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The spatial profile of visual attention in mental curve tracing

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Abstract

In a curve-tracing task, subjects have to judge whether items are located on a single, continuous curve. Spatially separate segments of such a curve are related to each other through grouping criteria, like collinearity and connectedness. These grouping cues need to be exploited during curve tracing, but it is still an open issue how grouping of contour segments is achieved by the visual system. Many contemporary theories of visual perception assume that grouping operations are carried out pre-attentively, with unlimited capacity. The present study examines this assumption by investigating the involvement of attention in curve tracing. The results show that attention is directed to contour segments that need to be grouped together. The distribution of attention is guided by grouping criteria, such as connectedness. Apparently, attention is required to group spatially separate contour segments into a coherent representation of a curve. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Contour integration; Curve tracing; Collinearity; Connectedness; Visual attention; Object-based attention

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1. Introduction

Everyday visual scenes are composed of many objects. At any time, visual attention can be directed to only one or a few of them. Attention usually selects an object in its entirety, even when it is spatially extended. In these situations, all parts of the object have to be segregated from the rest of the image. Usually, object components exhibit special, non-accidental relationships. These relationships can be exploited by the visual system as grouping criteria, in order to recover all parts of the object. An example of such a grouping criterion is connectedness, because object components are usually connected to each other (Palmer & Rock, 1994; Roelfsema & Singer, 1998). Another grouping cue is collinearity, since contour segments in collinear configurations typically belong to the same edge (Kellman & Shipley, 1991; Field, Hayes, & Hess, 1993; Kapadia, Ito, Gilbert, & Westheimer, 1995). Indeed, connectedness and collinearity are among the grouping criteria that were discovered by the Gestalt psychologists in the beginning of the last century. They referred to collinearity and connectedness as ‘good continuation’ (Koffka, 1935; Rock & Palmer, 1990).

How the visual system evaluates grouping criteria is still an open issue. Most theories of visual perception assume that grouping criteria are applied in parallel to the entire visual scene and with unlimited capacity (Neisser, 1974; Treisman & Gelade, 1980; Posner & Presti, 1987; Duncan & Humphreys, 1989; Wolfe, 1994). In some tasks collinearity indeed appears to be evaluated in parallel (Field et al., 1993; Kovács & Julesz, 1993). This would imply that grouping on the basis of these Gestalt criteria is independent of visual attention. However, this view is challenged by evidence suggesting that Gestalt grouping does not occur if attention is directed elsewhere (Ben-Av, Sagi, & Braun, 1992). An alternative proposal is that object components are grouped together, if they have been labeled by attention. According to this proposal, attention spreads in time from one component to the next on the basis of Gestalt criteria. The object has been segregated successfully as soon as all of its components are attended (Roelfsema, Lamme, & Spekreijse, 2000).

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Here, we investigate whether attention is involved in the retrieval of spatially separate object components by using a curve-tracing task (Jolicoeur, Ullman, & MacKay, 1986; Pringle & Egeth, 1988; Roelfsema, Scholte, & Spekreijse, 1999). A curve-tracing example is illustrated in Fig. 1, where the task is to switch on the light. The visual system can use the Gestalt law of good continuation, in order to group together contour segments that belong to one of the cables and to identify the correct plug. The hypothesis at stake predicts that attention is directed to all contours segments of the cable that has to be traced.

The present study tests this hypothesis by using a dual-task design. The primary task is to determine whether two locations in the visual field are connected to each other by a curve. As a secondary task, subjects have to report the color of contour segments that belong to curves in the image. The performance on this secondary task will provide a measure of the spatial distribution of attention during curve-tracing.

2. Methods

2.1. Subjects

Here we report on two experiments that used similar procedures. Four subjects (age 18–25) participated in experiment 1 and eleven subjects (age 19–27) in experiment 2. Informed consent was obtained from all subjects, who reported normal visual acuity and no history of neurological disease.

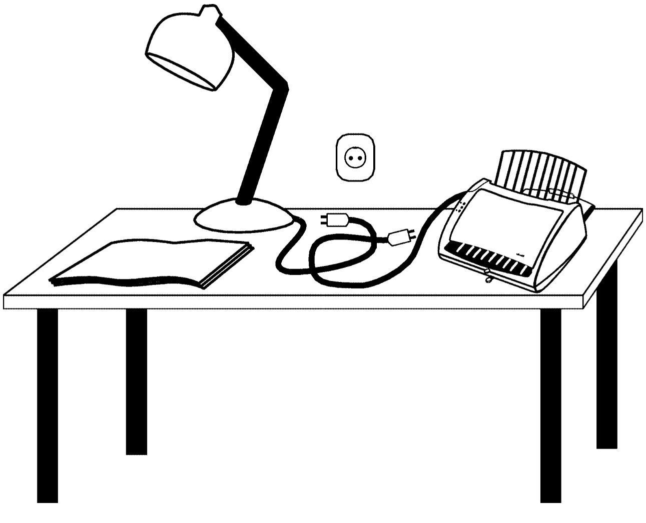

Fig. 1. A natural scene that requires curve-tracing. In order to identify the plug that belongs to the light, the visual system can group together contour segments of one of the cables.

2.2. Task and experimental design

A dual task design was used to measure the distribution of attention during curve-tracing (Fig. 2). The primary task was to trace a curve, and a secondary task was added in order to probe the spatial distribution of visual attention. A trial started with the presentation of a fixation point for 300 ms, which was followed by one of 8 (experiment 1) or 16 (experiment 2) stimuli (Fig. 2a,c). In the primary curve-tracing task, subjects had to indicate whether the curve that started at the fixation point (referred to as target curve, Fig. 2b) was connected to a left or right circle. A second curve (distractor curve) could be ignored. Subjects had to press a button with their left hand if the target curve connected the fixation point to the left circle, and a button with their right hand if the fixation point was connected to the right circle. During the primary task, some curve segments ('hotspots', white segments in Fig. 2) were shown in one of six randomly chosen isoluminant colors. Isoluminance was determined by means of heterochromatic flicker (16 Hz). These hotspots were irrelevant for a correct response in the primary task. Immediately after the response in the primary task, a mask was presented for 300 ms (Fig. 2c). The mask consisted of a superposition of all stimuli, drawn in the six isoluminant colors that were chosen at random for each of the segments. This was followed by an uncolored image in which one of the hotspots was cued by a circle. It was the secondary task to name the color that had been presented at the cued location during the primary task. Each hotspot had an equal probability to be cued (25% in experiment 1 and 33% in experiment 2). The percentage of correctly reported colors will be used as a measure of the amount of attention paid to the hotspots. Eye movements were recorded by means of EOG and trials with detected eye-movements or blinks were removed from analysis. Data were obtained in blocks of 300 trials. Subjects of experiment 1 completed on average 837 trials without eye-movements, and subjects of experiment 2 completed on average 870 trials.

The objective was to measure the spatial distribution of attention during the curve-tracing task. The addition of a secondary task might, in principle, change the subjects' strategy. A number of precautions were taken to discourage such strategy changes, by ensuring that the subjects could not concentrate on the secondary task. First, the importance of an accurate and speedy response in the primary task was stressed during the task instructions. Second, subjects first performed 240 trials in a practice session with only the primary curve-tracing task, at the beginning of the experiment. Responses were pooled across stimuli that were each other's mirror image, which resulted in 4 stimulus categories (numbered I–IV in Fig. 2a). These categories

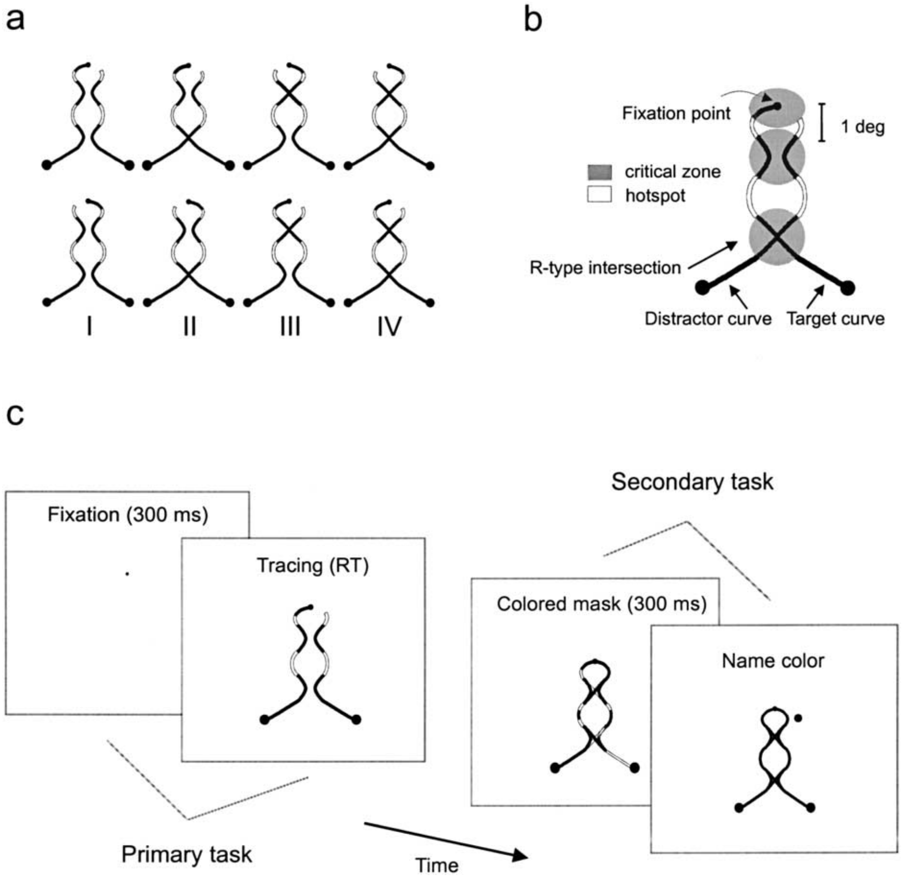

Fig. 2. Design of stimuli and dual task procedure. (a) The eight stimuli of the primary task in experiment 1. Subjects indicated which of two circles was connected to the fixation point by pressing a button. Responses were pooled across stimuli that were mirror images (shown above each other), which resulted in four stimulus categories (I–IV). Hotspots, which were shown in a randomly chosen color, are shown as white segments. These hotspots were irrelevant in the primary curve-tracing task. (b) The curve that makes the connection is referred to as target curve, the other curve as distractor curve. Differences between stimuli were confined to three critical zones (gray regions). In the upper critical zone the fixation point was either connected to the left or right curve. In the lower two critical zones the target and distractor curve could cross each other (R-type intersection). (c) After a response in the primary task, the stimulus was masked with randomly colored segments. Thereafter, one of the hotspots was cued, and it was the secondary task to name the color that this hotspot had before the mask.

differed from each other in the number and location of intersections between the target and distractor curve. Thus, the practice session yielded a baseline distribution of curve-tracing reaction times for each of these stimulus categories. Thereafter, the secondary color-naming task was added, and subjects were tested in the dual task session. Whenever curve-tracing reaction times in the dual-task session were longer than the 90th percentile of the corresponding single-task distribution, subjects were instructed to speed up in the primary task. Third, in a post-hoc analysis, reaction times in the dual-task session were compared to the reaction times in the single-task condition, for each stimulus category. Two subjects had reaction times that were significantly longer in the dual-task session, in spite of instructions and feedback. These subjects were removed from analysis. Data of a third subject were not evaluated, because of a misunderstanding of the instructions. Thus, the remaining subjects did not spend additional time to concentrate on the hotspots during curve-tracing. Finally, the probability of probing a hotspot on the target curve was equal to the probability of probing a hotspot on the distractor curve. Thus, the secondary task provided no incentive to attend more to one of the curves than to the other.

2.3. Stimuli

A total of eight stimuli were used in experiment 1 (Fig. 2a), and 16 stimuli were used in experiment 2 (Fig. 4d shows half of them). They were displayed on a 21″ Dell Ultrascan monitor, viewed from a distance of 115 cm. The frame rate of the monitor was 70 Hz. The stimuli consisted of bright contours (the constituent contour segments were third-order polynomials) with a width of 0.04°. The luminance of the contours was 85 cd/m^2, and that of the background was 1.5 cd/m^2.

2.4. Data analysis

An ANOVA was used to assess the significance of differences in reaction time between stimulus categories in the primary task. A mixed model was adopted, with subjects as random variable. To analyse the significance of performance differences in the secondary color-naming task, a Monte-Carlo procedure was used (Press, Flannery, Teukolsky, & Vetterling, 1986). The null hypothesis is that performance at a particular hotspot is similar for the various stimuli, irrespective of whether the hotspot belongs to the target or distractor curve. The null hypothesis does, however, allow differences in performance between subjects and between eccentricities. Suppose that the number of responses of subject s for hotspots h and j (at the same eccentricity) are Nh_s and Nj_s of which Ch_s and Cj_s are correct, respectively. An unbiased estimate of the performance of this subject according to the null-hypothesis is $Perf_s = (Ch_s + Cj_s)/(Nh_s + Nj_s)$. The expected value of $Perf_s$ should equal the expected value of both Ch_s/Nh_s and Cj_s/Nj_s, according to the null hypothesis. The expected value of $Ch_s/Nh_s - Cj_s/Nj_s$ should therefore be 0, for each subject s. This implies that the expected value of the hj_difference $= \Sigma_s (Ch_s/Nh_s - Cj_s/Nj_s)$, summed across subjects, should also be 0. In the Monte Carlo procedure, 20.000 experiments were simulated. In every simulated experiment Nh_s and Nj_s responses were generated for each subject s. The probability for a correct response for both hotspots was set to $Perf_s$. The significance of a difference in performance between hotspots was determined by comparing the experimental hj_difference to the distribution of 20.000 simulated hj_differences.

3. Results

3.1. Experiment 1: does contour grouping require visual attention?

The curve tracing task of the present study is illustrated in Fig. 2. On each trial one of the eight stimuli of Fig. 2a was presented. Subjects had to fixate a point at the top of the stimulus. They had to indicate whether a left or right circle was connected to the fixation point by a curve, while their gaze remained on this point. We will refer to the curve that connects the fixation point to one of the circles as target curve, and to the other curve as distractor curve (Fig. 2b). This curve-tracing task can be solved by a perceptual grouping operation that groups the segments of the target curve together. Grouping of contour segments that belong to the target curve should be easy, because these contour segments are connected to each other, and locally collinear.

The differences between the stimuli were confined to three ‘critical zones’ (shaded in Fig. 2b). In the upper critical zone the fixation point was connected to either the left or the right curve. The other two critical zones could contain an intersection between the target and distractor curve (these are called R-type intersections, because they are relevant for a correct response in the contour grouping task). Intersections are special, because here the curves are connected to each other and only collinearity remains as a grouping cue. Permutations at the critical zones give rise to a total of 8 stimuli. Responses were pooled across stimuli that were mirror images of each other, resulting in 4 stimulus categories (I–IV in Fig. 2a).

In order to measure the distribution of attention during curve-tracing, a secondary probe task was added. Four contour segments that were outside the critical zones were colored, and we will refer to these segments as hotspots (white in Fig. 2a,b). The colors of the hotspots were irrelevant in the primary curve-tracing task. After the response in the primary task, the colors of the hotspots were masked. Thereafter, a circular cue appeared next to one of the hotspots, and it was the secondary task to verbally report the color that this hotspot had before the mask. The color of an attended curve segment is more likely to be reported correctly than that of a non-attended segment. Therefore, the performance in the secondary task should reflect the distribution of attention during curve-tracing. In principle, the addition of a secondary task might change the subjects’ strategy during the primary task. Such strategy changes were discouraged, however, as outlined in Section 2.

The distribution of attention during curve-tracing will allow us to distinguish between three models of contour integration. According to the first model, contour grouping occurs pre-attentively, and with unlimited capacity. Attentive selection of contours segments is not required. Moreover, reaction times should be uniformly short, because grouping occurs in parallel across the entire visual field. In the second model, attention is deployed strategically, and only to the critical zones. Note that the critical zones contain the information that is both necessary and sufficient to solve the task, since the eight stimuli are identical elsewhere (Fig. 2a,b). Thus, in this model attention need not be directed to curve segments outside the critical zones. The third model is the attentive contour grouping hypothesis. This hypothesis predicts that grouping is achieved by attending all segments of the target curve. Thus, attention should also be directed to segments of the target curve that are outside the critical zones.

3.2. Primary contour-grouping task

The performance in the curve-tracing task itself also provides constraints on models of contour integration.

Reaction times and error rates of the primary task are shown in Fig. 3a, averaged across four subjects. The number of R-type intersections, which differed among stimulus categories, is shown on the abscissa. Intersections between the target and distractor curve were associated with considerable delays in the curve tracing process. Each intersection prolonged the reaction time by 115 ms, on average ($F(3,9) = 50$, $P < 1 \times 10^{-5}$). This provides a first indication that contour grouping on the basis of collinearity and connectedness is not performed with unlimited capacity.

3.3. Secondary color-naming task

As a measure for the spatial distribution of attention, the percentage of correctly reported colors of the secondary task was compared between corresponding hotspots (at the same eccentricity) on the target and distractor curve (Fig. 3b). The percentage of correct responses ranged from 69% to 87% for hotspots on the target curve, and from 28% to 53% for hotspots on the distractor curve. Performance was significantly superior for both the upper and lower hotspots of the target curve in each of the four stimulus categories (all eight pairwise comparisons $P < 0.01$, see Methods). Performance for the hotspots on the target curve remained superior even when they were located at different sides of the distractor curve (stimulus category III and IV). These results imply that visual attention is directed to the curve that is connected to the fixation point. It is not only directed to the critical zones, but also to segments of the target curve that are outside these zones. The segments that belong to a curve are locally collinear and connected to each other. A process that groups contour segments together on the basis of these criteria would provide the solution to the primary curve-tracing task, because it would identify the circle that is connected to the fixation point. The present results indicate, however, that such a grouping operation is not applied pre-attentively. Instead, segments of the target curve are labeled by visual attention. This attentional label may be responsible for the integration of spatially separate curve segments into a coherent representation (Roelfsema et al., 2000).

The performance for the hotspots on the target curve was relatively constant across the four stimulus cate-

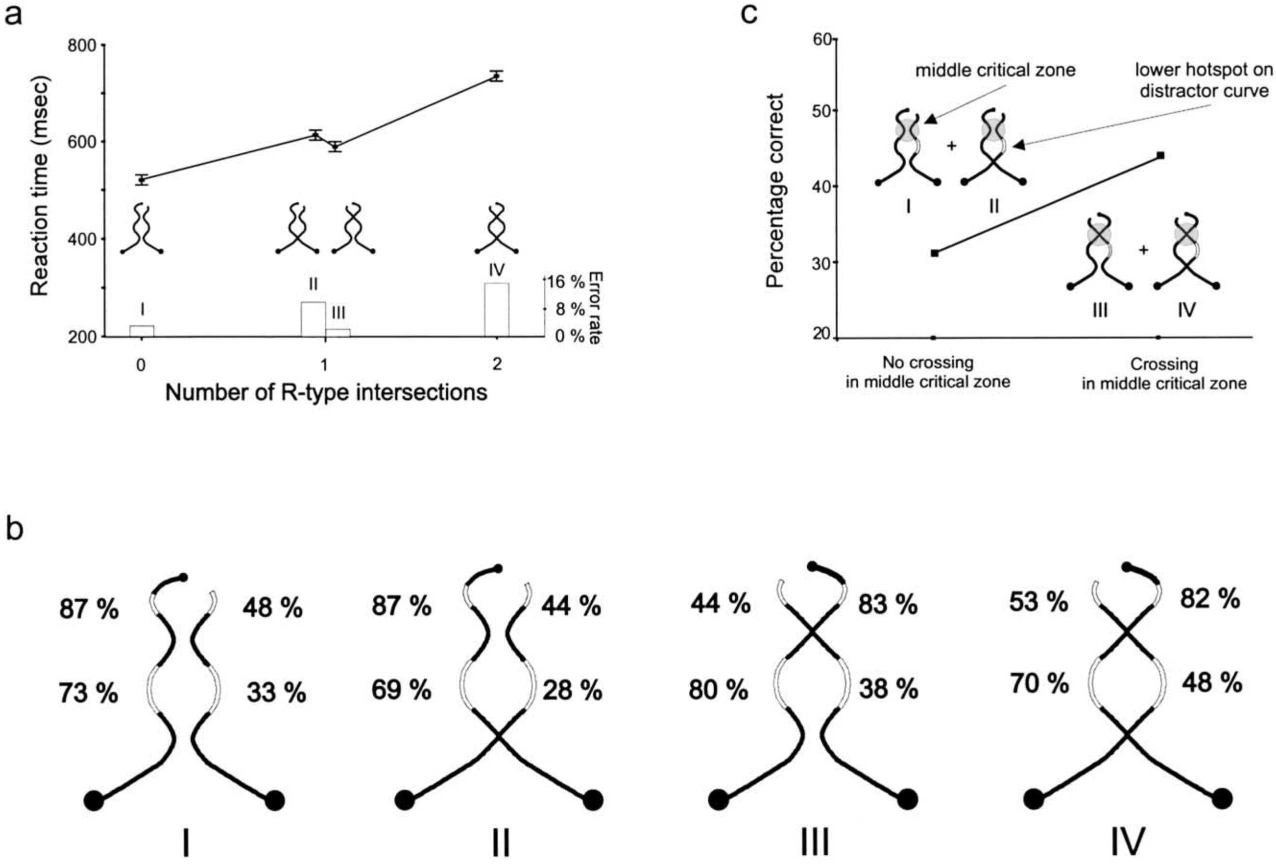

Fig. 3. Reaction times and distribution of attention during curve tracing. (a) Average reaction times for the four stimulus categories (I–IV, see insets). The abscissa shows the number of R-type intersections, which differed among stimulus categories. Bars indicate the error rates in the primary task. (b) Performance in the secondary task for the hotspots of the four stimulus categories. (c) Comparison of the performance for the lower hotspot on the distractor curve between stimuli with (pooled across category III and IV) and without (category I and II) an intersection at the middle critical zone.

gories (Fig. 3b). This was also the case for the performance for the upper hotspot of the distractor curve. Unexpectedly, the performance for the lower hotspot of the distractor curve depended on the presence of an intersection at the middle critical zone. This is illustrated in Fig. 3c, which compares the performance for the lower hotspot of the distractor curve between stimuli with and without an intersection at the middle critical zone. Performance increased from 30% to 43% if there was an intersection at this position ($P < 0.01$). Why does performance for this hotspot on the distractor curve depend on an intersection with the target curve?

Intersections are special, because here the two curves are connected to each other. Thus, only collinearity remains as a grouping cue at an intersection, and attention might 'leak' from the target curve into the distractor curve. This could account for the observed improvement of performance for the lower hotspot on the distractor curve (Fig. 3c) (see also Kramer & Jacobson, 1991). A second experiment investigated whether attention indeed tends to leak into curves that are crossed by the target curve.

3.4. Experiment 2: is there leakage of attention at intersections?

This experiment was designed to investigate the attentional leakage hypothesis: does attention leak into curves that have an intersection with the target curve? To address this question, an additional curve was introduced in the stimuli (labeled 'irr' in Fig. 4a,b). This curve was irrelevant for a correct response in the primary curve-tracing task. The irrelevant curve could either cross the target curve (Fig. 4a) or the distractor curve (Fig. 4b). This yielded a total of 16 stimuli, eight of which are shown in Fig. 4d (the other eight stimuli are mirror images). There were three different types of intersections. The first type is the now familiar R-type intersection at which the target curve crosses the distractor curve (these were also present in experiment 1). The second type will be called T-type intersection, and is between the target curve and the irrelevant curve (Fig. 4a). Here, attention might leak from the target curve into the irrelevant curve. The third type, between the distractor curve and the irrelevant curve, is called a D-type intersection (Fig. 4b). The distractor curve receives little attention, and a D-type intersection should not result in leakage of attention into the irrelevant curve.

The attentional leakage hypothesis can therefore be tested by comparing the spatial distribution of attention between stimuli with a T- and D-type intersection. There were three hotspots. The first hotspot was on the target curve, the second was on the distractor curve, and the third hotspot on the irrelevant curve. The attentional leakage hypothesis predicts that performance for the hotspot on the irrelevant curve is higher for stimuli with a T-type intersection than for stimuli with a D-type intersection.

3.5. Primary contour-grouping task

Fig. 4c shows reaction times in the primary task, averaged across eight subjects. Values on the abscissa of Fig. 4c show the number of R-type intersections that differ between the stimulus categories (as in experiment 1). On average, each R-type intersection prolonged the reaction time by 73 ms, in accordance with experiment 1 ($F(3,21) = 27.5$, $P < 1 \times 10^{-6}$). Intersections with irrelevant curve also influenced reaction times. On average, responses to stimuli with a T-type intersection were delayed by 27 ms relative to stimuli with a D-type intersection (Fig. 4c) ($F(1,7) = 23.0$, $P < 0.001$). Longer reaction times in case of a T-type intersection are consistent with the hypothesis that attention is distributed across the target curve. At a T-type intersection the irrelevant curve can interfere with the spread of attention across the target curve. Interference with the spread of attention across the target curve cannot be caused by a D-type intersection, because this type of intersection does not involve the target curve (Roelfsema et al., 1999).

3.6. Secondary color-naming task

In the secondary task, performance for the hotspot on the target curve ranged from 91% to 98%, and was superior to performance for the hotspot on the distractor curve, which ranged from 50% to 80% ($P < 0.01$, for each of the 8 pairwise comparisons) (Fig. 4d). Thus, the target curve receives more attention than the distractor curve, in accordance with experiment 1. To test whether attentional leakage occurred, performance for the hotspot on the irrelevant curve was compared between stimuli containing a T-type and a D-type intersection. The color of this hotspot was reported more reliably in the presence of a T-type intersection in each of the four stimulus categories (Fig. 5) ($P < 0.05$, for each of four pairwise comparisons). This suggests that attention indeed leaks from the target curve into the irrelevant curve at the T-type intersection.

There remains, however, one possible confound that might contribute the improvement for the hotspot on the irrelevant curve caused by a T-type intersection. Reaction times were longer for stimuli with a T-type intersection than for stimuli with a D-type intersection (Fig. 4c). Colors were masked after the response in the primary task, and they were therefore longer visible for stimuli with a T-type intersection. In order to exclude the possibility that the improvement in color performance was caused by the prolonged exposure to the

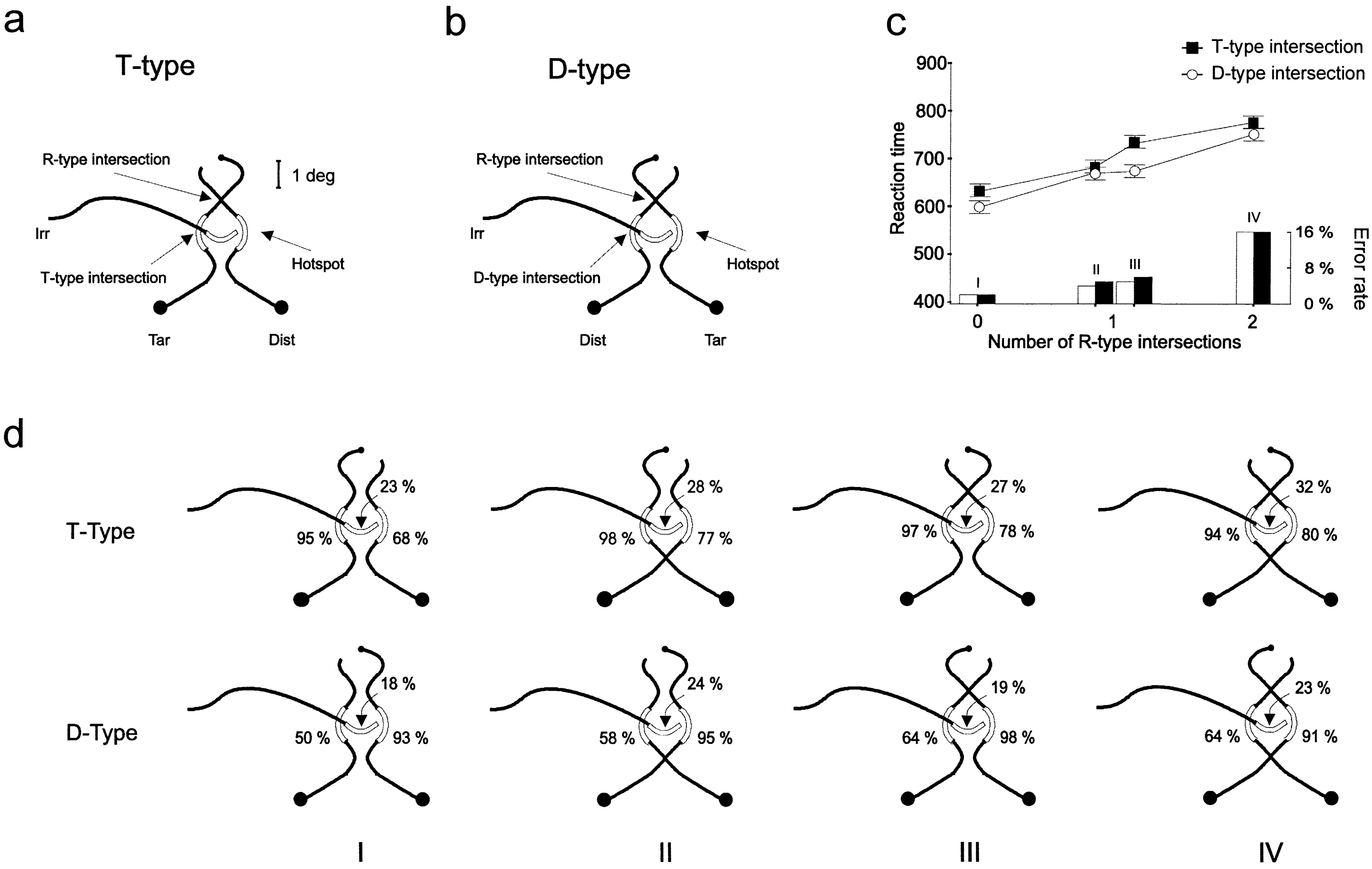

Fig. 4. Influence of an irrelevant curve on the distribution of visual attention during curve-tracing. (a, b) The irrelevant curve had a different shape than the target and distractor curve, and crossed either the target curve (a, T-type intersection) or the distractor curve (b, D-type intersection). Tar, target curve; Dist, distractor curve; Irr, irrelevant curve. (c) Reaction times and error rates in the primary task. Abscissa, number of R-type intersections that differ between the stimulus categories I–IV. Squares and circles show reaction times for stimuli with a T-type and D-type intersection, respectively. Bars show error rates in the primary task for stimuli with a T-type (black bars) or D-type (white bars) intersection. (d) Eight of the 16 stimuli that were presented in this experiment, their mirror images are not shown. Upper row, stimuli with a T-type intersection. Lower row, stimuli with a D-type intersection. Hotspots are shown as white segments. Percentages indicate performance in the secondary, color-naming task. For each of the stimuli, performance on the target curve was superior to that on the distractor curve, which in turn was superior to performance on the irrelevant curve.

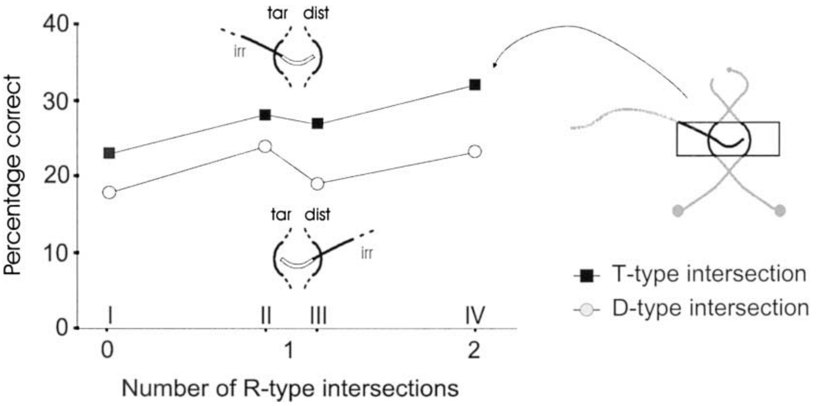

Fig. 5. Performance for the hotspot of the irrelevant curve for the four stimulus categories, in case of a T-type (black squares) or D-type intersection (white circles). Insets show enlargement of the contour configuration in the vicinity of the hotspot of the irrelevant curve (see box on the right). As an example, the stimulus on the right illustrates a T-type intersection of stimulus category IV.

colors, the reaction time data were subjected to a stratification procedure. Reaction time distributions for each subject and stimulus category were computed for stimuli with a T- and D-type intersection, using a binwidth of 40 ms. The number of trials in each 40 ms bin was made identical for the two distributions by removing randomly chosen trials of either the stimulus with a T-type intersection or the stimulus with a D-type intersection. This removed 25% of trials from analysis, but also in this reduced data set performance on the irrelevant curve was better in case of a T-type intersection ($P < 0.05$, for each of four pairwise comparisons). Thus, prolonged exposure to the colors cannot account for the improvement on the distractor curve caused by a T-type intersection. This improvement is consistent with a leakage of attention from the target curve into the irrelevant curve.

3.7. Negative priming of an irrelevant curve

Unexpectedly, there was also a marked difference between the performance for the hotspot on the distractor curve and the hotspot on the irrelevant curve. Performance for the hotspot on the distractor curve ranged from 50% to 80%, which is superior to the performance for the hotspot on the irrelevant curve, which ranged from 18% to 32% ($P < 0.01$, for each of the eight pairwise comparisons) (Fig. 4d). Although the hotspot on the irrelevant curve is located in between the other hotspots, the performance for this hotspot is poorest. The superior performance for the hotspot on the target curve is in accordance with the attentional labeling hypothesis, but what causes the inferior performance for the irrelevant curve?

We would like to suggest that the difference in performance between the distractor curve and the irrelevant curve might be related to negative priming (Tipper, Weaver, Cameron, Brehaut, & Bastedo, 1991; Maljovic & Nakayama, 1996). During curve tracing, segments of the irrelevant curve never need to be attended, and a sustained inhibition of its representation may build up over trials. This would account for the poor performance for the irrelevant curve. In contrast, segments of the distractor curve have typically been part of the target curve in previous trials. Attending an item erases negative priming effects that may have build up in these previous trials (Tipper et al., 1991; Maljovic & Nakayama, 1996). Thus, a build up of negative priming cannot occur for segments of the distractor curve, and this would explain why performance for the hotspot of the distractor curve is better than performance for the hotspot of the irrelevant curve.

The findings that have been described so far are consistent with the hypothesis that curve tracing is implemented by labeling the target curve with visual attention. Attention may spread along the target curve on the basis of collinearity and connectedness. At intersections, segments of two curves are connected, which should promote grouping, because only collinearity remains to segregate the curves. This can explain why attention leaks into a curve that crosses the target curve, and why reaction times are increased.

3.8. Feature migrations as a measure for grouping strength

In order to investigate whether segments of crossing curves also tend to group together, feature migrations were evaluated. Feature migrations are image features that are perceived at erroneous locations. They can be used as a measure for grouping strength, because features are more likely to migrate within the same perceptual group, than into a different group (Prinzmetal, 1981; Cohen & Ivry, 1989). Performance for the hotspot on the irrelevant curve of the second experiment was relatively poor. This gave an opportunity to assess feature migrations from the target and distractor curve onto the irrelevant curve. For the analysis, data were pooled across stimulus categories with either a T-type or a D-type intersection (Fig. 6).

If subjects were simply guessing in trials in which they failed to report the color of the irrelevant curve, the color of either target or distractor curve should be named in 20% of the error trials (there were five colors other than that of the irrelevant curve). However, in the presence of a T-type intersection, subjects reported the color of the target curve in 42% of the error trials (Fig. 6). Instead, the color of the distractor curve was named in only 30% of the erroneous trials. This is significantly less than the fraction of trials in which the color of the target curve was named ($P < 0.01$). Thus, in the presence of a T-type intersection features are more likely to migrate from the target curve than from the distractor curve onto the irrelevant curve.

A D-type intersection reversed the outcome (Fig. 6). Now subjects reported the color of the distractor curve in 39% of the error trials. The color of the target curve was reported in only 31% of the error trials, which is significantly less ($P < 0.05$). Thus, in the presence of a D-type intersection, features tend to migrate from the distractor curve rather than from the target curve onto the irrelevant curve. These results, taken together, indicate that features have an enhanced probability to be exchanged between two curves that meet in an intersection.

4. Discussion

The present results allow a distinction between three models of contour integration. The first model holds that contour grouping occurs at the pre-attentive stage, because it is based on the Gestalt criteria of collinearity and connectedness (Neisser, 1974; Treisman & Gelade, 1980; Posner & Presti, 1987; Duncan & Humphreys, 1989; Wolfe, 1994). This model can be rejected on two grounds. First, the pattern of reaction times is not consistent with a contour grouping operation that has unlimited capacity, because intersections between the target and distractor curve cause substantial delays (see also Roelfsema et al., 1999). Delays in contour grouping have also been observed for stimuli without intersections. Previous curve-tracing studies showed that the reaction time for stimuli without intersections depends

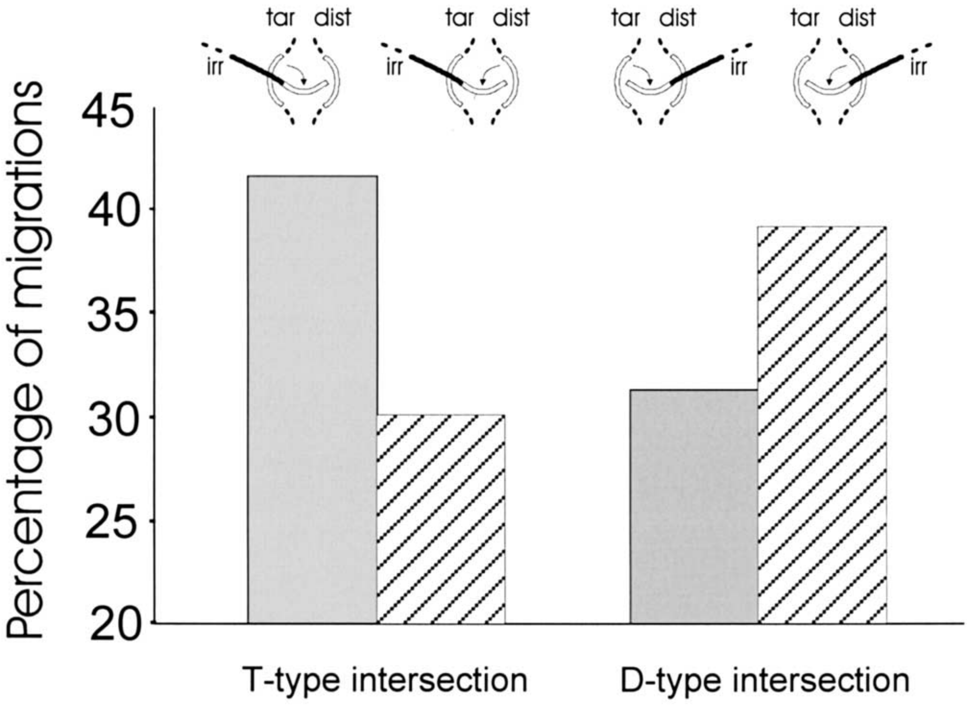

Fig. 6. Feature migrations in the color-naming task. Trials were evaluated in which the subject gave an incorrect response for the hotspot of the irrelevant curve, in the presence of a T-type (left) or D-type intersection (right). The percentage of these error trials in which the color of the hotspot of the target curve was named is shown as gray bars, and the percentage of trials in which the color of the distractor curve was named is shown as striped bars. Insets show the contour configuration in the vicinity of the hotspots, and the arrows illustrate the feature migrations.

on the distance that needs to be traced along the target curve (Jolicoeur et al., 1986; Pringle & Egeth, 1988). Thus, considerable temporal delays occur during curve tracing in spite of the fact that the object that needs to be segregated is a simple curve, whose segments are easily identified because they are locally collinear and connected to each other. Second, the results of the secondary color probe task are also inconsistent with pre-attentive contour grouping. These results indicate that attention is directed to the target curve in each of the stimulus categories, including the one without intersections (category I, Fig. 3b).

The second model that can be rejected deploys attention strategically. This model suggests that attention needs only to be directed to the critical zones, because the information in these zones is both necessary and sufficient to solve the task. Instead, the data show that attention is also directed to contour segments outside the critical zones that belong to the target curve.

The results support a third model of contour integration, which suggests that attention has to label spatially separate contour segments to group them into a coherent representation. Attention may spread over the segments of the target curve because these are collinear and connected to each other. The present task would be solved as soon as the target curve is labeled by attention in its entirety, since this would identify the circle that is connected to the fixation point. In this view, reaction times during curve tracing tasks reflect the delays that occur during the distribution of attention (Roelfsema et al., 2000).

If the curve that is traced intersects with another curve, reaction time increases substantially. Intersections among curves that need not be traced have less effect on the reaction time (Fig. 4c). Two curves are connected at an intersection, and only collinearity remains as a cue to segregate the curves. Intersections with the target curve may therefore impede a selective attentional labeling of this curve. Indeed, at such intersections attention leaks into the crossing curve. These intersections also promote the migration of features from the target curve onto the crossing curve.

The present results are in good correspondence with a recent physiological study of curve tracing in the primary visual cortex of awake monkeys (Roelfsema, Lamme, & Spekreijse, 1998). Neural responses to a traced curve were enhanced relative to responses to a distractor curve. This also occurred when the traced curve crossed another curve. Thus, at a neurophysiological level, the entire target curve is labeled by an enhanced neuronal response. The present results indicate that this neuronal response enhancement provides a correlate of visual attention, which is directed to the target curve.

Previous studies that used different techniques have also reported that visual attention is required for grouping on the basis of Gestalt criteria (Ben-Av et al., 1992; Mack, Tang, Tuma, Kahn, & Rock, 1992). One of these studies (Mack et al., 1992) investigated perceptual grouping under conditions of 'inattentional blindness'. In this study, subjects had to make a judgement about a cross that was superimposed onto a pattern composed of small texture elements. On one of the trials, elements of the texture pattern could unexpectedly be grouped together on the basis of their proximity, luminance or their orientation. Remarkably, when subjects were queried about the texture elements, they usually failed to report the grouping. However, Moore and Egeth (1997) argued that the failure to report about the perceptual organization of a pattern does not imply that grouping is absent. Indeed, their study demonstrated that grouping can occur without attention, and that groupings that cannot be consciously recollected may nevertheless influence subjects' judgements on another task. At this point, the reader may get the impression that we are left with a number of conflicting studies on the relationship between Gestalt grouping and attention, and that the present results only add to the confusion. How can we reconcile all these conflicting findings into a single conceptual framework?

We would like to argue that reconciliation is possible if a distinction is made between two types of grouping (Roelfsema et al., 2000). The first type of grouping is called base grouping, and reflects the tuning of individual neurons in the visual cortex. The activation of neurons that are selective to the shape of a face, for example, implicitly groups together the contours that belong to the mouth, the eyes, and other components of the face. Shape selective cells are abundant in the inferotemporal cortex, and many of these neurons are activated within 100 ms of stimulus presentation (Oram & Perrett, 1992; Kobatake & Tanaka, 1994; Lamme & Roelfsema, 2000). Thus, base groupings are available at an early point in time, although the neurons encoding them may be at a relatively high level of the visual cortical processing hierarchy.

The scope of base grouping has to be limited. Indeed, it is unlikely that there are cells in higher visual areas that are tuned to arbitrary feature constellations (von der Malsburg, 1995). An additional type of grouping, called incremental grouping, is required if base grouping fails to do the job (Roelfsema et al., 2000). Incremental grouping is a time consuming process involving visual attention. It is necessary if relationships need to be established between features that are not encoded by individual neurons. Regarding curve tracing, for example, it is unlikely that there are neurons that are tuned to curves of arbitrary shape. Thus, in order to group all segments of an elongated curve together, incremental grouping is required, and this appears to be implemented by labeling an entire curve with visual attention.

The distinction between base grouping and incremental grouping may explain why some studies (e.g. Moore & Egeth, 1997) obtained evidence for grouping in the absence of attention, whereas other studies (e.g. Ben-Av et al., 1992) and the present study seem to imply that grouping does not occur without attention. Moore and Egeth (1997) obtained evidence for grouping of a row of black elements on a gray background, in the absence of attention. However, it is likely that base grouping would account for their results, since the row of black elements formed a straight contour, at least when viewed at a low spatial resolution, and neurons tuned to such contours are abundant in the visual cortex. In the present task, however, contour segments of a relatively contorted target curve had to be grouped together. This presumably requires incremental grouping, since it is unlikely that there are neurons tuned to such arbitrary shapes in the visual cortex.

The present results as well as our interpretation are partially consistent with the feature integration theory of Treisman and Gelade (1980), which also suggested that attention needs to be directed to an object in order to integrate all its features into a coherent representation. However, the present attentional hypothesis deviates from the feature integration theory in a number of respects. First, grouping on the basis of Gestalt criteria was suggested to occur with unlimited capacity in the feature integration theory, and should therefore not be associated with temporal delays. Temporal delays in the feature integration theory are caused by shifts of attention from one object to another, but not by the need to distribute attention over the various components of a single object. Second, feature integration theory selects an object on the basis of its spatial location, and attention has the shape of a spotlight. Many visual objects are spatially compact, and their features can indeed be grouped on the basis of spatial location. However, grouping on the basis of proximity alone breaks down for spatially extended, or overlapping objects (Duncan, 1984; Lavie & Driver, 1996; Blaser, Pylyshyn, & Holcombe, 2000). In these situations other grouping cues like colinearity and connectedness need to be evaluated.

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