

Rapid Integration of Contour Fragments: From Simple Filling-in to Parts-based Shape Description

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Line drawings are easy to recognize, although the only information to the visual system is the contour itself. Starting from information theory and a theory of decomposition in parts, we investigated whether certain regions of such a contour are perceptually more relevant than others, using a deletion detection paradigm. In this paradigm, high detectability means poor contour integration, and vice versa. Regions of interest were curvature singularities, namely positive maxima (M+), negative minima (m-) and inflection points (I), of smooth, closed contours. In Experiment 1, we performed a first exploration of the detectability of deletions around these three types of curvature singularities. M+ deletions were easier to detect than the deletions around the other two singularities, a result that is explained using a post hoc combination of both mentioned theoretical frameworks. In Experiment 2, we replicated these findings using figure-background reversal, so that the same physical deletions could either be M+ or m-. Again, the M+ deletions were easier to detect than m- deletions. Although both types of singularities involve regions of high curvature changes, they differ in that m- deletions create gaps that concur with spontaneous segmentation.

Line drawings of objects are easy to recognize. This demonstrates how much information is carried at the visible contours of objects when we perceive them in real-world circumstances. The importance of visual contours is also supported by the fact that neurons in the primary visual cortex respond to contours as such, regardless of whether they are defined by a contrast in texture, colour, or motion; they even respond strongly to illusory contours (Peterhans & von der Heydt, 1991).

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Some regions of an object's visible contour may be more important than others, in the sense that they are important for the construction of a representation of the shape, or for the perception of the contour as a single unitary object. Contour deletion is an interesting paradigm to study whether some regions are perceptually more relevant than others and it has been used in a variety of theoretical contexts in recent research (see Boucart, 1996, for a more extensive review). For example, Biederman (1987) and Biederman and Cooper (1991) have used different types of contour deletion to build a case for the role of a specific type of intermediate-level representations for object recognition, which rely on certain regularities in the image called "non-accidental properties" to derive volumetric primitives called "geons". Boucart, Delord, and Giersch (1994) have used fragmented forms to study the role of organizational principles such as collinearity and proximity in form perception, whereas Boucart, Grainger, and Ferrand (1995) have introduced specific types of deletions to test the importance of three-dimensional features for object recognition. Snodgrass and colleagues (e.g. Snodgrass & Corwin, 1988; Snodgrass & Feenan, 1990; Snodgrass & Hirshman, 1994) have created fragmented variants of their famous set of line drawings (Snodgrass & Vanderwart, 1980) to use picture fragment completion as an indirect or implicit memory test.

Deletion introduces gaps and thus destroys the closeness of the contour. In the more extreme cases, when the deletions are made sufficiently large, they may result in the perception of few isolated line fragments instead of a single unitary object. In more moderate cases, however, the visual system is able to integrate the several pieces of contour into a single unit. Given enough processing time, the observer perceives an object with some gaps in it. Thus, integration can occur at different levels in the visual system, ranging from the level of early visual processing where simple perceptual filling-in may be supported by the functional architecture of primary visual cortex to the higher-level of shape perception where different parts are integrated into the structural representation of the whole object. In this special issue on perceptual integration, we do not have to expand on these different kinds of integration. For the role of stimulus-specific synchronization of oscillatory neuronal responses in spatial feature binding, we are happy to refer the reader to Eckhorn's (this issue) review elsewhere in this issue. For some issues surrounding the function and construction of structural descriptions, we are equally happy to refer to Sanocki's paper (this issue).

In this paper, we investigate the role of several curvature singularities in both these simple and complex aspects of shape perception. We asked human observers to detect deletions or gaps in very briefly presented shapes. The rationale of this deletion detection task is the following. When certain deletions are easily spotted, the region that was deleted is more important for the perception of that shape than those regions whose deletion is not easily detected. When a certain deletion is not readily perceived, one could argue that integration has

happened seamlessly, whereas detectable gaps could be the result of a more difficult integration. In other words, we study integration of different types of contour fragments indirectly by testing the detectability of different types of contour deletion.

The present study is part of a more elaborate research interest in special points of curvature. In previous, unpublished studies (Lamote, Wagemans, & d'Ydewalle, 1995), we have used rather complex tasks such as mental rotation and reflection detection, which made the task of attributing the results to certain types of processing difficult because a wide variety of conscious and unconscious processes is involved in them. The advantage of the present task of contour deletion detection is its simplicity and its ability to tap into the early stages of form perception. In subsequent research, we can then extend our investigation of the role of curvature singularities towards more natural stimuli such as line drawings of everyday objects and more natural tasks such as picture identification (see Wagemans, Notebaert, & Boucart, 1998, for a first attempt in that direction).

Before discussing the perceptual role of different curvature singularities, we define curvature. Intuitively, curvature is an easy concept to grasp. A straight line has no curvature (i.e. curvature is zero in each point), whereas a circle has constant curvature. Curvature reflects the change of direction of the tangent line in each point. In the case of a straight line, the tangent lines in the successive points have the same direction. Hence, curvature is zero, because there is no change in direction. In a circle, the change of direction of the tangent line from point to point is fixed, resulting in a constant curvature in every point. Since we are dealing with closed contours or figures, it is easier to parameterize a curve using some path length variable t . The curve is then expressed as:

$$C = \{x(t), y(t)\}$$

and curvature is defined as:

$$\kappa = \frac{\ddot{x}\dot{y} - \dot{x}\ddot{y}}{\sqrt{(\dot{x}^2 + \dot{y}^2)^3}}$$

The sign of curvature is determined by the direction in which the curve is traversed. By convention, the contour is traced in such way that the inside of the figure is on the left. This way, outward-pointing pieces of the figure will have positive curvature, whereas inward-pointing pieces will have negative curvature. Several special points can be distinguished on a curve on the basis of their curvature. Points where curvature reaches a local positive maximum are called positive maxima (M+), whereas points where curvature reaches a local negative minimum are called negative minima (m-). Where the curvature changes sign, inflection points are located (I). Curvature goes through zero at these points. Together, these special points are known as curvature singularities.

Attneave (1954) was among the first to point out the special role of curvature singularities for shape perception. Working from information theory (Shannon & Weaver, 1949), he argued that what is available in the visual field is often redundant. Information is not uniformly distributed but concentrated in places where changes in certain variables occur. For example, the contour of an object is informative, since it is the place where intensity, texture, and/or colour change abruptly. However, not all points on a contour are equally important. The points where curvature changes most, the so-called extrema (M+ and m-) are more informative than others (as later formalized by Resnikoff, 1985).

Attneave illustrated the relevance of curvature singularities by a few informal demonstrations. In one demonstration, subjects chose extrema when they were asked to summarize a closed, smooth contour with a limited number of points. Another demonstration has become known as "Attneave's cat". Starting from a line drawing of a sleeping cat, the extrema were extracted and connected with straight lines. The drawing was still clearly recognizable (but see Biederman, 1988; Lowe, 1985).

Since Attneave's seminal work, more formal, computational theories have been proposed in which curvature singularities play an important role. A well-known example is Hoffman and Richards' (1984) codon theory of object representation. According to this theory, the human visual system recognizes objects using a decomposition-into-parts strategy. This partitioning is done on the basis of the object's contour, more specifically, at pairs of negative minima (or deep concavities). This rule is called the minima rule of segmentation and has been corroborated empirically (e.g. Braunstein, Hoffman, & Saidpour, 1989; Waeytens, Hanouille, Wagemans, & d'Ydewalle, 1994). The resulting parts are then described on the basis of the curvature singularities. Six primitive contour parts, or codons, are distinguished and all planar shapes with smoothly curved, closed contours are represented as a sequence of such codons.

The computational scheme behind this codon theory extracts curvature singularities by tracing a contour and then representing shape by an economical sequential (i.e. one-dimensional) description. Although recent empirical work by Jolicoeur and his colleagues has demonstrated that human perceivers are capable of such a curve tracing operation (Jolicoeur & Ingleton, 1991; Jolicoeur, Ullman, & MacKay, 1986, 1991), we doubt that a one-dimensional contour description is sufficient to capture human representation of two-dimensional shapes (see Wagemans, Hanouille, Waeytens, & d'Ydewalle, 1994). However, for the purpose of this paper, the role of curvature singularities can be studied without assuming that they are stored in one-dimensional shape descriptions.

Curvature singularities play other roles in still other theories, both in human and computer vision (see, for example Leyton, 1988, 1989, for the role of extrema in inferring the casual history of shape; Moons, Pauwels, Van Gool, & Oosterlinck, 1995 and Pauwels, Moons, Van Gool, Kempnaers, & Oosterlinck, 1995, for the role of inflections in semi-differential invariants for

recognition; and Ullman, 1989, for the role of curvature singularities as alignment keys). A discussion of these is beyond the scope of the present paper.

So far, we have two general theoretical frameworks that allow us to derive predictions about performance in our deletion detection task. According to information theory, both types of extrema ($M+$ and $m-$) are equally important because they are both equally informative. Hence, deletions at $M+$ and $m-$ regions should be equally detectable. According to decomposition theory, $m-$ deletions should be hardest to detect because they reinforce spontaneous shape decomposition. Experiment 1 was designed to explore contour deletion detection in the light of these theories.

EXPERIMENT 1

Methods

Subjects. Eight advanced undergraduate or graduate students at the University of Leuven volunteered to participate in the experiment. All of them had previous experience with psychophysical studies, but none of them was aware of the purpose and hypotheses of the present experiment. Their eye-sight was normal or corrected-to-normal.

Apparatus. The experiment was run on an IBM-compatible machine equipped with a graphics card able to generate images of 800×600 pixels at a vertical refresh rate of 120Hz. Stimuli were presented on a 21-inch Philips monitor as white images on a black background. The room was dimly lit. Stimuli subtended about 5° horizontally as well as vertically. Subjects gave their response using a two-button response box. Half of the subjects used their dominant hand for the positive (deletion) response; the other half used their non-dominant hand.

Stimuli. Stimuli consisted of closed, smoothly curved contours, made by a spline-fitting program. This program is able to fit a spline through a series of user-defined points (which we shall call "knots"), using the method outlined by Akima (1970). The initial placing of the knots is done by mouse, as is their optional repositioning. Each time the knots are moved, the spline is updated, allowing the experimenter to create forms in an interactive way. Also, curvature is calculated and curvature singularities can be displayed on the form. The more knots that are used, the more complex one can make a form. Stimuli in this experiment were created using eight to twelve knots.

We tried to adhere to the following general guidelines when making our forms. First, there had to be a sufficient amount of curvature variation. Second, we wanted a more or less even distribution of positive and negative curvature. Third, singularities had to be spaced sufficiently far from one another, in order

to be able to introduce the deletions. Stimuli were then displaced so that their centre of gravity coincided with the middle of the screen and scaled so that they just fitted in a virtual circle with a radius of 145 pixels.

Forty different standard shapes were created. Each standard shape yielded four different versions: The complete (non-deleted) form, the M+ deleted form, the m- deleted form, and the I deleted form. For each type of singularity, the three most important instances were deleted. In the case of M+ and m- "important" was defined as having high (absolute) curvature. Because inflection points are always located between a positive maximum and a negative minimum, we defined the most important inflection point as the one for which the smallest absolute curvature of these special neighbours was maximal. Deletion was performed symmetrically around the three most important singularities. Twenty pixels on each side were erased, resulting in a gap of 41 ($2 \times 20 + 1$) pixels. In Figure 1, the four variants of one of the forty standard shapes are shown.

Design and Procedure. Two variables were manipulated, presentation time and deletion. The three types of deletion (M+, m-, and I) have been discussed in the preceding section. We have also used four different presentation times defined by the number of consecutive frames during which a stimulus is

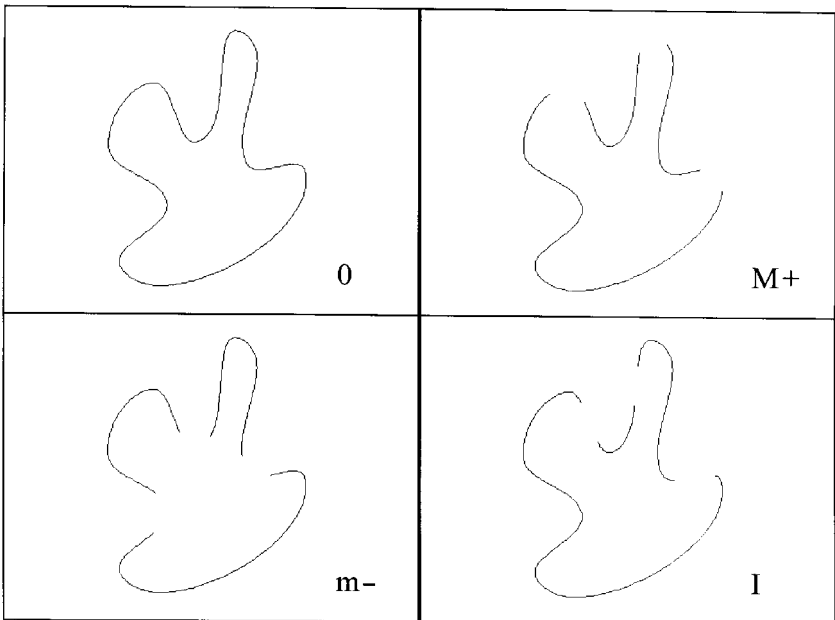


FIG. 1. The four deletion versions (0 deletion, M+ deletion, m- deletion, and I deletion) of one of the 40 stimuli used in Experiment 1.

displayed. The number of frames could be 3, 4, 5, or 6; at a refresh rate of 120Hz, this results in presentation times of 25, 33.3, 41.6, and 50msec, respectively. The combination of these two factors yields 12 conditions. Since we were interested in calculating d 's, we presented these conditions in separate blocks of 80 trials each, 40 non-deleted stimuli and 40 stimuli of one particular deletion condition. The sequence of blocks was randomized and the possibility for a short break was provided after each block. Participants were presented with the 12 blocks three times, in separate sessions on three consecutive days.

Each trial consisted of the following sequence of events. First, a fixation circle was presented for 500msec, followed by a 250msec blank screen interval. Then, the stimulus was presented for a very brief interval (25, 33.3, 41.6, or 50 msec, depending on the condition), immediately followed by a mask that remained on the screen for 250msec. The mask consisted of 200 circles with randomly varying radii and screen positions. Stimuli were given a new random orientation on each trial. A practice session, consisting of one of the long presentation time blocks of the experiment, was run before the actual experiment started. Subjects never received feedback.

Results and Discussion

Since we were interested in the participants' ability to detect a deletion, we calculated d 's for each combination of Presentation Time, Deletion, and Session (i.e. for each block of 80 trials). The resulting d 's were then subjected to an Analysis of Variance (ANOVA).

All three main effects were statistically significant. This not at all surprising for Presentation Time, $F(3, 245) = 292.95$; $MSE = 0.467$; $p < .0001$, since we can readily expect that deletions are easier to detect with longer viewing time. For 3, 4, 5, and 6 frames d 's were 0.29, 1.41, 2.67, and 3.41, respectively. The effect of Session, $F(2, 245) = 19.67$; $MSE = 0.467$; $p < .0001$ can be interpreted as a practice effect. For sessions 1, 2, and 3, d 's were 1.60, 2.05, and 2.19, respectively. The most interesting effect, Deletion, $F(2, 245)$; $MSE = 0.467$; $p < .005$, can be interpreted on its own, since none of the interactions were statistically significant. M+ deletions were most easily detected ($d' = 2.13$), followed by I deletions ($d' = 1.88$) and m- deletions ($d' = 1.83$). A Tukey HSD test ($p < .05$) showed that M+ deletions differed reliably from both I deletions and m- deletions, which were statistically indiscriminable.

M+ deletions are thus more easily spotted than I or m- deletions. Following the logic outlined earlier, this indicates that integration of contour fragments does not occur as easily or as strongly at regions around positive maxima than at regions around inflections or negative minima. How can we explain this? From an *information theory* point of view, we could argue that M+ deletions are less easily filled in than I deletions because curvature changes much at extrema and it is much harder to predict how the contour will continue. But the same argu-

ment would hold for $m-$ deletions and they turned out to be equally detectable as I deletions. Using a *decomposition theory* framework, we could explain the effect by noticing that $M+$ deletion disrupts the natural parts decomposition, but the same is also true for I deletions. In sum, neither of these theories can give a full account of our findings.

However, these theories are not mutually exclusive. Both could capture a different aspect of the truth. A tentative *post hoc* combination of both theories may offer an explanation (Table 1): $M+$ deletions have two reasons why contour integration is difficult and, therefore, detection is easy, whereas I and $m-$ deletions each have only one. Because of the post hoc nature of this explanation, we try to replicate and further investigate it in Experiment 2. Because the relative difficulty of $M+$ and $m-$ deletions is most diagnostic with respect to the theoretical explanations, they will be the main focus in Experiment 2.

EXPERIMENT 2

It could be argued that, in Experiment 1, $M+$ and $m-$ deletions always concerned different regions of the figures, which might differ in other aspects that are equally important as curvature sign. Absolute curvature might, for example, be higher in positive curvature regions than in negative curvature regions. However, there is a way to avoid this problem, by exploiting the fact that the sign of curvature is determined in relation to the object. Pieces of contour that are pointing inwards, towards the middle of the figure, have negative curvature, whereas outward pointing regions have positive curvature. The exact same contour can undergo a curvature sign reversal depending on its relation to the object it belongs to. In this way, it is possible create certain deletions that, depending on the overall configuration, can be either an $M+$ deletion or an $m-$ deletion. Experiment 2 exploits this fact about curvature to pit $M+$ and $m-$ deletions against each other in a better controlled way.

Peterson and colleagues (e.g. Peterson & Gibson, 1993, 1994a, 1994b; Peterson, Harvey, & Weidenbacher, 1991) have used figure-ground reversal

TABLE 1
A Schematic Representation of Our Tentative Post Hoc Explanation
of the Findings in Experiment 1

<i>Deletion Type</i>	<i>Filling-in is automatic, according to information theory</i>	<i>Resulting parts are natural, according to decomposition theory</i>
$M+$	NO	NO
I	YES	NO
$m-$	NO	YES

$M+$ deletions have two reasons why contour integration is difficult explaining their higher detectability.

to investigate the impact of object recognition processes on organizational processes (see Peterson, 1994, for a brief review), while Baylis and Driver (1994, 1995a) have used it to study the visual system's detection of mirror symmetry and repetition in relation to visual attention (see Baylis & Driver, 1995b, Driver & Baylis, 1995, for brief reviews). But the experiment that follows is, to our knowledge, the first to use figure-ground reversal to explicitly test the perceptual role of positive maxima (or convexities) and negative minima (or concavities) in the context of contour deletion and contour integration.

Methods

Subjects. Thirteen first-year psychology students and seven higher-class students participated in the experiment. None of them were aware of the purpose and hypotheses of the experiment. Their eyesight was normal or corrected-to-normal.

Apparatus. The apparatus was the same as in Experiment 1, except that now a 15-inch screen was used. Stimuli subtended about 6.3° of visual angle horizontally as well as vertically.

Stimuli. Stimuli were constructed in two steps. First, 40 smoothly curved pieces of contour were made (but not closed), by adding two sinusoidal curves as follows: $\sin(a \times x) + \sin(b \times x)$. The parameters a and b were added to introduce some variety. Parameter a took values between 0.2 and 1.5 in steps of 0.25. For each value of a , a random value of b was chosen between 0.3 and 1.2, with the constraint that $|a-b| > 0.15$. We let x range between 0 and $6 \times \pi$. The contour was appropriately scaled to fit the screen. For each contour segment constructed in this way, curvature was determined analytically, and from this we extracted the two most important positive maxima (M+), negative minima (m-), and inflection points (I) in the same way as in Experiment 1. Figure 2 shows an example of such a contour segment. In a second step, we made a closed figure by adding to the curved contour segment a set of three straight lines (forming a kind of trapezium). From each segment, two figures or two configurations were made, by closing the curved segment either on its left side or on its right side. Each "trapezium" has four corner points. Two of them are the beginning and the ending of the curved segment. Of the remaining two, one was positioned at the same vertical position as the beginning point of the curved segment and the other at the vertical position of the ending point of the curved segment, but either 250 pixels to the left or right of them (see Figure 3).

All of the stimuli were centred in the screen, using the mean of the four corner points as the middle. Each time a stimulus was presented, it was rotated by a random amount.

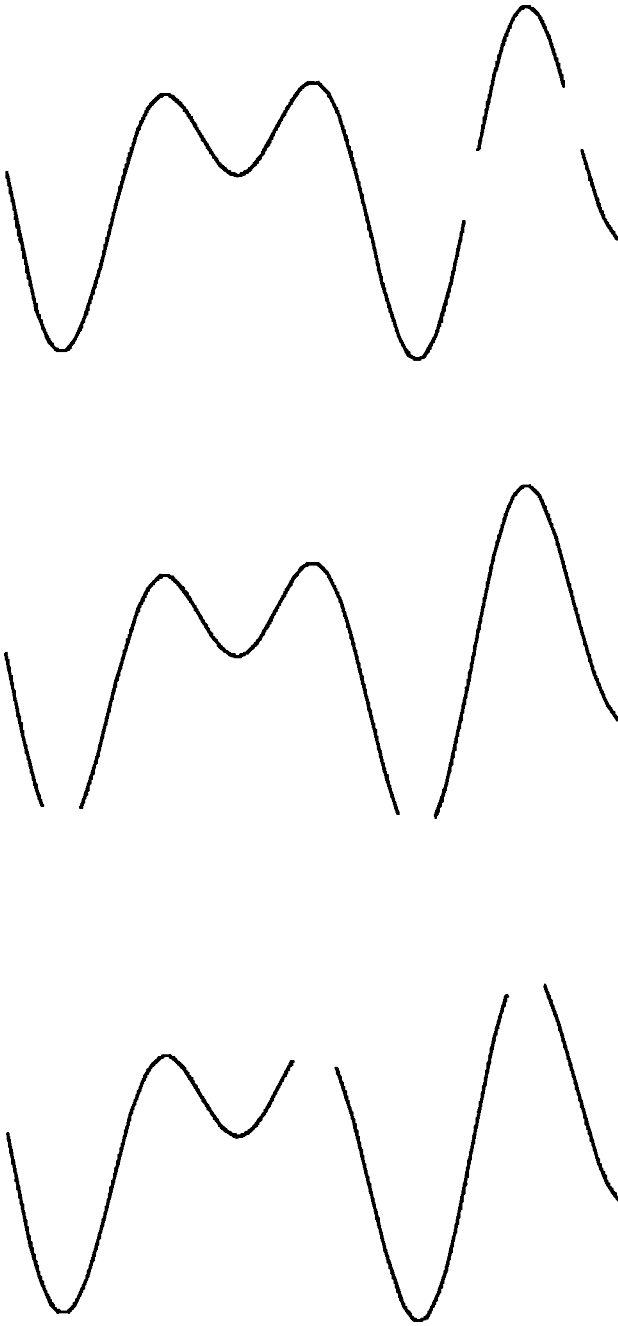


FIG. 2. The type of contour segment used to construct the stimuli in Experiment 2. Three deletion versions are shown. The left and middle figures depict deletions at regions of high absolute curvature, whereas the right figure depicts a deletion near inflections. Depending on the Configuration (on how the figure is closed) the left and middle figures depict M+ and m- deletions, or vice-versa.

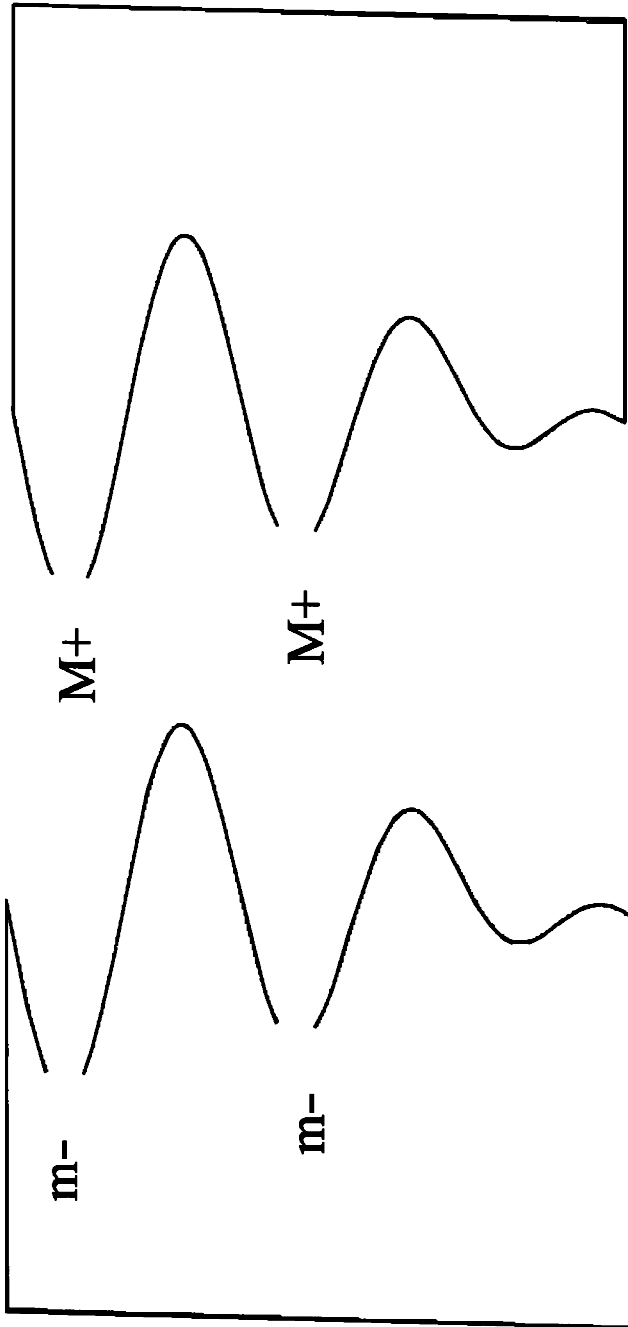


FIG. 3. An example of two stimuli used in Experiment 2. It also illustrates how the same curve segment with a particular physical Deletion (in this case Deletion 2), can be part of two different Configurations. Depending on the Configuration, the same deletions can either be M+ or m-. On the left is an example of Configuration 1, on the right Configuration 0.

Design and Procedure. In order to have more data points per condition, we did not want to vary presentation duration as we did in Experiment 1. On the other hand, this introduces the possibility that the contour deletion detection task would be too easy for some subjects to obtain reliable differences between the different types of deletions. Obviously, the detection of a deletion only poses a problem for the visual system if the stimulus is presented briefly enough. Because the majority of the participants in Experiment 2 were first-year students without any experience as psychophysical observers, we used an exposure duration close to the longest one used in Experiment 1, namely, 53msec (i.e. four frames at 75Hz).

Configuration and Deletion were, therefore, the only two independent variables. However, in contrast to Experiment 1, the levels of Deletion are not explicitly named as either M+ or m-, since the real status of the deletion depends on the Configuration. This is illustrated in Table 2. A full combination results in six conditions, which were presented to the subjects in six blocks of uniform trial type, presented in a random order. A block consisted of 80 trials, with 40 non-deleted stimuli and 40 deleted ones. Breaks were provided after each block.

The events constituting a trial were the same as in Experiment 1. A practice session, consisting of two blocks, was run before the actual experiment started. In a first practice block, stimuli were presented fairly long (146msec); in the second block, the experimental presentation time (53msec) was used. Stimuli of Experiment 1 were used in the practice session.

Results and Discussion

A first general look at the global percentage correct per subject (across all blocks), showed that for several subjects this task was not as difficult as we had hoped for. For most higher-class students, who already had some experience with psychophysical experiments, the presentation time of 53msec seemed too long for them to make a sufficient number of errors. We expect that when pre-

TABLE 2
The Six Conditions in Experiment 2

<i>Configuration</i>	<i>Deletion</i>	<i>Actual Deletion</i>
0	1	m -
0	2	M+
0	3	I
1	1	M+
1	2	m -
1	3	I

The same physical deletion can lead to a different actual deletion depending on the configuration

sentation time is long enough, all deletions can easily be perceived. We only expect to find a difference in the earliest stages of processing. With 53msec exposures, the experienced participants could well be a few processing steps ahead compared to others. In order to deal with this problem, we have restricted our subsequent analyses to those subjects for whom the task was difficult enough. We did this by focusing on the results of the participants who obtained a general performance level of 80% correct responses or less. The nine participants who scored above this cut-off obtained a mean score of 85.8% (SD = 2.8); the mean score of the remaining eleven participants was 72.2% (SD = 3.4).

We performed direct a priori tests of our predictions. Our first set of predictions was that the same physical Deletion would have different effects depending on the Configuration. More specifically, we predicted, based on the findings of Experiment 1, that Deletion 1 would be more easily detected in Configuration 1, where the actual deletion is M+, than in Configuration 0, where the actual deletion is m-, while for Deletion 2, this pattern would be reversed. For Deletion 3, we did not expect any differences, since in both configurations the actual deletion is an I deletion. The data are presented in Figure 4. All three predictions were corroborated. For Deletion 1, detectability for Configuration 1 ($d' = 1.26$) was higher than for Configuration 0 ($d' = 0.66$): $F(1, 50) = 4.33$, $MSE = 0.4906$, $p < .05$. For Deletion 2 detectability for Configuration 1 ($d' = 0.73$) was lower than for Configuration 0 ($d' = 1.35$):

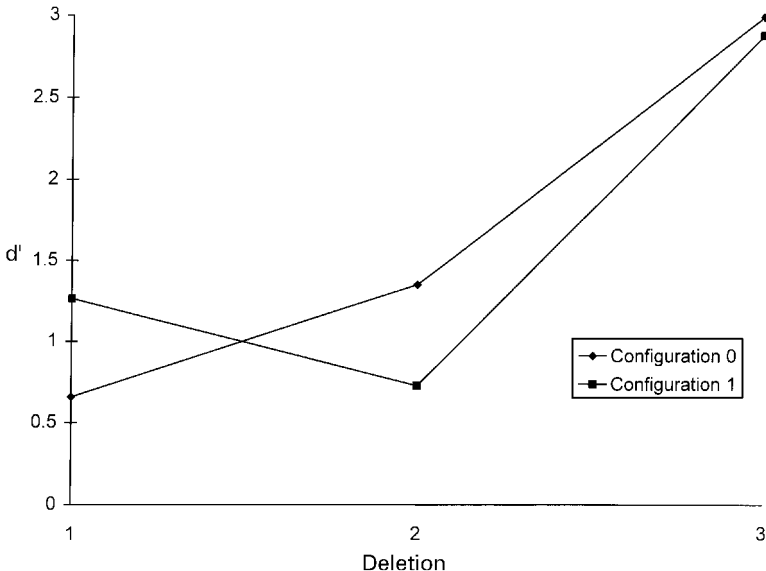


FIG. 4. The mean d' s for the six conditions (2 Configurations \times 3 Deletions) in Experiment 2.

$F(1, 50) = 4.13$, $MSE = 0.4906$, $p < .05$. For Deletion 3, no significant difference was found between the two Configurations, $F < 1$.

Looking at the data in another way, by recoding the Configuration and Deletion combination into one new "Actual Deletion" variable, we can, as in Experiment 1, compare performance under M+, m- and I deletions. Based on our previous findings, we predicted that M+ detectability would be better than m- detectability. This prediction was supported by the data, $d' = 1.31$ for M+ > $d' = 0.69$ for m- $F(1, 53) = 23.77$; $MSE = 0.2410$; $p < .0001$. In addition and in contrast with Experiment 1, in this experiment, I deletions were easiest to detect ($d' = 2.93$), significantly compared to M+, $F(1, 53) = 12.5$; $MSE = 0.2410$; $p < .001$ as well as to m-, $F(1, 53) = 70.76$; $MSE = 0.2410$; $p < .0001$.

A plausible post hoc explanation of this increased performance for I deletions compared to Experiment 1 lies in the fact that we used sinusoidal curves in Experiment 2. These curves are much more peaked than the stimuli used in Experiment 1. Despite the fact that an equal number of pixels were deleted for each curvature singularity, the perceived size of the gap depends on the type of deletion. When the absolute curvature is large (as with M+ and m- deletions), the two-dimensional distance separating the end points of the gap is much shorter than the contour length. This may lead to the perception of a larger gap in the case of I deletions where the size of the two-dimensional gap is much more similar to the one-dimensional contour length. Another possible reason, also a result of the stimuli used, might be that the two I deletions on a curve lie on the same "arm" (as, for example, in Figure 2). Sometimes, this can give the impression of an invisible rectangular occluder lying on top of the curve, involving other perceptual organization processes we are not primarily interested in. Please note that none of these possible objections can be applied to the M+ or m- deletions, since in this experiment M+ and m- deletions could be made from the same physical deletion, thanks to the configuration manipulation.

GENERAL DISCUSSION

In this paper, we have studied the integration of contour fragments created by deletions at different types of curvature singularities. The experimental paradigm allowed us to look at rapid (perhaps automatic) integration rather indirectly by examining the relative difficulty of detecting different types of contour deletions: If detection of a gap is difficult it must mean that the visual system has neglected or perhaps closed the gap by some sort of integration process.

In Experiment 1, deletions around inflections were found to be relatively difficult. This is understandable because it is easy to close such gaps by simple perceptual filling-in: A straight line will suffice generally because there is little variation in curvature in the actual part of the contour that has been deleted. If

exposure duration is limited to 50msec or less, the visual system will sometimes miss this type of deletion because of that. From this perspective, it is not surprising that deletions around positive maxima were easier: It is much harder to fill those gaps because curvature changes much in such a region. Somewhat unexpectedly, however, deletions around negative minima were equally hard to detect as inflection deletions, although they do not support easy filling-in as an automatic contour integration process. We speculated that our observers sometimes failed to notice the negative minima deletions because they created parts that fit well with the spontaneous segmentations that the visual system makes in natural shape description. In other words, if corroborated by further research, this would indicate that the same 50msec exposures would be sufficient to instigate a much more advanced type of integration, namely the integration of parts in a parts-based structural description of visual shapes. This result need not surprise us when considering Sanocki's recent findings (this issue) with respect to the role of featural relations such as connectedness and proximity early on in the construction of structural representations (i.e. with an average target duration of 63msec).

We tested the role of parts-integration further in Experiment 2, where we have used the same regions of the contour to create both types of deletions, positive maxima and negative minima, making use of the fact that the sign of curvature changes depending on the side where the contour bounds the object. The results convincingly showed that the same deletions become harder to detect when they are incorporated in a figure that turns them into negative minima or concavities than when they belong to a figure in which they form convexities. In Experiment 2, inflection deletions turned out to be easiest to detect probably because the gaps created were perceived to be larger than those in the other conditions, or because the gaps were strengthened even further by the perceptual system's filling-in of a virtual occluder. We leave it to future research to disentangle these effects further. In any event, the results of Experiment 2 confirmed that contour integration is not a simple matter of easy filling-in at regions of low curvature: Even when the curvature change is large, different parts of the contour can become integrated so strongly (as parts in a structural shape description) that their physical gap can sometimes go unnoticed.

In sum, in both experiments we have found that deletions around positive maxima are easier to detect than similar (Experiment 1) or identical (Experiment 2) deletions around negative minima. This is so despite the fact that minima are almost always closer to the foveal region of fixation and both types of curvature singularities are equally informative (i.e. much less redundant than inflections). Collectively, these findings support the idea that contour integration is a process that plays a role at different levels in the visual system, from the early level filling-in (at regions of low curvature) to the more complex level where parts bounded by negative minima are integrated spontaneously in a structural description of the whole shape. Because our experimental paradigm

encouraged observers to avoid these integrations, we are tempted to conclude that they occur virtually automatically.

REFERENCES

- Akima, H. (1970). A new method of interpolation and smooth curve fitting based on local procedures. *Journal of the Association for Computing Machinery*, *17*, 589–602.
- Attneave, F. (1954). Some informational aspects of visual perception. *Psychological Review*, *61*, 183–193.
- Biederman, I. (1987). Recognition-by-components: A theory of human image understanding. *Psychological Review*, *94*, 115–147.
- Biederman, I. (1988). Aspects and extensions of a theory of human image understanding. In Z.W. Pylyshyn (Ed.), *Computational processes in human vision: An interdisciplinary perspective* (pp. 370–428). Norwood, NJ: Ablex.
- Biederman, I., & Cooper, E.E. (1991). Priming contour-deleted images: Evidence for intermediate representations in visual object recognition. *Cognitive Psychology*, *23*, 393–419.
- Baylis, G.C., & Driver, J. (1994). Parallel computation of symmetry but not repetition within visual shapes. *Visual Cognition*, *1*, 377–400.
- Baylis, G.C., & Driver, J. (1995a). Obligatory edge assignment in vision: The role of figure and part segmentation in symmetry detection. *Journal of Experimental Psychology: Human Perception and Performance*, *21*, 1323–1342.
- Baylis, G.C., & Driver, J. (1995b). One-sided edge assignment in vision: 1. Figure-ground segmentation and attention to objects. *Current Directions in Psychological Science*, *4*, 140–146.
- Boucart, M. (1996). *La reconnaissance des objets*. Grenoble, France: Presses Universitaires de Grenoble.
- Boucart, M., Delord, S., & Giersch, A. (1994). The computation of contour information in complex objects. *Perception*, *23*, 399–409.
- Boucart, M., Grainger, J., & Ferrand, L. (1995). Three-dimensional features facilitate object recognition. *Visual Cognition*, *2*, 451–478.
- Braunstein, M.L., Hoffman, D.D., & Saidpour, A. (1989). Parts of visual objects: An experimental test of the minima rule. *Perception*, *18*, 817–826.
- Driver, J., & Baylis, G.C. (1995). One-sided edge-assignment in vision: 2. Part decomposition, shape description, and attention to objects. *Current Directions in Psychological Science*, *4*, 201–206.
- Eckhorn, R. (this issue). Neural mechanisms of visual features binding investigated with microelectrodes and models. *Visual Cognition*, *6*, 231–265.
- Hoffman, D.D., & Richards, W. (1984). Parts of recognition. *Cognition*, *18*, 65–96.
- Jolicoeur, P., & Ingleton, M. (1991). Size invariance in curve tracing. *Memory and Cognition*, *19*, 21–36.
- Jolicoeur, P., Ullman, S., & MacKay, M. (1986). Curve tracing: A possible basic operation in the perception of spatial relations. *Memory and Cognition*, *14*, 129–140.
- Jolicoeur, P., Ullman, S., & MacKay, M. (1991). Visual curve tracing properties. *Journal of Experimental Psychology: Human Perception and Performance*, *17*, 997–1022.
- Lamote, C., Wagemans, J., & d'Ydewalle, G. (1995). *On the role of curvature singularities in mental rotation* (Psych. Rep. No. 179). Laboratory of Experimental Psychology, University of Leuven, Leuven, Belgium.
- Leyton, M. (1988). A process-grammar for shape. *Artificial Intelligence*, *34*, 213–247.
- Leyton, M. (1989). Inferring causal history from shapes. *Cognitive Science*, *13*, 357–387.
- Lowe, D.G. (1985). *Perceptual organization and visual recognition* (PhD thesis, Department of Computer Science, Stanford University, 1985). Boston, MA: Kluwer.

- Moons, T., Pauwels, E.J., Van Gool, L.J., & Oosterlinck, A. (1995). Foundations of semi-differential invariants. *International Journal of Computer Vision*, *14*, 25–47.
- Pauwels, E.J., Moons, T., Van Gool, L.J., Kempenaers, P., & Oosterlinck, A. (1995). Recognition of planar shapes under affine distortion. *International Journal of Computer Vision*, *14*, 49–65.
- Peterhans, E., & von der Heydt, R. (1991). Subjective contours— bridging the gap between psychophysics and physiology. *Trends in Neuroscience*, *14*, 112–119.
- Peterson, M.A. (1994). Object recognition processes can and do operate before figure–ground organization. *Current Directions in Psychological Science*, *3*, 05–111.
- Peterson, M.A., & Gibson, B.S. (1993). Shape recognition inputs to figure–ground organization in three-dimensional displays. *Cognitive Psychology*, *25*, 383–429.
- Peterson, M.A., & Gibson, B.S. (1994a). Must figure–ground organization precede object recognition? An assumption in peril. *Psychological Science*, *5*, 253–259.
- Peterson, M.A., & Gibson, B.S. (1994b). Object recognition contributions to figure–ground organization: Operations on outlines and subjective contours. *Perception and Psychophysics*, *56*, 551–564.
- Peterson, M.A., Harvey, E.M., & Weidenbacher, H.J. (1991). Shape recognition contributions to figure–ground reversal: Which route counts? *Journal of Experimental Psychology: Human Perception and Performance*, *17*, 1075–1089.
- Resnikoff, H. (1985). *The illusion of reality: Topics in information science*. New York: Springer-Verlag.
- Sanocki, T. (this issue). Constructing structural descriptions. *Visual Cognition*, *6*, 299–318.
- Shannon, C.E., & Weaver, W. (1949). *The mathematical theory of communication*. Urbana, IL: University of Illinois Press.
- Snodgrass, J.G., & Corwin, J. (1988). Perceptual identification thresholds for 150 fragmented pictures from the Snodgrass and Vanderwart picture set. *Perceptual and Motor Skills*, *67*, 3–16.
- Snodgrass, J.G., & Feenan, K. (1990). Priming effects in picture fragment completion: Support for the perceptual closure hypothesis. *Journal of Experimental Psychology: General*, *119*, 276–296.
- Snodgrass, J.G., & Hirshman, E. (1994). Dissociations among implicit and explicit memory tasks: The role of stimulus similarity. *Journal of Experimental Psychology: Learning Memory, and Cognition*, *20*, 105–160.
- Snodgrass, J.G., & Vanderwart, M. (1980). A standardized set of 260 pictures: Norms for name agreement, image agreement, familiarity, and visual complexity. *Journal of Experimental Psychology: Human Learning and Memory*, *6*, 174–215.
- Ullman, S. (1989). Aligning pictorial descriptions: An approach to object recognition. *Cognition*, *2*, 193–254.
- Waeytens, K., Hanouille, I., Wagemans, J., & d'Ydewalle, G. (1994). Human representation of closed contours. In F. Dillen, I. Van de Woestijne, & L. Verstraelen (Eds.), *Geometry and topology of submanifolds*, VI (pp. 298–306). Singapore: World Scientific.
- Wagemans, J., Hanouille, I., Waeytens, K., & d'Ydewalle, G. (May, 1994). *Are curvature singularities sufficient to represent shape?* Annual meeting of the Association for Research in Vision and Ophthalmology (ARVO). Sarasota, Florida. [From *Investigative Ophthalmology and Visual Science*, 1994, *35*(4), 1918, Abstract No. 3065.]
- Wagemans, J., Notebaert, W., & Boucart, M. (1998). Lorazepam but not diazepam impairs identification of pictures on the basis of specific contour fragments. *Psychopharmacology*, *138*, 326–333.

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