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Visual comparisons within and between object parts: evidence for a single-part superiority effect

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Abstract

Subjects judged whether two marks placed at different positions along a curved contour were physically the same. When targets were separated by a concave curvature extremum—corresponding to a part-boundary—decision latencies were longer than when they straddled an equally curved convex extremum, demonstrating a "single-part superiority effect". This difference increased with both stimulus duration and the magnitude of contour curvature. However, it disappeared when the global configuration was not consistent with a part-boundary interpretation, suggesting a critical role of global organization in part decomposition.

Keywords: Shape; Curvature; Psychophysics

1. Introduction

Many theories of shape representation in the human visual system assume that shapes are divided into perceptual *parts* or units. The influential recognition theories of Marr and Nishihara (1978) and Biederman (1987) suggest that viewed shapes are indexed to a stored database via their constituent parts and the spatial relations among them. More recent research on figure-ground assignment, symmetry detection (Baylis & Driver, 1995), category learning (Goldstone, 2000; Schyns & Rodet, 1998) and the perception of transparency (Singh & Hoffman, 1998) has also implicitly or explicitly assumed a division of shapes into distinct parts.

What rules or mechanisms determine the division of shapes into parts? An influential suggestion was that of Hoffman and Richards (1984), who proposed that the visual system parses object contours at extrema of concave curvature, an idea they referred to as the *minima rule* (Fig. 1). It can be shown that curvature minima occur generically when convex shapes intersect (Bennett & Hoffman, 1987), and indeed such points often correspond to subjective part boundaries. A more subtle demonstration in support of the minima rule (also suggested by Hoffman & Richards, 1984) is what happens when the figural assignment of the contour changes (i.e. the interior and exterior of the shape exchange roles). In this case, the sign of curvature along the boundary reverses, turning concave extrema into convex extrema and vice versa; and indeed the perceptual assignment of parts completely changes, exactly as would be predicted by the minima rule.

Such intuitive demonstrations have been augmented in recent years by more rigorous investigations of part interpretation. Hoffman and Singh (1997) showed that the "salience" of an inferred shape part (that is, the strength of the percept that it is a distinct part) depends on the relative size of the part, on the degree to which it protrudes into the background, and on the depth of the concavities at its boundaries (as measured for example by contour curvature or by turning angle). Singh, Seyranian, and Hoffman (1999) argued that the visual system tends to create parts by linking up part boundaries that are as close as possible (the *short-cut rule*). Siddiqi, Tresness, and Kimia (1996) suggested that the *global* configuration in which contour segments are embedded can influence the resulting part decomposition. They proposed several standard patterns in which part arrangements can occur, such as *necks* (two convex regions connected by a narrow band) and *limbs* (narrow protrusions emanating from a larger convex body).

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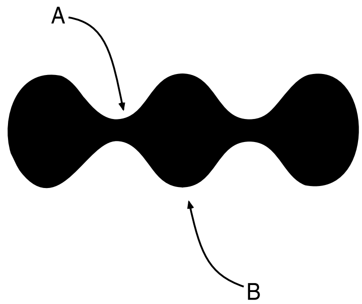

Fig. 1. The Minima Rule states that extrema of *negative* curvature (A) are interpreted as part boundaries, effectively dividing the shape into two separate parts. However, *positive* extrema of the same curvature (B) are *not* interpreted as part boundaries.

Most studies examining these issues have used somewhat subjective measures (e.g., asking subjects to manually pick out an object's parts). It would be desirable to augment these studies using methods that are less susceptible to subjective decision criteria and conscious reasoning. One of our primary goals in the current research is to investigate several of the above proposals using more "objective" methodology. An intriguing new source of evidence about part decompositions has recently been suggested by Watson and Kramer (1999): the use of effects associated with "object-based attention." This phrase actually denotes a constellation of effects (see Baylis & Driver, 1993 and Scholl, Pylyshyn, & Feldman, 2001 for recent reviews and discussion) involving how attentional selection is constrained and influenced by the perceived spatial organization of an image.

A very influential finding in this connection was that of Duncan (1984), who asked subjects to report two properties of a display, either both contained within a single phenomenal "object" or located on distinct objects. Subjects were faster and more accurate in the single object condition, a result usually referred to as a *single object superiority effect*. A common way of describing this result in the attentional literature is that attention moves more easily *within* than *between* objects, thus facilitating the comparison of the two locations within a single object. [1] Behrmann, Zemel, and Mozer (1998) drew a similar conclusion, based on a task in which subjects were asked to compare two small features and respond "same" or "different." Again, subjects responded more rapidly when the two features were located on the same perceptual unit or object (even despite an intervening occluding object), while the inter-target distance was held constant. Again the conclusion is that some process of scanning or comparison (possibly involving the movement of a "window of attention") is sensitive to the perceptual organization of the image into objects or units.

Drawing on these and other, similar findings, Watson and Kramer (1999) tested for a delay in moving attention between distinct *parts* within a single object Their experiments used wrench-shaped objects, in which two approximately convex regions were connected by a narrow band (roughly similar to the "peanut" in Fig. 1). Their subjects were asked to report two properties of the wrenches, either at two ends of the same wrench or on two distinct wrenches. They then found the usual object-based attention pattern: faster responses in the same-object than different-object condition. Critically, however, the extent of this effect was dependent on the level of curvature of the parsing point between the two target regions; that is, as the two ends of the wrench became more perceptually distinct as separate parts, they were treated more like distinct objects and the same-object advantage was diminished. Watson and Kramer inferred that attentional movement is constrained by part boundaries as well as by object boundaries; just as comparisons are slowed by the need to cross between objects, they are slowed somewhat, albeit less, by the need to cross between perceptually distinct parts. Similarly, Vecera, Behrmann, and McGoldrick (2000) and Vecera, Behrmann, and Filapek (2001) showed subjects multi-part figures and found that cued judgments were more accurate when they concerned two parts of the object then a single part.

However, these conclusions are weakened by what we see as an important confounding factor. In both of the above studies, every judgment that involved a comparison between distinct parts also involved a comparison along a contour with high *curvature*. It is extremely plausible that contour curvature itself inhibits or slows the movement of attention (or, if one prefers to describe this in non-attentional terms, inhibits the execution of the perceptual comparison). However, according to the minima rule, not every contour segment with high curvature, and not every curvature extremum, is perceived as a part boundary; only *concave* curvature extrema (that is, negative minima of curvature) are so treated. Convex extrema, bearing precisely the same local contour geometry, except for the sign of curvature, would normally only be perceived as exterior boundary points within an object part.

[1] For clarity of discussion in the current paper we will occasionally refer to "moving attention" around the image, but the reader should keep in mind that we do not depend on this as a literal model of the mechanisms underlying our experimental task. It suffices to note that some authors (e.g., Sperling & Weichselgartner, 1995) dispute the claim that attention actually "moves" in the linear fashion the word implies. However our employment of object-based attentional effects in what follows does not depend on whether attention can be spatially localized, or indeed whether any of these effects actually involve attention at all. Rather, as will be clear below, our methodology only depends on the idea that certain kinds of spatially remote comparisons are hindered by perceptually constructed divisions—in our case, part boundaries.

Hence a definitive test for the existence of a deficit for perceptual judgments that cross part boundaries requires a comparison between contour segments of identical local geometry—in particular, identical magnitude of curvature—but opposite sign of curvature. Any slowing effect common to both cases might be due to the presence of contour curvature itself, independent of the part decomposition. However, a *differential* deficit of the concave compared to convex cases can be unequivocally attributed to the presence of a part boundary. (It is worth remarking at this point that an effect of curvature regardless of sign on perceptual judgments, while not constituting evidence for a part-boundary effect, would still be an important, and as far as we know novel, finding in the context of understanding the representation of contours.)

2. Experiment 1

The primary purpose of Exp. 1 is to determine whether there is a measurable cost, analogous to the same-object/different-object difference described above, when a judgment must be made about two regions of a shape separated by a negative minimum of curvature along the contour. Each of our displays contain both negative minima and positive maxima of curvature (that is, both convex and concave extrema) that are identical in terms of local geometry (they are actually the peaks and troughs of a sinusoidal contour; see Fig. 2).

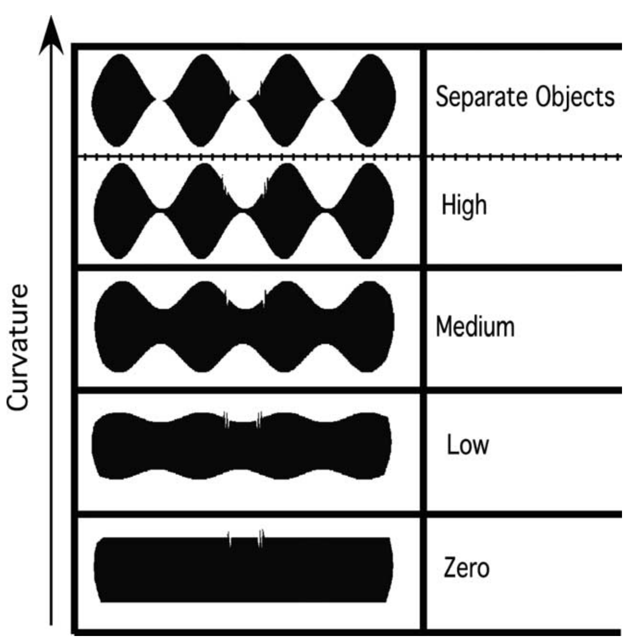

Fig. 2. Example of stimuli used in Exp. 1. There were four levels of curvature—obtained by varying the amplitude of the sine-waves forming the contours of each shape—and a fifth 'separate' condition.

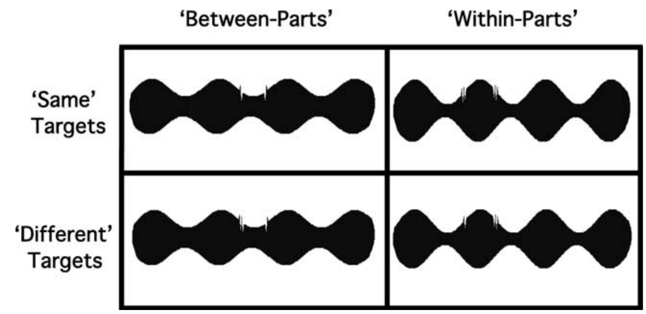

Fig. 3. Examples of different target-types and locations. 'Same' targets had an equal numbers of spikes while 'different' targets did not. Targets could be separated by a concavity ('between-parts') or a convexity ('within-part').

We use a variant of the simple probe comparison task used by Behrmann et al. (1998), which we refer to as the *distant comparison task*. Subjects are asked to compare two small marks along the contour, separated by curvature extremum, indicating whether the two marks were the same or different (marks were either singly or doubly peaked; see Fig. 3). The principal experimental manipulation was the sign of curvature at the intervening extremum. Consistent with the minima rule, only the negative extrema, i.e. concavities, ought to be interpreted as part boundaries. Hence an increase in response latency on the negative (concave) as compared to positive (convex) trials would (a) corroborate the role of the minima rule in determining perceived part boundaries and (b) establish the influence of part boundaries per se (as opposed to simply curved contour segments) on perceptual comparisons along the boundary of a shape.

In addition, we also varied the magnitude of curvature at the extremum, independent of its sign. The purpose of this manipulation was two-fold. First, we wanted to know whether the curvature confound we suspected was real; that is, whether contour curvature in and of itself could slow perceptual comparisons of points along the contour. Second, manipulating the curvature of the putative part boundary allowed us to test Hoffman and Singh's (1997) claim that the magnitude of curvature influences the salience of the resulting part boundary. If this assertion is correct, more acutely curved minima ought to produce a larger slowdown in subjects' execution of the same/different task than less curved minima. Hence we included five levels of curvature, ranging from zero curvature (straight) to extremely bowed (see Fig. 2). We also included a completely separated objects case where the band between the two "parts" was deleted (so as to produce two completely distinct bounded objects; Fig. 2) as a way of estimating the full single-object superiority effect in our task for comparison with the hypothetical "single-part superiority effect." To avoid terminological confusion, note that what we describe as "high" curvature cases have high *absolute value* of curvature, which will mean positive maxima in the convex cases and negative minima in the concave cases, in conventional terminology.

Finally, we also included three levels of inter-target distance between the two marks, as a "sanity check" to ensure that our task actually showed evidence of requiring scanning. Our expectation was that response time would increase in proportion to scanning distance, but that on top of this there would be an additional slowdown for comparisons between parts as compared to within a part.

2.1. Method

2.1.1. Subjects

Twenty four naïve subjects with normal or corrected to normal vision participated in Exp. 1. Subjects were undergraduates from an introductory psychology class and received credit in return for their participation.

2.1.2. Procedure

In each trial, a fixation cross appeared with its midpoint at the center of the screen. Subjects were instructed to keep their eyes focused on the position where the fixation point had been even after it was replaced by a stimulus shape. After an interval of 50 ms the fixation cross was replaced by a stimulus shape. The stimulus shape remained on the screen until the observer had responded by depressing a key on the keyboard, after which it was replaced by a fixation cross to begin the next trial.

The subject was asked to judge whether the two marks on the contour were the same or different (see Fig. 3 for examples), and respond by pressing a key on the computer keyboard. The computer produced a loud tone on incorrect responses. The computer recorded the response and response time (RT) for each trial. Subjects used a chin rest that kept their heads fixed at 46 cm viewing distance.

2.1.3. Stimuli

Stimulus shapes were constructed from sinusoidal contours joined with their mirror images (see Fig. 2) via a short span of curved contour at each end. This resulted in a "peanut"-shaped object with four distinct lobes (except at extreme levels of curvature; see below). As discussed above, the resulting shape has convex curvature extrema and concave extrema with identical local geometry but opposite signs of curvature. The amplitude of the sinusoid was varied in order to control the magnitude of curvature at the extrema. There were five levels of curvature, including: a zero curvature case, which had straight sides and thus no perceived parts; three levels of non-zero curvature: low, medium, and high; and the completely-separate object case mentioned above (created by simply deleting the narrow connecting band from the highest curvature case). [2] Note that for simplicity of presentation we treat the separate-objects condition as a level of the curvature variable even though curvature is undefined in this case because the contour is discontinuous.

The target marks appeared equidistant from one of two possible curvature extrema on the shape, one on either side. On half the trials this was a convex extremum and on the other half it was a concave extremum; we will usually refer to these conditions as "*within-parts*" and "*between-parts*" respectively. There were two levels of overall scale, with the large shapes subtending about 16 deg of visual angle at 46 cm viewing distance, and the smaller about 10 deg. Each shape was presented at a random orientation in the plane, centered at the location where the fixation point had previously appeared. Distance between the two targets was one of three fixed distances: short, medium, or long (substending, respectively, 1.6, 2.1 and 2.6 deg for the large scale and 1, 1.3 and 1.6 deg for the smaller scale). These distances insured that both of the targets were within foveal view and contained within a single "lobe" of the shape on each trial (see Fig. 3). Half of the trials were "same" trials and half were "different."

2.1.4. Design

The five factors (within/between parts [i.e. convex/concave], magnitude of curvature, inter-target distance, scale, and same/different) were fully crossed to yield 120 ($= 2 \times 5 \times 3 \times 2 \times 2$) trials per block in random order. Each subject ran 12 blocks for a total of 1440 trials per subject.

2.1.5. Analysis

The first block for each subject was discarded as practice, leaving 1320 per observer for analysis. RT's more than two standard deviations above the mean, calculated separately for each subject, were discarded. Moreover data from subjects performing at less than 90% accuracy were discarded. One such subject was excluded from the dataset in this experiment leaving 23 subjects.

2.2. Results

No interaction was found between scale and any of the other factors. Therefore all following analyses reflects data collapsed over the two levels of scale.

Fig. 4a shows the mean RT's for each of the three levels of inter-target distance for within-part and be-

[2] Note that for the sake of simplicity we treat stimuli of different scale but similar global geometry as having equivalent levels of "curvature" even though, strictly, the smaller stimuli have greater values of curvature (i.e. the inverse of the radius of the inscribed circle) at each level.

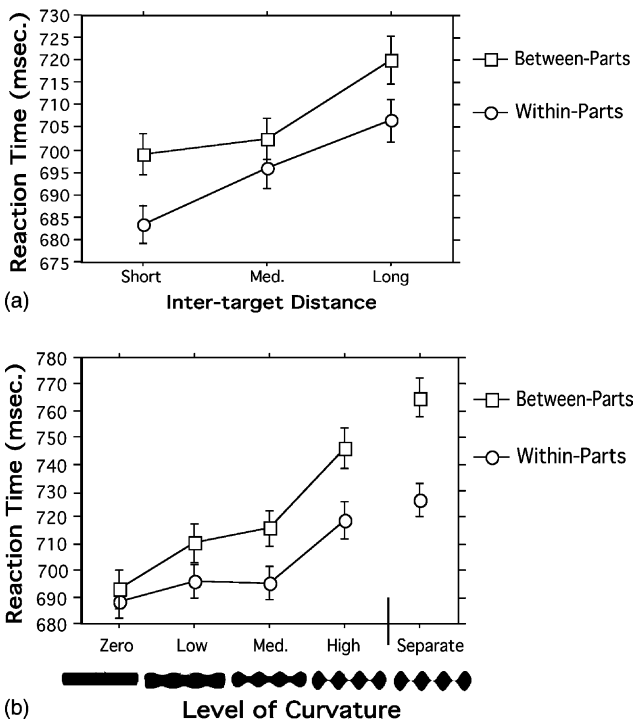

Fig. 4. (a) Mean reaction times (RT's) for the three levels of target distance in Exp. 1. (b) Mean reaction times for the five curvature conditions in Exp. 1. Error bars indicate standard error of the mean (s.e.).

tween-part conditions. As predicted, RT's rose monotonically with inter-target distance ($F(2,21) = 22.072$, $p < 0.0001$) in both the within-parts and between-parts conditions. Critically, within-part judgments were faster than between-part judgments at all levels of inter-target distance (with the "separate" and zero-curvature trials removed), $F(1,22) = 10.86$, $p < 0.01$, establishing the basic "single-part superiority effect."

Fig. 4b shows the effect of contour curvature on the within parts/between parts effect. As curvature increases, the differential between within and between cases increases. In the zero curvature case, where there are no phenomenal parts, as one would expect, there is no difference between the "within" and "between" cases ($t(22) < 1$). An analysis of variance found a significant interaction between the level of curvature and whether the targets were within or between parts ($F(4,19) = 3.19$, $p < 0.013$). As curvature increases, the effect generally grows, corroborating the prediction of Hoffman and Singh (1997) that part salience increases with the depth of the concavity at the boundary. The largest within-between effect is seen in the completely separate objects case, which provides a useful comparison for putting the parts effect into quantitative perspective: the single-part superiority effect is generally smaller in magnitude than the conventional single-object superiority effect, but only slightly so when the parts are highly salient.

As can be seen in Fig. 4b, there was a pronounced effect of curvature on response time: perceptual comparisons were significantly slowed by contour curvature ($F(4,19) = 54.46$, $p < 0.0001$) collapsing over whether the scanning was within or across a part. The curvature effect was significant even with the within-part cases taken alone and with the separate-object case removed ($F(3,20) = 13.52$, $p < 0.0001$). Hence our concern that curvature constitutes a confounding factor when searching for a parts-based deficit was well-founded; some scanning slowdown can be expected based entirely on the contour curvature even when no part boundaries are present.

2.3. Discussion

The main result of this study is to establish the existence of a single-part superiority effect, unconfounded by contour curvature: perceptual comparisons are expedited when they fall within a single perceptual part, and retarded when they must cross a part boundary. Comparisons of points along a contour are generally slowed if the intervening contour is curved, but the effect is differentially increased when the curvature is concave compared to when it is convex. As discussed above, one can interpret this result as meaning that the movement of attention is slowed by presence of part boundaries, although our methodology does not speak to the question of whether attentional selection or some other mechanism is responsible. Regardless of the processes involved in executing the perceptual comparison in our task, the main point is that the comparison is slowed by part boundaries.

Because the slowdown observed in our paradigm is tied specifically to curvature extrema of negative sign, our results may also be interpreted as direct evidence for Hoffman and Richards' (1984) minima rule itself. As discussed above, there are many convincing demonstrations of the minima rule, and much evidence derived from "instant psychophysics" and subjective tasks, but relatively little objective evidence not mediated by conscious phenomenology or verbal report. Because our task does not depend in any way on conscious classification by the subject of parts or part boundaries, but rather on latency to execute an objective comparison under speeded conditions, this experiment provides perhaps the cleanest evidence to date for the minima rule, and for the psychological reality of part boundaries themselves.

The results of Exp. 1 also address a more specific issue concerning the computation of part boundaries: they corroborate Hoffman and Singh's (1997) prediction that deeper curvature minima give rise to more salient parts. However it is unclear from our results whether part salience derives from the degree of curvature at the part boundary or from the degree of protrusion of the part into the surrounding space. The sinusoidal construction of our shape boundaries meant that more sharply curved cusps (minima) were always accompanied by parts that protruded more into the background space, another factor proposed by Hoffman and Singh (1997). Hence from our data it is impossible to say which of these two factors cited by Hoffman and Singh (1997) is primarily responsible for the effect. One conclusion we can draw from our data, however, is that part-boundaries are not an "all-or-none" phenomenon: as the curvature (or degree of protuberance) of a part boundary increased, the resulting inhibition of perceptual comparisons crossing it increased fairly smoothly.

Finally, the data from Exp. 1 suggest that perceptual comparisons are impeded not only by intervening part boundaries but also by contour curvature *regardless of sign*. This effect, above and beyond its role as a potential confound in the investigation of part-boundary effects, might prove independently important. First, it provides hard "objective" evidence of the psychological importance of contour curvature, as famously postulated by Attneave (1954). Second, it suggests a potential psychophysical tool for investigating the representation of contours and shape boundaries; this possibility will be discussed in greater detail below.

Upon review, several concerns were raised that might cast doubt on our interpretation of Exp. 1. First, although observers were instructed not to move their eyes while the stimulus was on the screen, the presence of the stimulus until response certainly allowed enough time for a saccade to take place. One reviewer also pointed out a difference between the within-parts and between-parts cases that is confounded with sign of curvature in our stimuli: in the within-parts condition the intervening space between the two targets was black while in the between parts case it was white, a 'low-level' contrast difference that might affect performance. Note however, that the observed increase of the differential with curvature is not explained by this account. We conducted a follow-up experiment to investigate these issues.

3. Experiment 1b

In order to determine whether the differential we observed between the within- and between-parts case was strictly due to a perceptual partitioning of the shape, we performed a control experiment using both black *and* white versions of the sinusoidal shapes used in Exp. 1, on a constant gray background. If the differential effect observed in Exp. 1 was due to a contrast difference between the within- and between-parts cases, then we should expect an *opposite* effect when the polarity is reversed. The presence of an advantage for within-parts comparisons—regardless of polarity—would thus be unambiguously attributable to a partitioning of the shape. In addition, we limited presentation of the stimuli to 200 ms, presumably too brief for eye movements to be initiated.

3.1. Method

3.1.1. Subjects

Twenty new naïve subjects participated in Exp. 1b. Subjects were undergraduates from an introductory psychology class and received credit in return for their participation.

3.1.2. Procedure

The procedure and instructions were identical to Exp. 1 with the exception that, rather then remaining on-screen until the subject responded, the stimulus shape was always presented for a fixed interval of 200 ms, after which it was replaced by a mask. Subjects could only respond once the mask was in place. The mask remained in place until the subject responded, after which a fixation cross would appear to start the next trial.

3.1.3. Stimuli

Stimuli were identical to those used in Exp. 1 with the following exceptions: we included both black and white versions of the sinusoidal shapes; furthermore, the background color of the screen, which had been white in Exp. 1, was set at a gray-level luminance approximately half-way between black and white.

3.1.4. Design

Because scale was not found to be a significant factor in Exp. 1, only one level of scale (the 'large' case) was used, which, after the addition of the new factor of black or white shapes, left five total factors. These were crossed, resulting in a total of 120 trials in each block. Each subject ran 12 blocks for a total of 1440 trials.

3.1.5. Analysis

The first block for each subject was discarded as practice, leaving 1320 trials for analysis. Treatment of outliers and poorly performing subjects was identical to Exp. 1. No subjects performed below the 90% criterion for inclusion.

3.2. Results and discussion

Fig. 5a and b shows the mean RT's for the within- and between-parts cases, as a function of curvature, for the white shape and black shape cases respectively while Fig. 5c shows the results for the two polarity conditions combined. There was a significant effect for within/between-parts for both the white shapes ($F(1,19) = 15.55$, $p < 0.001$) and the black shapes ($F(1,19) = 8.40$, $p < 0.01$), with an advantage for the within-parts comparisons. As discussed above, if the effect of Exp. 1 were

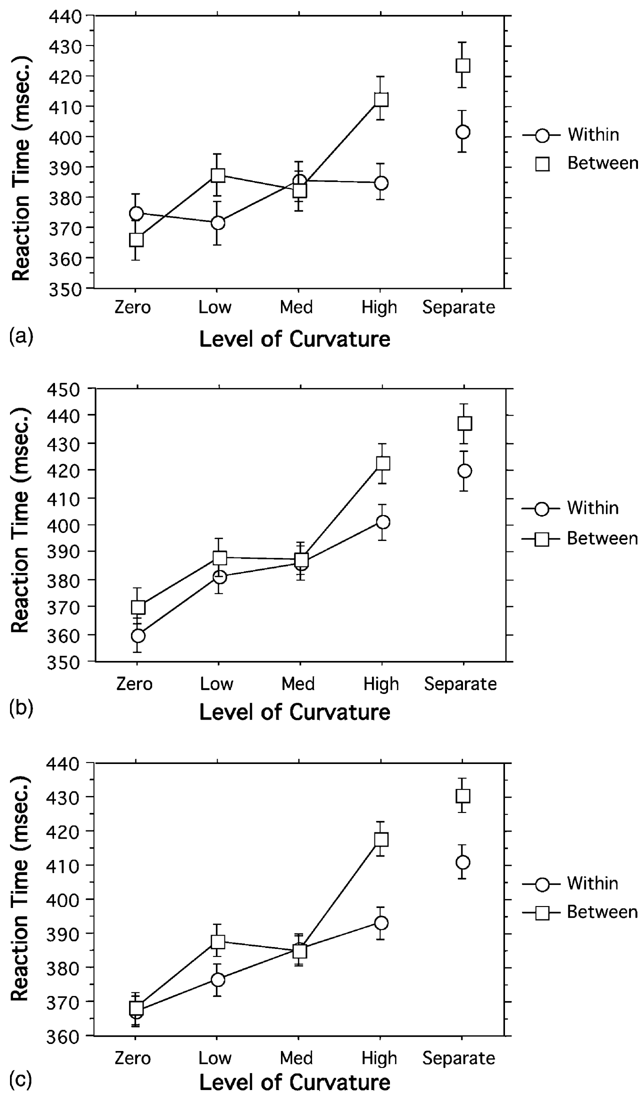

Fig. 5. (a) Mean reaction times (RT's) for the five levels of curvature for the black condition in Exp. 1b. (b) Mean reaction times for the five levels of curvature in the white condition in Exp. 1b. (c) Mean reaction times for the five levels of curvature for the black and white conditions combined. Error bars indicate standard error of the mean (s.e.).

due to a low-level contrast difference between the within and between-parts conditions, then we would actually have expected an *opposite* effect—an advantage for the between-parts condition—when polarity is reversed. Thus we can safely rule out this possibility.

A closer inspection of Fig. 5c ('black' and 'white' combined) shows that the within/between effect we found in Exp. 1 was replicated for the briefer viewing times used in this experiment at the 'low' and 'high' curvature levels (low: $t(19) = 2.592$, $p < 0.02$; high: $t(19) = 2.272$, $p < 0.04$). However, somewhat surprisingly, no effect is present at the 'Medium' curvature level ($p > 0.9$). There are several possible explanations for what seems to be a somewhat diminished effect in this experiment as compared with Exp. 1. It is known that perceptual organization requires some time to be fully completed (e.g., see Reynolds, 1978; Sekuler & Palmer, 1992). Hence, the brief viewing times used here may not have allowed sufficient time for the shape and/or part interpretation to fully develop. Alternatively, despite instructions not to saccade, it could be that the longer viewing times allowed for some unexplained role of eye movements in producing the larger effect in Exp. 1. However, it is unclear exactly how eye movements would relate to part boundaries, or whether they might be sensitive to the sign of curvature. Finally, this difference may simply reflect the inherent variability of this response measure. Overall we believe that, while some role for eye movements cannot be ruled out in Exp. 1, the presence of a concavity effect—albeit diminished—when viewing times were brief, supports the conclusion that performance was influenced by the presence of part boundaries.

4. Experiment 2

The main result of Exps. 1 and 1b were that latency to execute perceptual comparisons depends in part on whether intervening curvature extrema are convex or concave. This classification depends in turn on the figural assignment in the shape—the interpretation of one side of the contour as "figure" and the other side as "ground." The pure curvature effect, on the other hand, depends only the local geometry of the curve, and ought to be independent of figural assignment. Hence a simple check on our interpretation of these data is to run a condition in which no figural assignment is possible. In such a case the distinction between concave and convex extrema disappears, and so we would expect the single part superiority effect to disappear, leaving only the pure curvature effect.

Hence in Exp. 2 we replicated the manipulations of Exp. 1, but drew the figures with only the top half of the sinusoidal contour (omitting the mirror-image completion), drawn as a black contour on a white background (Fig. 6); we refer to this as the *contour-only* condition. The perceptual comparisons were exactly as in Exp. 1, except here, because there is no figure and no ground, there is no meaningful distinction between convex and concave extrema (nor between positive and negative curvature). For clarity of exposition, and to highlight the comparison with Exp. 1, we will continue to describe as "concave" (or "convex") those extrema that *would* have been concave (or convex) had the contour been completed, i.e. as they were in Exp. 1. Likewise we will also use the terms "within-part" and "between-parts" to denote judgments crossing convex or concave extrema respectively. However it should be kept in mind that these terms no longer have their usual meanings in Exp. 2, and that because concavity and convexity are no

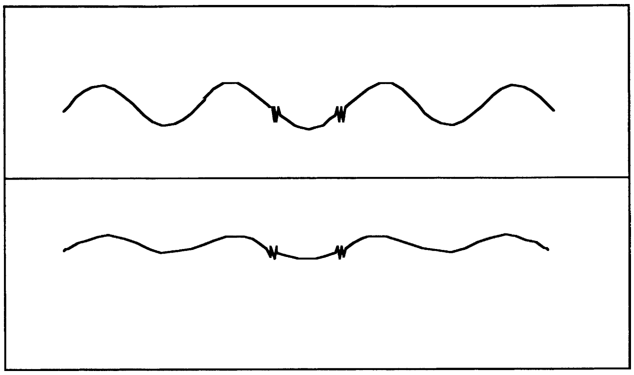

Fig. 6. Example of stimuli used in Exp. 2 consisting of a single sinusoidal contour of varying curvature.

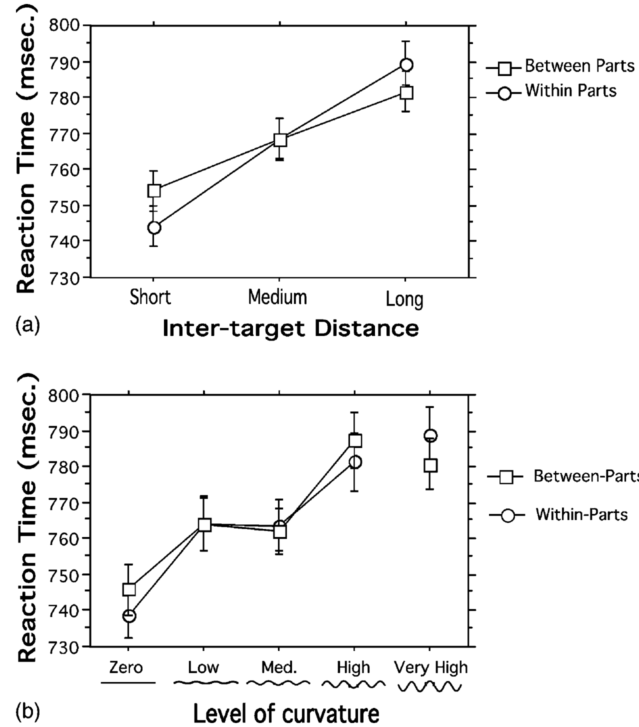

Fig. 7. (a) Mean reaction times (RT's) for the three levels of target distance in Exp. 2. (b) Mean reaction times for the four curvature conditions in Exp. 2. Error bars indicate standard error of the mean (s.e.).

longer well-defined, we predict *no* effect of "within-" vs. "between-" parts.

4.1. Method

4.1.1. Subjects

Seventeen new naïve subjects participated in Exp. 2. Subjects were undergraduates from an introductory psychology class and received credit in return for their participation.

4.1.2. Procedure

The procedure and instructions were identical to Exp. 1.

4.1.3. Stimuli

Stimulus contours were constructed exactly as in Exp. 1, except using only what would have been the top contour of the shapes used there, drawn only as a black contour on white background. Examples are shown in Fig. 6. Again notice that in these stimuli contour segments differing in the direction of curvature, which in Exp. 1 would have been perceived as convex or concave, here appear simply as curving one way or the other without any definite figural polarity.

As in Exp. 1, three levels of inter-target distance and five levels of curvature (with the "separate" case replaced by a "very-high" curvature condition) were used. Half of the target comparisons crossed a "concave" boundary while the other half crossed a "convex" boundary.

4.1.4. Design

The design was as in Exp. 1, with all five factors crossed resulting in a total of 120 trials in each block. Each subject ran 12 blocks for a total of 1440 trials.

4.1.5. Analysis

The first block for each subject was discarded as practice, leaving 1320 trials for analysis. Treatment of outliers and poorly performing subjects was identical to Exp. 1. No subjects performed below the 90% criterion for inclusion.

4.2. Results

Fig. 7a shows mean RT's for each of the three inter-target distances in within-part and between-part conditions. An ANOVA reveals a significant effect of inter-target distance ($F(2,15) = 10.78$, $p < 0.0001$), but no effect of within/between parts ($F(1,16) < 1$). The effect of curvature (Fig. 7b) was significant ($F(4,13) = 11.745$, $p < 0.0001$), and was of slightly larger magnitude then in Exp. 1.

4.3. Discussion

As predicted, when figural assignment is undetermined, concavity/convexity is meaningless, part boundaries are impossible to identify, and the single part superiority effect disappears. The complete disappearance of the within/between effect in Exp. 2 also corroborates our attribution of the corresponding effect in Exp. 1 to the presence of part boundaries per se, as opposed to some artifact of the stimulus geometry, because the target locations were identical in the two experiments.

By contrast, even when there is no figural assignment, the slowing effect due purely to curvature (regardless of sign) persists. This corroborates our claim above that the curvature effect is not due entirely to concave cases, i.e. to part boundaries. Rather, even in the absence of figural assignment, contour curvature impedes perceptual judgments, and in fact does so to a degree proportional to the magnitude of curvature. This claim is further corroborated by a linear regression of RT on curvature, which is highly significant ($F(1, 17770) = 44.18$, $p < 0.0001$).

5. Experiment 3

As discussed above, some debate has centered on whether the interpretation of part boundaries depends only on local aspects of the contour geometry, or whether global factors also play a role. The minima rule is local in nature; it invokes only information available within a neighborhood near a given point—namely, nearby variations in curvature, and the local figural polarity. But global information may be necessary to determine how part boundaries are linked up to form complete object parts, e.g., Singh et al.'s (1999) short-cut and local symmetry rules.

More subtly, Siddiqi et al. (1996) (see also Siddiqi & Kimia, 1995) have also suggested that global factors influence whether a given curvature minimum will be perceived as a part boundary in the first place. They suggest that in certain configurations, even perfectly well-defined curvature minima may *not* appear subjectively to be part boundaries, because the global shape does not support a division of the shape into parts. A good example are the "snakes" in Fig. 8 in which the curvature minima seem to part of a globally bending object lacking parts. This situation represents a critical challenge to our understanding of the mechanisms underlying part computations: is a curvature minimum embedded in such a configuration perceived as a part boundary or not? This question tests whether part interpretation is a purely local process, or whether, conversely, global factors exert a decisive influence. This is especially crucial in our "objective" task, which presumably reflects the earliest and most bottom-up part boundary assignment in the system, rather than later conscious reflection on the part of the subject, which might be more prone to reflect aspects of the complete "gestalt." If global factors are decisive in the determination of part boundaries in our task, then they probably are decisive in general.

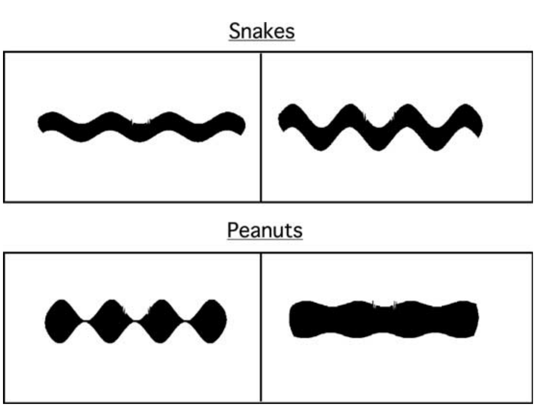

Fig. 8. Example of stimuli used in Exp. 3. 'Snake' shapes consisted of identically oriented contours while 'peanut' shapes (identical to those used in Exp. 1) consisted of mirrored contours.

Hence the main purpose of Exp. 3 is to investigate whether curvature minima embedded in Siddiqi et al.'s "snake" configuration function like part boundaries in the distant-comparison task—that is, delay execution of the comparison. To accomplish this, we again use the same sinusoidal contours as in Exps. 1 and 2, but this time complete them either mirror symmetrically (the "peanut" configuration, identical to Exp. 1) or with a parallel sinusoid (the "snake" configuration, Fig. 8). In the peanut condition we expect a part-superiority effect (as we found in Exp. 1), meaning slower responses when the same/different judgment crosses a concave extremum than when it crosses a convex extremum. Precisely the same concave and convex extrema are present in the snake condition, and (unlike in the contour-only condition of Exp. 2) are perfectly well-defined as convex and concave (given the presumed assignment of the interior as "figure"). However, in this condition the global configuration does not (according to Siddiqi et al.) support an interpretation of the curvature minima as part boundaries. Hence the question is: will the single-part superiority effect disappear in the snake condition?

5.1. Method

5.1.1. Subjects

Twenty-five new naïve subjects participated in Exp. 3. Subjects were undergraduates from an introductory psychology class and received credit in return for their participation.

5.1.2. Procedure

The procedure was identical to Exp. 1.

5.1.3. Stimuli

Stimulus shapes were constructed in two ways. In the peanut condition, shapes were exactly as in Exp. 1. In the snake condition, the upper sinusoidal contour was completed with an identical (parallel, not mirror reflected) boundary below, joined at the ends with a short curved segment (Fig. 8). As before, three levels of intertarget distance and five levels of curvature were used. Half of the target comparisons crossed a concave boundary while the other half crossed a convex boundary.

5.1.4. Design

The five factors (snake/peanut, within/between parts [i.e. convex/concave], curvature, inter-target distance, scale, same/different) were all crossed. This resulted in 240 ($= 2 \times 2 \times 5 \times 3 \times 2 \times 2 \times 2$) trials per block. Each subject ran six blocks for a total of 1440 trials.

5.1.5. Analysis

The first block for each subject was discarded as practice, leaving 1200 trials for analysis. Treatment of outliers and poorly performing subjects was identical to Exps. 1 and 2. In Exp. 3, two subjects were omitted because of performance below 90% criterion.

5.2. Results

As in Exps. 1 and 2, responses were slower at longer distances ($F(2,21) = 26.20$, $p < 0.001$). Also as in Exps. 1 and 2, responses generally slowed with increasing curvature ($F(4,19) = 55.53$, $p < 0.0001$).

The main comparison in this experiment is between the peanut case and the snake case. As before, the most vivid way to see the single part superiority effect is by plotting response times in concave and convex conditions as a function of curvature. Fig. 9 shows these curves separately for the peanut case (a) and the snake case (b). As can be seen in the figure, the peanut case essentially replicates the results of Exp. 1, with a generally increasing convex/concave (i.e. within/between parts) differential as curvature increases. A two-way analysis of variance found a significant effect for both curvature ($F(4,19) = 41.58$, $p < 0.0001$) and within/between parts ($F(1,22) = 12.75$, $p < 0.001$). A separate analysis of variance including only the data from the three intermediate curvature conditions yielded a significant effect for within/between-parts ($F(1,22) = 4.89$, $p < 0.03$). In the snake case, however, while there was a significant effect for curvature ($F(4,19) = 15.58$, $p < 0.0001$), there was *no* significant differential between the convex and concave response times, i.e. within vs. between parts ($F(1,22) < 1$).

5.3. Discussion

The main result of Exp. 3 is that the single part superiority effect, evident in the peanut case (and in Exp. 1), disappears in the snake configuration. That is, concavities in and of themselves do not inhibit perceptual comparisons that cross them (compared to convexities); they only do so if they are interpreted as part boundaries, and they are not interpreted as part boundaries in the snake configuration.

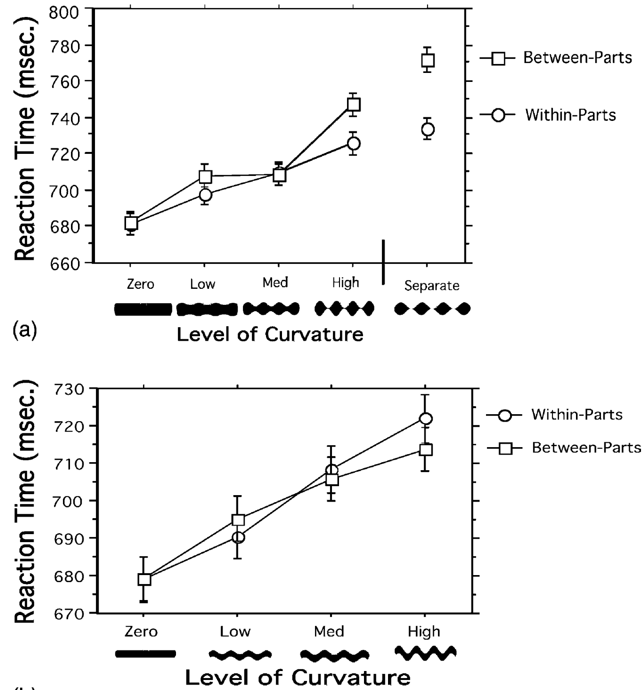

Fig. 9. (a) Mean reaction times (RT's) for the four levels of curvature for the 'peanut' condition in Exp. 3. (b) Mean reaction times for the four levels of curvature in the 'snake' condition in Exp. 3. Error bars indicate standard error of the mean (s.e.).

Putting this another way, consistent with Siddiqi et al.'s (1996) argument, concave curvature extrema are not interpreted as part boundaries when the global configuration suggests an alternative non-part-based interpretation for the concavity, such as a global bending operation. Thus the minima rule is not the sole contributor to the determination of part boundaries. Rather, it seems to be only the local front-end to a more complex global computation.

It should be clear however that our result does not reveal much about the details of the global factors that contribute to the ultimate determination of part boundaries. It may be, as Siddiqi et al. argue, that the "snake" is not interpreted as having parts because its pattern of concavities does not fit into a standard part-based pattern (see their "shape triangle", two corners of which are "parts", essentially our peanut case, and "bends", essentially our snake). Alternatively, consistent with Singh et al. (1999), it may be that the snake case is not interpreted as having salient parts because local symmetry and the short cut rule generate part cuts that produce a weak part interpretation. Finally, some completely novel mechanism might be involved. The main point here is that out data demonstrate that part boundary determination does not end with the local analysis of the contour.

6. General discussion

The major results of the experiments reported in this paper include:

(i) Perceptual comparisons were faster crossing curvature maxima (convexities) than minima (concavities), i.e. faster within perceived parts than across part boundaries (the single-part superiority effect). This difference grew more pronounced with the magnitude of curvature. The effect of concavity was retained, albeit to a diminished degree, when viewing times were limited to 200 ms. These results, using objective methodology, corroborate Hoffman and Richards' minima rule and demonstrate that part boundaries are a real and perceptually significant component of the mental representation of shape. These findings are consistent with earlier investigations by Watson and Kramer (1999) and Vecera et al. (2000, 2001) who found a psychophysical deficit due to the presence of extrema of curvature. However, to our knowledge our study is the first to report a deficit specific for *negative* minima, as compared to positive maxima of equal magnitude, an effect that is uniquely attributable to part-boundaries (i.e. disambiguated from the role of general curvature). This effect might have been diminished at briefer viewing times.

(ii) Perceptual comparisons were slowed by contour curvature regardless of the sign of curvature, above and beyond the part boundary effect. The degree of slowing was approximately proportional to curvature at eachfixed scale. This result helps confirm the fundamental importance of contour curvature in shape representation.

(iii) The slowing effect of curvature minima disappeared when the curvature minimum was embedded in a global configuration that inhibited a part-boundary interpretation, such as Siddiqi et al.'s (1996) snake. This finding suggests that global factors can be decisive in the determination of part boundaries.

Thus contour curvature seems to play a central role in shape representation, and extrema of negative curvature a particularly special role. The snake case, however, suggests that the full system whereby negative extrema and other contour points are pieced together to form a full-fledged part interpretation is more complex and remains largely to be explored. It may be that curvature minima, as determined in parallel by local operators (Dobbins, Zucker, & Cynader, 1987, 1989) are fed as candidate part boundaries into some later more global system. The final determination of part boundaries would then be made by some more complex global mechanism not yet fully understood.

While some may find it useful to couch the current findings of these experiments in attentional terms, it should be stressed that the validity of these results is not dependent on this particular interpretation. Rather, we simply conclude that there is a psychophysical deficit when visual comparisons must cross a part-boundary, as defined by some set of local and global criteria. We also note that this deficit is neatly analogous to that found when judgments concern two distinct objects rather then a single object, i.e. the basic single-object superiority effect.

7. Conclusion

The importance of our findings lie in the intriguing, albeit complex, picture of perceptual organization they suggest. Much discussion of grouping and perceptual organization in the literature assumes a division of the visual field into complete and unitary objects. Our findings, by contrast, suggests that perceptual segregation is more continuous, involving degrees of grouping and binding both within and between whole objects (cf. Feldman, 1999). The full organization of the visual field is thus probably hierarchical and complex, with visual elements aggregated together to various degrees and in various ways depending on the spatial relations among them. A fuller understanding of this system remains elusive.

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