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Detection of change in shape: an advantage for concavities

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Abstract

Shape representation was studied using a change detection task. Observers viewed two individual shapes in succession, either identical or one a slightly altered version of the other, and reported whether they detected a change. We found a dramatic advantage for *concave* compared to *convex* changes of equal magnitude. Observers were more accurate when a concavity along the contour was introduced, or removed, compared to a convexity. This result sheds light on the underlying representation of visual shape, and in particular the central role played by part-boundaries. Moreover, this finding shows how change detection methodology can serve as a useful tool in studying the specific form of visual representations.

Keywords: Change detection; Shape; Part-boundaries; Convexity; Concavity

1. Introduction

The representation of shape remains one of the most difficult puzzles in visual cognition. One obstacle to progress has been a lack of good experimental methods for evaluating shape representations. In this paper, we introduce a method for analyzing visual shape representation that is based on a change detection task. In our task, observers view two sequentially presented shapes that are either identical or slightly different and attempt to determine whether they are the same or not, or in other words, to determine whether there has been a *change* to the stimulus. While change detection is of course not new, past

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studies have focused largely on the architectural limitations – such as constraints of memory, attention, etc. – that influence detectability of change in complex displays. By contrast, in our study we are interested in *comparing* sensitivities to different *types* of changes taking place along the contour of a single, simple shape. In the spirit of Marr (1982), we assume that visual representations make explicit particular aspects of the structure of the scene while discarding others or leaving them implicit. Thus, we predict that observers will be preferentially sensitive to changes in those aspects that the visual system represents explicitly, and relatively insensitive to those that it does not. By this argument, detectability differences among types of shape change would shed light on the underlying representation of shape.

A number of important elements of shape representation have been identified. The magnitude of curvature along a contour has long been understood to be an important psychological dimension (Attneave, 1954), with an especially significant role played by curvature *extrema* (points where curvature, or the degree of "bending", is locally maximal). More recently the distinction between concave and convex bending (called negative and positive curvature, respectively) has been found to be psychologically important, with maximally concave extrema (technically called negative minima of curvature) serving as candidate *part-boundaries* (Hoffman & Richards, 1984; Koenderink, 1984; see also Barenholtz & Feldman, in press; Hoffman & Singh, 1997). These findings mirror regularities in the visual world, where concave contour segments often correspond to loci where one part of an object ends and another begins: for example, at the intersection of a tabletop with one of its legs.

Can the representational asymmetry between convexity and concavity be manifested in change detection? If it is indeed the case that concavities have a special status in the representation of visual shape, then we might expect that human observers will be more sensitive to changes that occur along concave segments of a shape than changes that occur along convex segments. Our experiment aims to test this hypothesis by presenting observers with convex and concave changes that are of equal magnitude. A differential sensitivity to one type of change over the other will thus point to a difference in the underlying representation.

The change detection methodology was first introduced by Phillips and Singer (Phillips, 1974; Phillips & Singer, 1973) to investigate the difference between low-level transient detection and visual short-term memory. In those studies, observers were shown two displays in succession with a variable inter-stimulus interval, and asked to indicate whether a change had taken place. More recently this paradigm has received a great deal of attention because of the finding that even gross changes in the scene (e.g. the addition or subtraction of an entire background object) can be extremely difficult to detect (sometimes called "change blindness"; Rensink, O'Regan, & Clark, 1997; Simons & Levin, 1997), especially if their location was not previously attended (Scholl, 2000), or foveated (Henderson & Hollingworth, 1999). These findings have caused some controversy, in part because they have sometimes been accompanied by strong claims about the degree to which the visual system maintains any representation of the scene (see for example Ballard, Hayhoe, Pook, & Rao, 1997). Our aim in the current study was not to engage these larger issues concerning the extent of processing and the limits of mental representation, but rather to use similar methodology to assess the actual content of representations. As

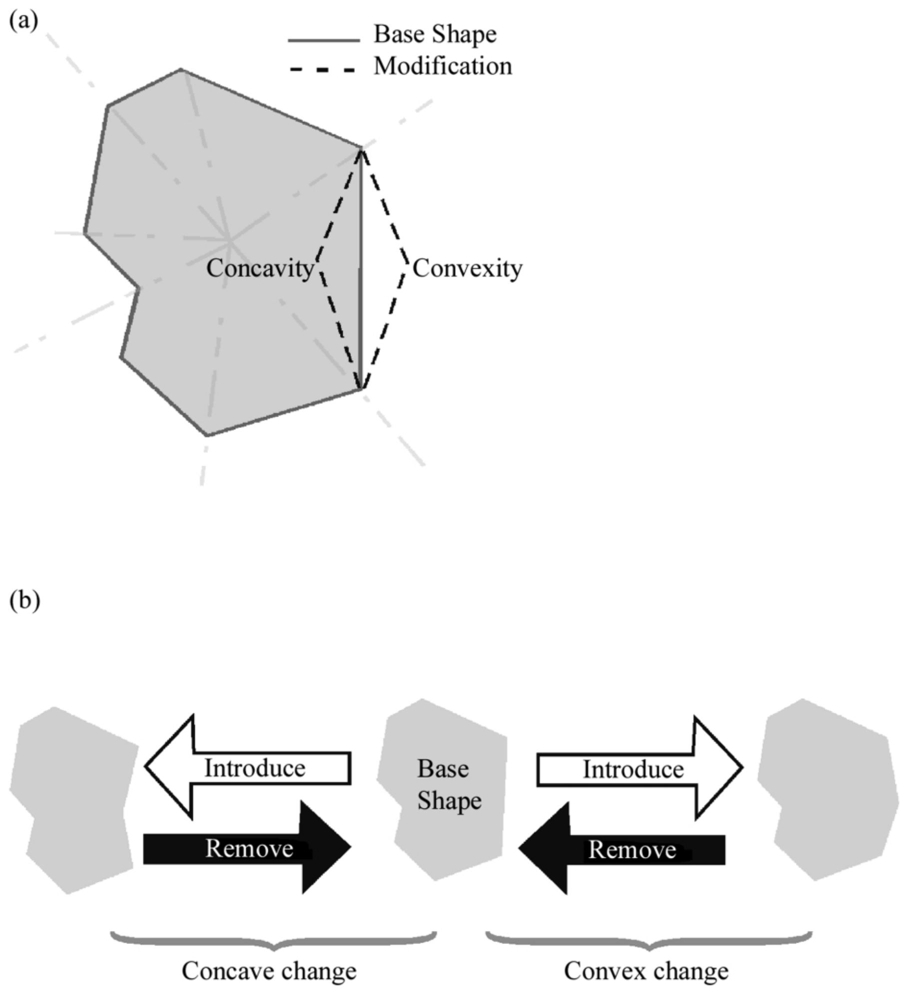

Fig. 1. (a) Polygon pairs used in the experiment consisted of a ‘Base’ shape and a modified version of this shape with either an additional concavity or convexity. (b) The four (2×2) types of changes that appeared in the experiment with the arrow directions signifying sequence order: in the “Introduce” case the base shape was presented first, followed by the modified shape, while in the “Remove” case this order was reversed.

discussed above, the presence of ‘change blindness’ has generally been found to occur within complex displays containing multiple objects. The observed deficits in these studies are generally described as a failure to process unattended regions or objects within the display. By contrast, our study, using displays that are limited to a single attended shape, is concerned not with the overall efficiency of change detection but rather with *comparative* sensitivities to different *types* of changes. If observers are systematically more sensitive to changes affecting one dimension of shape as compared to another – regardless of where within the shape they take place – we may infer that that dimension is more explicitly represented in the visual system. Differential sensitivity implies differential representation.

2. Experiment

Each of our stimuli consisted of a single unfamiliar "nonsense" polygon, generated randomly under certain constraints (see methods below). An alternate version of this basic shape was created by either *adding* (introducing) or *subtracting* (removing) a single vertex from the base shape, in such a way that the new vertex either lay inside or outside the original shape yielding, respectively, either a concave indentation or a convex protrusion (see Fig. 1). This yielded a 2×2 factorial design of change *direction* (introduce or remove) by change *type* (concave or convex). (For examples of the displays, see http://ruccs.rutgers.edu/~elanbz/changedemos.htm.) On change trials (50% of trials), these two shapes were then shown in succession, with a brief mask intervening; on no-change trials, shapes shown on successive screens were identical. The observer's forced-choice task was to indicate "change" or "no-change". In contrast to most studies in the change detection literature, we report observers' performance in terms of absolute sensitivity (d'), so that we may distinguish between true differences in sensitivity and shifts in the criterion for responding "change". This also allows us to clearly identify conditions of absolute "change blindness" ($d' = 0$).

2.1. Method

2.1.1. Observers

Eleven Rutgers undergraduates served as naive observers for course credit.

2.1.2. Stimuli

Stimuli were computer-generated filled polygons (of randomly assigned color) measuring approximately 2.4–4.8 degrees in both height and width. The polygons were generated as triads consisting of a "base" shape and two "changed" versions of that shape: one with an additional concavity and one with an additional convexity (see Fig. 1a). The base shape was generated by choosing between nine and 12 points, each lying at a random location along successive (clockwise) radial axes, projecting from the center of the screen, and joined by line segments. As each successive point was chosen it was checked to determine whether it resulted in a convex or concave vertex; if the vertex resulted in a concavity, it was discarded and a new point was chosen. Once this convex shape was complete, between zero and two concavities were added (procedure described below). An equal number of zero-, one-, and two-concavity shapes were included in the set of base shapes.

The two "changed" versions were each generated by modifying the base shape in one of two ways: by introducing an additional concavity or by introducing an additional convexity. The procedure for introducing both concavities and convexities was to randomly choose an edge of the base shape, translate its midpoint perpendicularly to the edge (towards the center for the concave version, and away for the convex version), and join this new vertex to its neighboring points with two new line segments (see Fig. 1b). The size of the concavity/convexity (measured as the distance of translation of the point) was randomly varied between five and 30 pixels on each trial. Translations of the changed

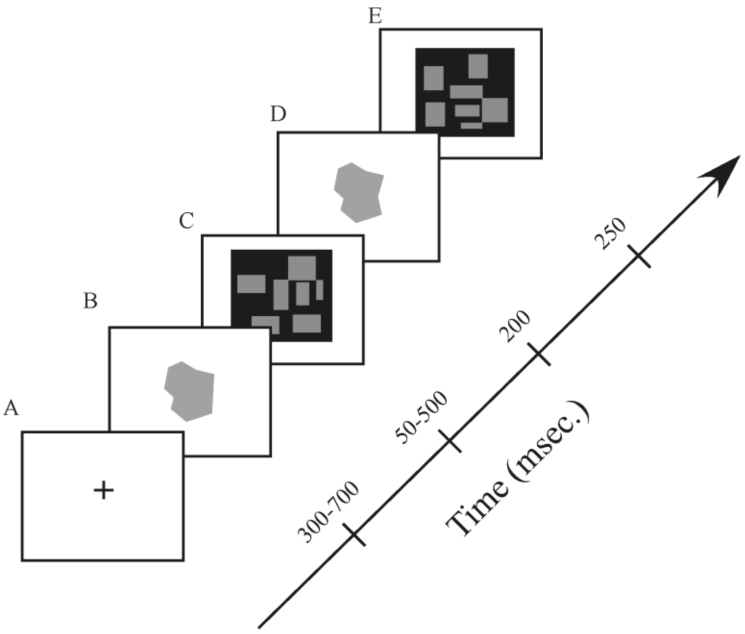

Fig. 2. Schematic diagram of the experimental sequence: (A) fixation point; (B) first shape stimulus; (C) mask; (D) second shape stimulus; (E) mask.

vertices measured between 0.06 and 0.37 degrees from the original edge. A new set of polygons was generated for each observer.

2.1.3. Procedure

The task was two-way, forced choice. On each trial, the observer was presented with the following sequence (Fig. 2): (1) a fixation cross presented for a variable duration between 300 and 700 ms; (2) the first shape stimulus for 250 ms; (3) a mask for 200 ms; (4) the second shape stimulus for 250 ms; and (5) the mask until response. There were two independent variables in the Change trials: Change *Type* (Concave/Convex), and Change *Direction* (Introduce/Remove). On the "No-Change" trials (half), the base shape was simply displayed twice. In the change trials, there were four possible types of "Change" (see Fig. 1b). In the "Introduce" cases, the base shape was shown first, followed by the "changed" shape (either concave or convex); this order was reversed for the "Remove" cases. The observer responded using the keypad, with feedback provided by a beep on incorrect responses.

2.1.4. Design

Each experimental block contained 96 trials (48 change, 48 no-change). This quantity allowed for the crossing of the two experimental variables (2×2) for change trials as well as balancing for both number of concavities and sides in the base shape for both change and no-change trials. Each observer ran eight blocks for a total of 768 trials.

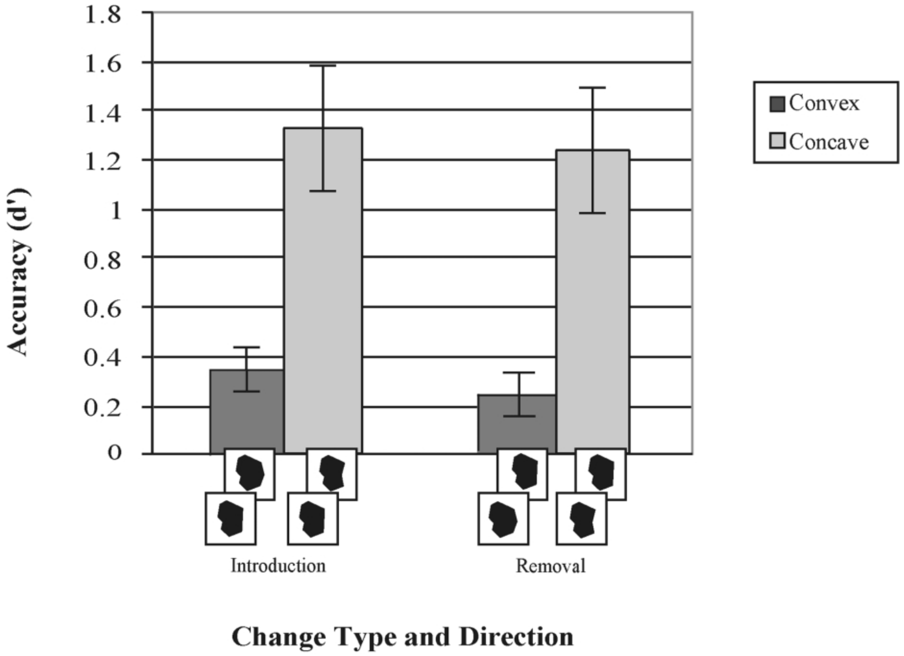

Fig. 3. Mean performance (d') as a function of change type (convex vs. concave) and change direction (introduction vs. removal).

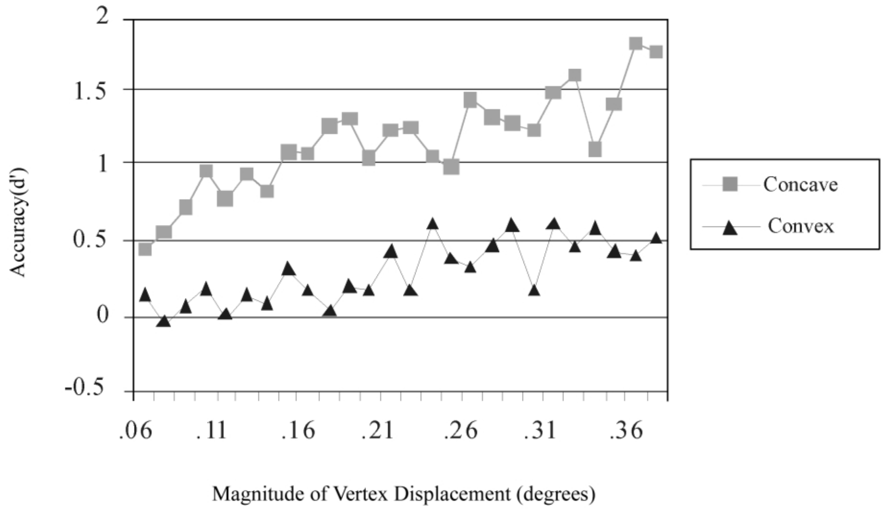

Fig. 4. Mean performance as a function of the magnitude of change. The *x*-axis corresponds to the average distance, in degrees visual angle, towards (concave changes) or away from (convex changes) the interior of the shape.

3. Results

Accuracy was much better for concave (mean = 70.83%, SE = 4.0%) than convex (mean = 36.94%, SE = 4.0%) changes. Fig. 3 shows mean performance converted to d' as a function of change type (convex vs. concave) and change direction (introduction vs. removal). d' performance (convex mean = 0.2960, SE = 0.089; concave mean = 1.2815, SE = 0.229) was subjected to an analysis of variance. The difference between concave and convex change was highly significant ($F(1, 10) = 40.34$, $P < 0.0001$). There was no significant effect of change direction (introduction vs. removal), and no significant interaction ($P > 0.25$ in both cases).

Fig. 4 shows accuracy as a function of the magnitude of change (i.e. the distance from the base shape to the new vertex in the changed shape). As one would expect, observers' ability to detect changes increased with magnitude. However, a substantial advantage for concave changes is evident at *all* magnitudes. This is especially important because concave changes are generally towards the center of the shape (and thus closer to fixation), which might be expected to lead to a detectability advantage. But as is clear from Fig. 4, even at small magnitudes – where the difference in eccentricity is negligible – there is still a large detectability advantage for concave over convex changes, demonstrating that the concavity effect cannot be attributed to eccentricity differences alone.

4. Discussion

These results provide strong evidence for the differential representation of concavities and convexities by the visual system. The advantage for detecting concavities compared to convexities was found whether the concavity/convexity was introduced or removed, and was stable across all the levels of magnitude – including the smallest levels, where subjects were essentially "blind" ($d' = 0$) to convex, but not concave, changes. The current findings are consistent with results in the domain of visual search (Hullman, te Winkel, & Boselie, 2000; Wolfe & Bennett, 1997) in which concavities have been found to behave as "basic features" (shapes with concavities "pop out" in a field of convex shapes but not vice-versa). Our results similarly point to the importance of concavities in visual shape representation.

There are at least two types of hypotheses that might account for the asymmetry between concavities and convexities, which can be termed "localist" and "globalist". The localist hypothesis is that concave sections of contour are inherently more salient, irrespective of the eventual role they play in shape decomposition. High-curvature segments of a curve literally carry more information than low-curvature sections (Attneave, 1954; Resnikoff, 1985), and concave segments more than convex ones (Feldman & Singh, 2003). The differential sensitivity observed here might stem directly from this informational asymmetry. Alternatively, given that global organization sometimes takes precedence (Palmer, 1977; Pomerantz, Sager, & Stoever, 1977), another possibility is that concave regions are especially detectable because – and only insofar as – they influence the global decomposition of the shape into parts. Introducing or removing a concavity often changes the number of perceived parts – a part either splits into two, or two parts coalesce into one – whereas introducing or removing a convexity leaves the number of perceived parts unchanged, influencing only the shape of an existing part. It may be that observers are only sensitive to changes in this overall organization per se (Bertamini, 2001; Keane, Hayward, & Burke, 2003), and not to changes in local contour regions. One intriguing variant of this account is that subjects might be preattentively determining the number of parts in the shape – i.e. subitizing them (cf. Trick & Pylyshyn, 1994; van Oeffelen & Vos, 1982) – and are especially sensitive to changes in this number. In any case, many questions remain to be resolved regarding the mechanisms by which contour structure influences the global part interpretation (see Siddiqi & Kimia, 1995; Siddiqi, Tresness, & Kimia, 1996; Singh & Hoffman, 2001; Singh, Seyranian, & Hoffman, 1999). Distinguishing between the localist and globalist accounts of our result is a piece in the larger puzzle of shape representation.

5. Conclusion

In a change detection task, observers exhibited far greater sensitivity to changes affecting concavities than changes affecting convexities. This large sensitivity difference suggests that concave and convex sections of a contour have extremely different perceptual representations, notwithstanding their very similar geometries. These results are also of great methodological interest: the change detection task employed here provides a potentially powerful tool for isolating representational differences, which may be readily extended to study many other aspects of visual representation.

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