. The differences in intercept between this experiment and Experiment 2A suggest that detection of concavities is faster than detection of symmetry. Both for present and for absent trials, the intercept is some 150 msec larger than that in Experiment 2A. However, some of this difference was caused by the 2,000-msec criterion for reaction times, which resulted in an underestimation for the reaction time for the largest display size.

Our results replicate those of Olivers and van der Helm (1998). The absence of any interactions involving target type indicates that symmetry cannot be used to guide visual search. Consequently, the results reported in Experiment 2A were not caused by the symmetry of the concave shape. We can now safely conclude that concave cusps are features. A manipulation of complexity did not influence the search asymmetry, and this lack of influence was not caused by a search for symmetry.

Since the answer to our first question—do concave cusps have a featural status?—is affirmative, we proceed to our second question: Is the featural status restricted to concave cusps, or do all concavities support pop-out?

There is reason to assume that it is not so much the type of concavity that determines whether it is considered a part boundary but, rather, its conspicuousness. Braunstein, Hoffman, and Saidpour (1989) ran an experiment in which they asked participants to draw part boundaries on an object containing both shallow circular concavities and deep negative curvature minima. None of the participants drew a part boundary at the circular concavities. This result was taken to indicate that only negative curvature minima were considered part boundaries. However, Siddiqi, Tresness, and Kimia (1996) reported an experiment in which participants drew part boundaries at both circular concavities and negative curvature minima. In this experiment, the curvature of the concavities was much higher. So, it seems that any concavity acts as a part boundary, as long as it is conspicuous enough. To test whether there is indeed no difference between concave cusps and other concavities in visual search, we decided to replicate our previous experiments, using a circular concavity instead of a concave cusp.

We designed two new shapes. The first shape contained a circular arc (Figure 2G). The second shape (Figure 2H) was completely convex and also contained the circular arc

Figure 7. The shape of the concavity varies with the value of a . The shapes used in Experiment 4 have values for a of 0.5, 1.0, and 1.5. The shapes with values of 0.0 and 2.0 were used in Experiments 2A and 3, respectively.

as part of its contour. If pop-out is restricted to concave cusps, this combination of shapes should not yield a search asymmetry.

EXPERIMENT 3

Method

Participants. Twelve participants (2 men and 10 women), all undergraduates at the University of Nijmegen, took part in this experiment. All had normal or corrected acuity by self-report. They received either course credit or a small payment for their participation.

Apparatus and Materials. The experiment was in every respect the same as Experiment 1, except for the stimuli. The concave target (Figure 2G) had a height of 2.2° and a width of 1.6° . The concavity consisted of a segment of a circle with a radius of 0.42° . The con-

vex target (Figure 2H) had the same width and height, and it also contained the segment of the circle as a part of its contour.

Results

The results are shown in Figure 6. Again, we see the familiar pattern in the reaction time data. There was a difference in slope between absent and present trials for convex targets, whereas there was no difference in slope between absent and present trials for the concave targets. This was supported by a three-way interaction between target type, display size, and presence [$F(2,10) = 35.91$, $p < .001$]. A separate analysis of the convex targets showed that the slope for the absent trials was larger than the slope of the present trials; the interaction between display size and presence was significant [$F(2,10) = 29.29$, $p < .001$]. A separate analysis of the concave targets showed no difference between the slopes for present and absent trials [$F(2,10) = 0.05$, n.s.], although the slopes did differ from zero [$F(2,10) = 62.86$, $p < .001$]. Furthermore, the reaction times were slower for the absent trials than for the present trials [$F(1,11) = 10.31$, $p < .01$].

In the accuracy data, there was no effect of target type (all $ps > .05$). The number of errors increased with display size for the present trials, whereas it decreased for the absent trials. This was shown by the significant interaction between display size and presence [$F(2,10) = 11.45$, $p < .003$]. There were somewhat more errors in the target present condition than in the target absent condition [$F(1,11) = 5.97$, $p < .033$].

Discussion

As before, in Experiments 1 and 2A, we find a strong asymmetry. The shape with a circular concavity was perceived effortlessly (6.7 and 6.6 msec/item for present and absent trials, respectively), whereas the shape with the corresponding convexity was not (18.8 msec/item for present trials and 34.0 msec/item for absent trials). The

Figure 8. Experiment 4: Search slopes for the various values of a . The error bars represent standard errors. The slopes for concave targets are indicated by a circle; the slopes for convex targets by a triangle. Filled symbols, present trials; open symbols, absent trials. The slopes for the values of 0.0 and 2.0 stem from Experiments 2A and 3, respectively.

Table 1
Slopes (in Milliseconds/Item) and
Intercepts (in Milliseconds) for Experiment 4

<i>a</i>	Target Type	Target Status	Slope	Intercept
0.5	concave	present	7.0	437.2
		absent	6.8	447.3
	convex	present	22.4	461.1
1.0	concave	absent	36.2	470.8
		present	8.9	442.4
	convex	absent	7.3	473.9
1.5	concave	present	22.2	465.6
		absent	34.3	498.2
	convex	present	7.2	428.1
		absent	6.5	454.5
		present	22.0	441.6
		absent	37.3	467.1

results are similar to the results found in Experiment 2A. Because we removed the cusps of Figures 2A and 2C but kept the concavity, we conclude that the concavity is the effective feature. This means that pop-out is not solely restricted to concave cusps.

The concave cusp we used in Experiment 2A and the circular concavity we used in Experiment 3 are the two extrema of a shape continuum. The results we obtained thus far suggest that any type of concavity will pop out. To explore this possibility more thoroughly, we performed several experiments with concavities that had shapes that lay in between a cusp and a circle. To this end, we parametrized the shape of the concavity with the following equation:

$$f(x) = \sqrt{R^2 + (a-2)xR + (1-a)x^2}.$$

For $a = 0$, this is the equation of a straight line, and for $a = 2$, this is the equation of a circle with radius R . Increasing a from 0 to 2 yields an increasingly more circular concavity. We used three values of a (0.5, 1.0, 1.5) in our next experiment.

EXPERIMENT 4

Method

Participants. Thirty-six participants (26 females and 10 males), undergraduates at the University of Nijmegen, took part in this experiment. All had normal or corrected acuity by self-report. They received either course credit or a small payment for their participation.

Apparatus and Materials. The experiment was in every respect the same as Experiment 1. Three groups of 12 participants were randomly assigned to a condition in which a concave and a convex shape were created with a particular value of a (0.5, 1.0, or 1.5). The radius of the circle on which the concavity was based was identical in all three conditions (0.42°). The shapes had a height of 2.2° and a width of 1.6° (see Figure 7).

Results and Discussion

The results are shown in Figure 8 and Tables 1 and 2. The patterns in reaction times and errors for the three values were virtually identical to the ones obtained in Experiments 2A and 3. In Figure 8, we see that smoothly changing the shape of the concavity from a cusp ($a = 0$) to

a circle ($a = 2$) did not have any marked influence on the search slopes. The slopes for the concave targets remained well below 10 msec/item for both present and absent trials. These results strongly suggest that the shape of the concavity does not matter and that search for any concavity is effortless.

Although any concavity used in our experiments produced pop-out, it is not clear whether the visual system discriminates between different types of concavities in the earliest stages of visual processing. For instance, it is possible that a concave cusp contains a feature that circular concavities lack. We therefore ran a final experiment in which a shape with a circular concavity (Figure 2I) was pitted against a shape with a concave cusp (Figure 2J).

EXPERIMENT 5

Method

Participants. Twelve participants (3 men and 9 women), undergraduates and graduates at the University of Nijmegen, took part in this experiment. All had normal or corrected acuity by self-report. They received either course credit or a small payment for their participation.

Apparatus and Materials. The experiment was in every respect the same as Experiment 1, except for the stimuli. The circular concavity target (Figure 2I) had a height of 2.2° and a width of 1.6° . The concavity consisted of a segment of a circle with a radius of 0.42° . The concave cusp target (Figure 2J) had the same width and height. The concavity of the concave cusp target was a triangle with a base size of 0.76° and a height of 0.38° .

Results

The results are shown in Figure 9. In the reaction time data, we did not see any differences between the target with a circular concavity and the target with a concave cusp. None of the effects involving target types was significant (all $ps > .23$) in a three-way (target type $\times$ display size $\times$ presence) repeated measures MANOVA. There was, however, a difference between present and absent trials. The slopes for the present trials were smaller than the slopes

Table 2
Error Proportions for Experiment 4

<i>a</i>	Target Type	Display Size	Target Present	Target Absent
0.5	concave	1	.039	.018
		6	.019	.008
		12	.024	.003
	convex	1	.028	.025
		6	.030	.002
		12	.065	.005
1.0	concave	1	.017	.013
		6	.017	.010
		12	.018	.010
	convex	1	.025	.023
		6	.034	.013
		12	.059	.016
1.5	concave	1	.022	.022
		6	.040	.008
		12	.041	.007
	convex	1	.025	.035
		6	.044	.017
		12	.073	.012

Figure 9. Experiment 5: Mean reaction times and search slopes (upper panel) and proportion of errors (lower panel). The error bars represent standard errors; the lines represent linear best fits. The results for concave circle targets are indicated by a circle; the results for concave cusp targets by a triangle. Filled symbols, present trials; open symbols, absent trials.

for the absent trials, as was shown by a significant interaction between presence and display size [$F(2,10) = 39.94$, $p < .001$].

In the accuracy data, we also did not find any difference between the targets with the circular concavity and the target with the concave cusp. Again, none of the effects involving target type was significant (all $ps > .06$). There was a very large difference in number of errors between present trials and absent trials for display sizes larger than one. This was supported by the interaction between presence and display size, which was significant [$F(2,10) = 79.62$, $p < .001$].

Discussion

There was no sign of pop-out for either the target with a concave cusp (47.2 and 77.8 msec/item for present and absent trials, respectively) or the target with a circular concavity (52.0 msec/item for present trials and 78.3 msec/item for absent trials). Although search for a target with a concave cusp was somewhat faster, there was no difference between the slopes. Neither was there a difference in the error proportions. The lack of differences indicated

that the concave cusp did not have any distinctive feature that the circular concavity did not have.

So, our experiments yielded indistinguishable results for different kinds of concavities. This suggests that all concavities have the same perceptual function: When they are conspicuous enough, they are all used as part boundaries. The results of Siddiqi et al. (1996) with circular concavities are a case in point. We should, however, distinguish the perceptual function of concavities from the mechanism that mediates the pop-out in the visual search task. In the next section, we will propose a candidate mechanism responsible for pop-out.

GENERAL DISCUSSION

Our results are clear-cut. We found a search asymmetry for concave cusps in both Experiment 1 and Experiment 2A. When the shape with a concave cusp was used as a target and the totally convex shape was used as a distractor, we found pop-out. When the roles were reversed, pop-out did not occur. In Experiment 2A, we showed that the results obtained in Experiment 1 were not sensitive to

manipulations of complexity. According to the complexity metric of Attneave (1957), we halved the complexity of the concave shape by making it perfectly symmetric, and we increased the complexity of the convex shape by increasing its asymmetry. Even so, the results did not change. Search rates remained well below 10 msec/item, and error rates for the largest display sizes became even lower. Any variation in slope or intercept for the concave targets between Experiments 1 and 2A is more parsimoniously explained by speed-accuracy tradeoff than by influences of complexity. Moreover, there was no decrease in the search slope for the convex target shape, despite an increase in its complexity.

It could be argued that a change in search slopes owing to the manipulation of the complexity of the convex and concave shapes was masked by a difference in symmetry. Recent research into the detection of bilateral symmetry by Olivers and van der Helm (1998) makes this possibility rather unlikely, but in the data of Olivers and Van der Helm, there was a trend toward more shallow search slopes when the stimuli became less complex. To be certain, we explicitly tested the usefulness of bilateral symmetry for detection purposes in Experiment 2B. We did not find any sign of pop-out; moreover, error rates were massive when the display sizes were larger than one. This supports the hypothesis that participants are unable to use bilateral symmetry and, therefore, that the bilateral symmetry was not responsible for the pop-out in Experiment 2A.

In Experiments 1 and 2A, we have shown that there is a difference between search for a concave cusp and search for a convex cusp. A target with a concave cusp pops out among distractors with a convex cusp, whereas a target with a convex cusp does not pop out among concave distractors. This implies that the unit of selection in visual search is an object, rather than a location. Only for objects is there a difference between concavities and convexities. Our results are in accord with those of Baylis and Driver (1995), who proposed that every contour is assigned to a single figural region and is subsequently segmented into component parts.

In Experiments 3 and 4, we showed that pop-out is not restricted to concave cusps, but that search for a range of different concavities is very efficient. Moreover, in Experiment 5, we showed that concave cusps do not have any extra distinctive feature. From our results, we conclude, therefore, that concavities can act as basic features in visual search, provided that they are salient enough (Hoffman & Singh, 1997). A lack of salience seems to be the reason that Elder and Zucker (1993) did not find pop-out in their experiment. Our results also suggest that any salient concavity is treated as a part boundary by the visual system.

What is it that constitutes the distinctive feature in a concavity? An interesting proposal has been made by Burbeck and Pizer (1995), who adapted the symmetric axis transform introduced by Blum (1973). They proposed that boundaries of objects are related to each other at a scale determined by an object's width, yielding so-called cores.

The interesting point in their model is that there are two types of cores: cores that lie inside an object and cores that lie outside an object. The second variety is produced only when an object contains a concavity. So, it is possible that participants detect the presence or absence of an external core. Both the lack of difference between the different concavities and the inefficient search for shallow concavities follow from their model. As can be seen from the simulations of Burbeck and Pizer, external cores are formed by every type of concavity, but only when the concavity is conspicuous enough.

According to Burbeck and Pizer (1995), cores that support high-resolution spatial judgments are not formed in parallel across the scene. However, the present task does not seem to require any high-resolution judgment. The mere detection of an external core at a reasonably coarse scale is enough.

The core model has received some support from work by Kovács and Julesz (1994), who found enhanced contrast sensitivity in locations where Burbeck and Pizer (1995) would predict strong cores. The shapes used in the experiment were totally convex, however, and a similar experiment in which shapes containing a concavity are used remains to be performed.

The distinction between concavities and convexities in the earliest stages of visual processing perhaps sheds some light on the discussion of whether there is a topologically based set of form features (Chen, 1982, 1990; Rubin & Kanwisher, 1985). After all, the change in topology of a shape by the introduction of a hole also means the introduction of a concavity.

On the basis of the search asymmetries reported here, we conclude that concavities can act as basic features in visual search. They belong to the category of form features, which, according to Wolfe (1994), are the most problematical and most debated of the basic features. It has been suggested by Enns and Rensink (1991) that preattentive vision is capable of some quite sophisticated processing. Since concavities are not a conjunction of more elementary properties, our results are a case in point.

REFERENCES

- ATTNEAVE, F. (1957). Physical determinants of the judged complexity of shapes. *Journal of Experimental Psychology*, **53**, 221-227.
- BAYLIS, G. C., & DRIVER, J. (1994). Parallel computation of symmetry but not repetition within single visual shapes. *Visual Cognition*, **1**, 377-400.
- BAYLIS, G. C., & DRIVER, J. (1995). Obligatory edge assignment in vision: The role of figure and part segmentation in symmetry detection. *Journal of Experimental Psychology: Human Perception & Performance*, **21**, 1323-1342.
- BIEDERMAN, I. (1987). Recognition-by-components: A theory of human image understanding. *Psychological Review*, **94**, 115-147.
- BLUM, H. (1973). Biological shape and visual science: Pt. 1. *Journal of Theoretical Biology*, **38**, 205-287.
- BRAUNSTEIN, M. L., HOFFMAN, D. D., & SAIDPOUR, A. (1989). Parts of visual objects: An experimental test of the minima rule. *Perception*, **18**, 817-826.
- BROWN, J. M., WEISSTEIN, N., & MAY, J. G. (1992). Visual search for simple volumetric shapes. *Perception & Psychophysics*, **51**, 40-48.
- BURBECK, C. A., & PIZER, S. M. (1995). Object representation by cores:

- Identifying and representing primitive spatial regions. *Vision Research*, **35**, 1917-1930.
- CHEN, L. (1982). Topological structure in visual perception. *Science*, **218**, 699-700.
- CHEN, L. (1990). Holes and wholes: A reply to Rubin and Kanwisher. *Perception & Psychophysics*, **47**, 47-53.
- COOPER, L. A., SCHACTER, D. L., BALLESTEROS, S., & MOORE, C. (1992). Priming and recognition of transformed three-dimensional objects: Effects of size and reflection. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **18**, 43-57.
- DUNCAN, J., & HUMPHREYS, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*, **96**, 433-458.
- DUNCAN, J., & HUMPHREYS, G. W. (1992). Beyond the search surface: Visual search and attentional engagement. *Journal of Experimental Psychology: Human Perception & Performance*, **18**, 578-588.
- ELDER, J., & ZUCKER, S. (1993). The effect of contour closure on the rapid discrimination of two-dimensional shapes. *Vision Research*, **33**, 981-991.
- ENNS, J. T., & RENSINK, R. A. (1991). Preattentive recovery of three-dimensional orientation from line drawings. *Psychological Review*, **98**, 335-351.
- GARNER, W. R. (1970). Good patterns have few alternatives: Information theory's concept of redundancy helps in understanding the Gestalt concept of goodness. *American Scientist*, **58**, 34-42.
- GOLDSMITH, M. (1998). What's in a location? Comparing object-based and space-based models of feature integration in visual search. *Journal of Experimental Psychology: General*, **127**, 189-219.
- HOFFMAN, D. D., & RICHARDS, W. A. (1984). Parts of recognition. *Cognition*, **18**, 65-96.
- HOFFMAN, D. D., & SINGH, M. (1997). Salience of visual parts. *Cognition*, **63**, 29-78.
- HULLEMAN, J., & BOSELIE, F. (1997). Visual attention and objects: New tests of two-object cost. *Psychonomic Bulletin & Review*, **4**, 367-373.
- KOVÁCS, I., & JULESZ, B. (1994). Perceptual sensitivity maps within globally defined visual shapes. *Nature*, **370**, 644-646.
- MARR, D., & NISHIHARA, H. K. (1978). Representation and recognition of the spatial organization of three-dimensional shapes. *Proceedings of the Royal Society of London: Series B*, **200**, 269-294.
- OLIVERS, C. N. L., & VAN DER HELM, P. A. (1998). Symmetry and selective attention: A dissociation between effortless perception and serial search. *Perception & Psychophysics*, **60**, 1101-1116.
- RENSINK, R. A., & ENNS, J. T. (1995). Pre-emption effects in visual search: Evidence for low-level grouping. *Psychological Review*, **102**, 101-130.
- RUBIN, J. M., & KANWISHER, N. (1985). Topological perception: Holes in an experiment. *Perception & Psychophysics*, **37**, 179-180.
- SCHARROO, J., STALMEIER, P. F. M., & BOSELIE, F. (1994). Visual search and segregation as a function of display complexity. *Journal of General Psychology*, **121**, 5-18.
- SIDDIQI, K., TRESNESS, K. J., & KIMIA, B. B. (1996). Parts of visual form: Psychophysical aspects. *Perception*, **25**, 399-424.
- STEVENS, K. A., & BROOKES, A. (1988). The concave cusp as a determinant of figure-ground. *Perception*, **17**, 35-42.
- TREISMAN, A., & GELADE, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, **12**, 97-136.
- TREISMAN, A., & SOUTHER, J. (1985). Search asymmetry: A diagnostic for preattentive processing of separable features. *Journal of Experimental Psychology: General*, **114**, 285-310.
- WINSTON, P. H. (1975). Learning structural descriptions from examples. In P. H. Winston (Ed.), *The psychology of computer vision* (pp. 157-209). New York: McGraw-Hill.
- WOLFE, J. M. (1994). Guided Search 2.0: A revised model of visual search. *Psychonomic Bulletin & Review*, **1**, 202-238.
- WOLFE, J. M. (1998). What can 1 million trials tell us about visual search? *Psychological Science*, **9**, 33-39.
- WOLFE, J. M., & BENNETT, S. C. (1997). Preattentive object files: Shapeless bundles of basic features. *Vision Research*, **37**, 25-43.
- WOLFE, J. M., FRIEDMAN-HILL, S. R., & BILSKY, A. B. (1994). Parallel processing of part-whole information in visual search tasks. *Perception & Psychophysics*, **55**, 537-550.

NOTE

1. Care must be taken in deciding whether a search qualifies as a feature search. In a recent meta-analysis of the results of the many visual search experiments performed in his laboratory, Wolfe (1998) concluded that an average slope of less than 10 msec/item is not enough to distinguish feature search. According to him, a more elaborate criterion is needed. Wolfe proposed a combined criterion for feature search: shallow slopes for both target-present and target-absent trials and a ratio between target-absent and target-present slopes of significantly less than 2.0.

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