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A gradual spread of attention during mental curve tracing

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The visual system has to segregate objects that are relevant to behavior from other objects and the background, if they are embedded in a visual scene. This segregation process can be time consuming, especially if the relevant object is spatially extended and overlaps with other image components, but the cause of the delays is presently not well understood. In the present study, we used a curve-tracing task to investigate processing delays during the grouping of contour segments into elongated curves. Our results indicate that contour segments that need to be grouped together are labeled with visual attention. Attention gradually spreads from contour segments that were labeled previously to other contours that are colinear and connected to them. The contour-grouping task is completed as soon as attention is directed to the entire curve. We conclude that processing delays during contour grouping are caused by a time-consuming spread of visual attention.

At any given moment, a wealth of information is presented to our visual system. We cannot act upon all of this information at once, and it is therefore necessary to segregate relevant objects from the background. Scene segmentation is usually assumed to be subdivided into two stages. The first, preattentive stage provides an initial parsing of the scene by applying grouping and segmentation cues in parallel across the entire image. It is generally believed that Gestalt criteria, such as colinearity and connectedness, are applied during this stage. If the preattentive parsing is insufficient for the task at hand, visual attention is brought into play, at the cost of additional processing time. Two classes of models have been proposed for attentive scene segmentation. In *spatial* attention models, visual features within the focus or spotlight of attention are grouped together and segregated from the rest of the image (e.g., Eriksen & St. James, 1986; Posner, 1980; Treisman & Gelade, 1980). According to *object-based* models, attention may also be directed selectively to the features of a spatially extended object (Egly, Driver, & Rafal, 1994), which is thereby segregated from other image components that may even be spatially overlapping (e.g., Driver & Baylis, 1989; Duncan, 1984). It has been noted that these models are not mutually exclusive (Behrmann, Zemel, & Mozer, 1998). Proponents of both types of models have assumed that the source of the additional temporal delays in attentive processing (as is manifested, for example, in visual search tasks) is the time that is needed for attention to shift to either successive locations or objects.

However, several experiments on contour grouping have reported temporal delays associated with the integration of information that belongs to a single, spatially extended object (Jolicœur, Ullman, & Mackay, 1986, 1991; Pringle & Egeth, 1988; Roelfsema, Scholte, & Spekreijse, 1999). These studies employed a curve-tracing task, in which subjects have to judge whether contour segments do or do not belong to the same elongated, smooth curve. All the segments of such a curve can be grouped, since they are locally colinear and connected to each other. However, the observed temporal delays imply that these Gestalt criteria are not invariably evaluated by an unlimited capacity mechanism. Two models have been proposed for these delays, and both suggest that the application of Gestalt criteria sometimes requires visual attention.

The first model is a spatial attention model (McCormick & Jolicœur, 1991). In this model, a curve is traced by shifting a beam of attention over its successive segments until some preset goal is reached. Shifts of this beam take time

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and account for the temporal delays during curve tracing. The second model is a spreading attention model (Roelfsema, Lamme, & Spekreijse, 2000). According to this model, attention *spreads* over the curve that is traced, from attended contour segments to other segments that are colinear and connected to them. Thus, although *locally* colinear and connected elements can be grouped preattentively, attention has to spread across the entire curve to integrate all contour segments into a coherent representation. In this model, temporal delays associated with the integration of the elements of a spatially extended object are a consequence of a time-consuming spread of visual attention.

In the present experiment, we investigated the cause of processing delays during the grouping of contour segments into a global object representation. To distinguish between the focal attention and the spreading attention model, we used a dual-task design. The primary task was a curve-tracing task that is illustrated in Figure 1. Subjects saw one of eight stimuli (Figure 1A) and had to decide whether a fixation point was connected by a curve to either a left or a right circle. We will refer to the curve that makes this connection as the *target* curve and to the other curve as the *distractor* (Figure 1B). In order to probe the distribution of attention at different stages of the curve-tracing process, colors were presented on different segments of both curves at various time intervals. The secondary task was to report one of these colors. If attention is directed to a segment of a curve, this segment should be perceptually enhanced relative to other segments. A color presented at that segment should, therefore, be reported more reliably than a color that is presented at an unattended segment (Scholte, Spekreijse, & Roelfsema, 2001).

Both models predict that all segments belonging to the target curve are attended at some point in time. However, they make different predictions regarding the spatio-temporal distribution of attention during curve tracing. According to the focal attention model, the processing focus moves over the curve, and attention does not need to linger at locations that were processed before. Colors will be reported reliably only when they are presented at the moment that the processing focus is passing over their location (Figure 2A). In contrast, the spreading attention model predicts that attention remains present at contour segments that were integrated into the coherent object representation at an earlier point in time. Therefore, performance in the color report task is expected to be high when a color is presented at any segment that has been reached by the spread of attention (Figure 2B). Both models predict that performance in the color report task is poor for the distractor curve, since attention is not directed to this curve.

METHOD

Subjects

Thirteen female and 5 male students (mean age, 22 years, $SD = 2$) received course credits for their participation in the experiment, which lasted 2 h. All reported normal or corrected-to-normal visual acuity and normal color vision. Informed consent was obtained from all the subjects. The data of 3 subjects were excluded from analysis because of poor performance on the primary task. They responded correctly to the stimulus category with two intersections (Category IV in Figure 1A) on fewer than two thirds of the trials.

Stimuli

The stimuli consisted of a fixation point, two curves, and two circles. The viewing distance was 129 cm, resulting in 5º of visual

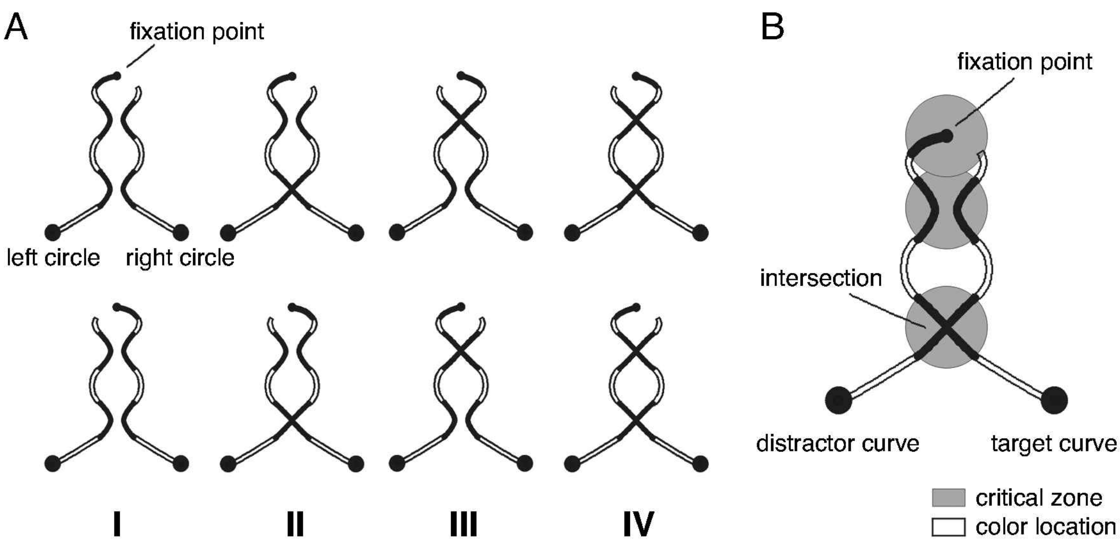

Figure 1. (A) The eight stimuli of the curve-tracing task. The subjects had to report whether a fixation point was connected to a left or a right circle. Results are pooled across stimuli that are each other's mirror image. This results in four stimulus categories (I–IV). (B) The stimuli differed from each other at three critical zones (gray circles). In the upper critical zone, the fixation point was connected to either the left or the right curve. At the other two critical zones, the curves could intersect each other.

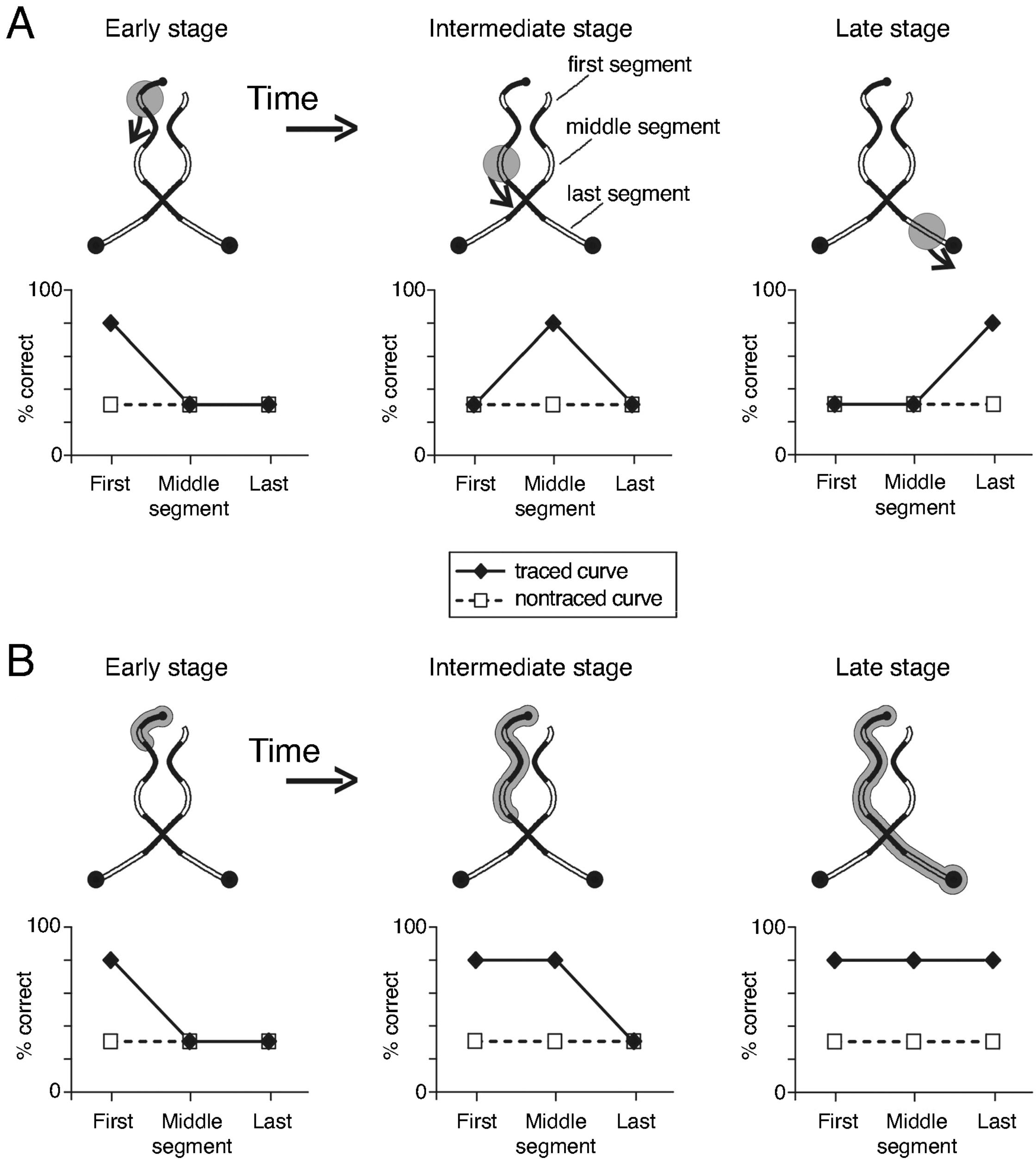

Figure 2. The expected results on the secondary (color report) task for the focal attention model (A) and the spreading attention model (B). The different graphs present the different stages of the tracing process at which a color can be presented. Lower panels show expected performance on the secondary task (ordinate) as a function of the location of the probed segment (abscissa). Diamonds depict the expected performance for the curve that is being traced (target curve); squares depict the performance for the nontraced (distractor) curve.

angle for the height of the patterns. The luminance of the stimuli was 20 cd/m^2, and that of the background was 0.7 cd/m^2. The stimuli differed from each other at three *critical zones* (Figure 1B). In the upper critical zone, the fixation point connected to either the left or the right curve. At the other two critical zones, the curves could intersect each other. Responses to mirror image stimuli were grouped, thereby creating four different stimulus categories (Figure 1A, I–IV). The primary task of the subjects was to decide whether the left or the right circle was connected to the fixation point by one of the curves, by pressing a button with the left or the right hand, respectively.

Dual-Task Procedure

Each subject was tested in six blocks consisting of 144 trials each. The sequence of events during a trial is illustrated in Figure 3. A trial started with the presentation of a fixation point for 300 msec. Thereafter, one of the eight stimuli of the primary task was presented until

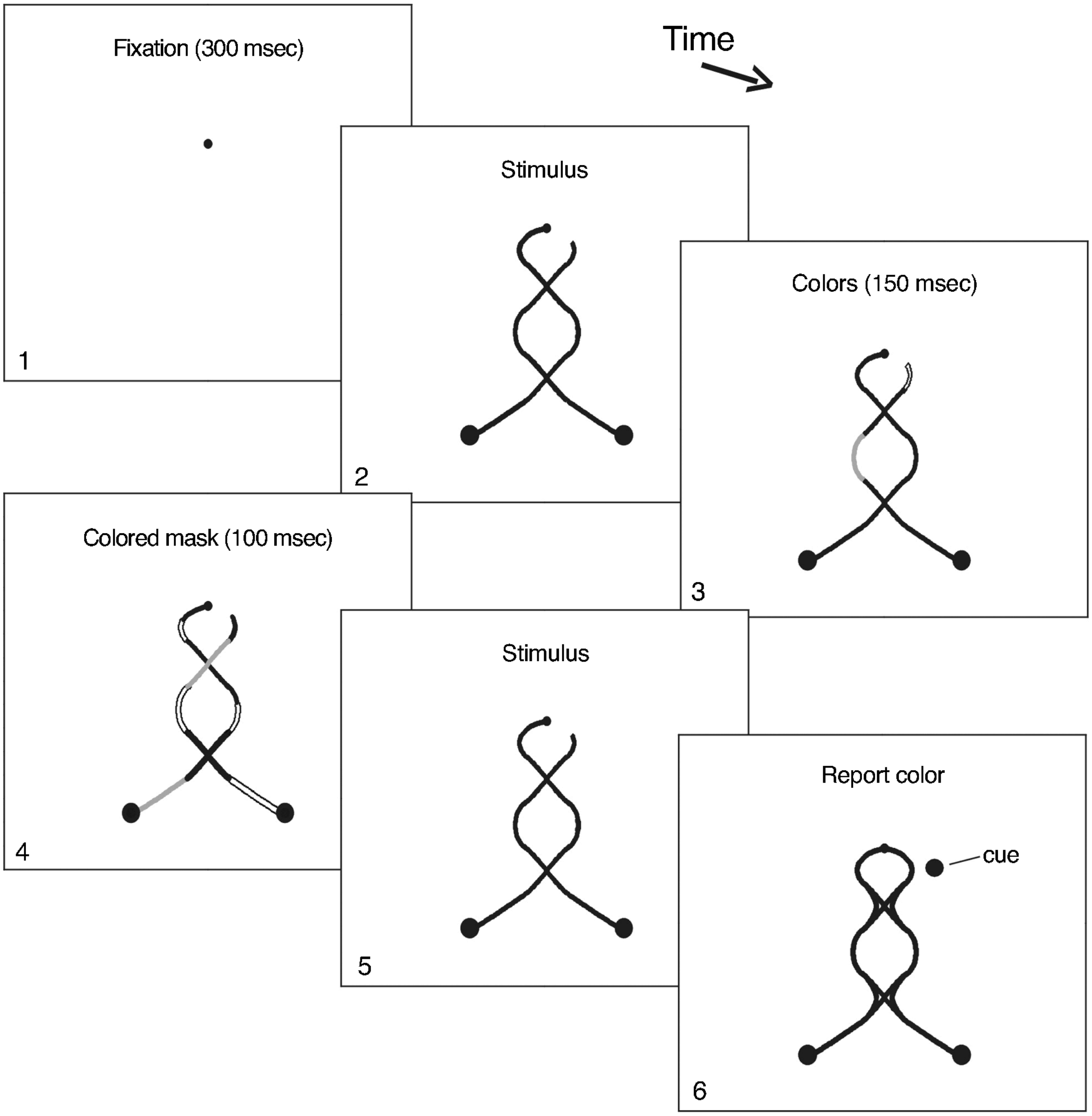

Figure 3. The sequence of events during a trial. Colors were briefly presented at two of six possible locations and were masked thereafter. After the response in the primary curve-tracing task, one of the two color locations was cued, and the secondary task was to report the color that had appeared at this location.

a response was made—that is, a press of the left or the right button. During the presentation of the stimulus, two of three randomly chosen isoluminant colors (red, green, and blue) were presented for 150 msec. The colors were presented at two of six possible locations at the upper, middle, or lower segment of the target or the distractor curve, outside the critical zones. They appeared at an early, an intermediate, or a late time interval during a trial. After their presentation, a colored mask was shown for 100 msec in yellow, purple, or light blue. These mask colors appeared at randomly chosen locations on the curves, covering the whole stimulus. When the subject had responded correctly in the primary task, one of the two previously colored segments was cued, and the subject had to verbally report the color that had been presented at the cued location. If the subject made an error in the primary task, no segment was cued, and the subject did not have to report a color. Thus, secondary task performance was analyzed only on trials on which the subjects responded correctly. Trials on which the mask had not been present for 100 msec, because of an early response of the subject, were also removed. This resulted in the exclusion of 2.5% of the trials. Equiluminance of the six colors was determined for each subject by using a heterochromatic flicker paradigm.

Determination of Color Intervals

Prior to the dual-task condition, each subject was first tested on 240 trials with the primary curve-tracing task only, to determine a baseline reaction time distribution for each of the four stimulus categories. The onset times of colors in the subsequent dual-task condition were derived from these distributions. The colors were always presented for 150 msec, and for each stimulus category there were three intervals. The first interval started at the stimulus onset ($t_{1\text{start}} =$

0 msec, t_{1end} = 150 msec). The start of the third interval equaled the 10th percentile of the baseline reaction times for a particular stimulus category minus 250 msec ($t_{3start} = t_{10th} - 250$ msec; $t_{3end} = t_{10th} - 100$ msec). The second interval was exactly between the first and the third interval. It started at $(t_{1start} + t_{3start})/2$ and ended 150 msec later.

Emphasis on Primary Task

The addition of the color report task might bias the subjects to concentrate on this secondary task and thereby change their strategy on the primary curve-tracing task. To ensure that the subjects concentrated on curve tracing, they were instructed to respond as fast and accurately as possible on the primary task. Moreover, if a reaction time on a trial in the dual-task session was longer than the 90th percentile of the distribution of reaction times during the baseline task for the corresponding stimulus category, the subjects were instructed to speed up in the primary task by means of auditory feedback immediately after the trial. Furthermore, in a post hoc analysis for each subject, reaction times in the dual-task session were compared with the reaction times in the baseline condition for each stimulus category. For each subject, an analysis of variance (ANOVA) with task and stimulus category as factors confirmed that reaction times in the dual-task condition were not significantly longer than those in the baseline task. In addition, there was no significant interaction between task (single or dual) and stimulus category. This suggests that the subjects did not change their strategy in the curve-tracing task when the color report task was added.

Eye Movement Recording

The subjects were instructed to maintain fixation at the fixation point. To verify this, eye movements and blinks were recorded by means of four electrodes placed around the right eye and one reference electrode placed on the forehead. Trials on which an eye movement or a blink was detected (off line) were excluded from the analysis.

RESULTS

Primary Task Performance

The reaction times in the primary task are presented in Figure 4, averaged across subjects. Mean individual reaction times were analyzed with an ANOVA with stimulus category as a factor. There was a main effect of stimulus category on reaction time [$F(3,42) = 154$, $p < .0001$]. More intersections led to longer reaction times, increasing from 580 msec at zero intersections to 649 and 677 msec at one intersection and to 856 msec at two intersections. Post hoc comparisons indicated that differences between the reaction times to all stimulus categories were significant ($p < .0001$, Tukey HSD). This was not due to a speed/accuracy tradeoff, since the percentage of errors increased with the number of intersections from 3.3% at zero intersections, to 5.1% and 5.0% at one intersection and to 19.6% at two intersections (Figure 4). An ANOVA indicated that there was a main effect of stimulus category on the number of errors [$F(3,42) = 65.81$, $p < .0001$]. This was due to a larger number of errors for the stimulus with two intersections than for any other stimulus category ($p < .0001$, Tukey HSD).

Secondary Task Performance

After the removal of trials in which the subjects responded incorrectly in the primary task, trials in which the mask had not been present for 100 msec, and trials in which an eye movement or a blink was detected, 80.6% of the

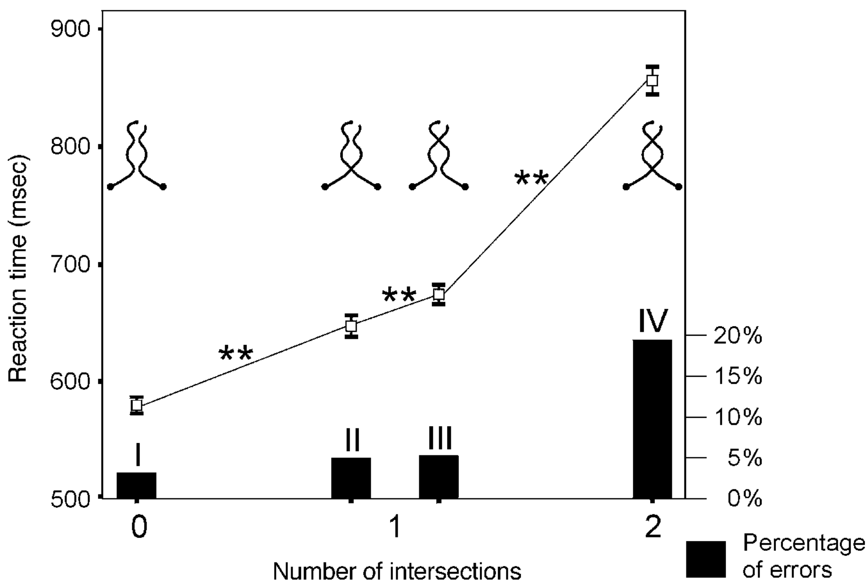

Figure 4. Performance on the primary curve-tracing task for each of the four stimulus categories (I–IV), pooled across subjects. Squares indicate average reaction times. Error bars indicate *SEM*s. Dark bars show the percentages of errors. A ** indicates a significant difference between stimulus categories at the .0001 level (Tukey HSD test).

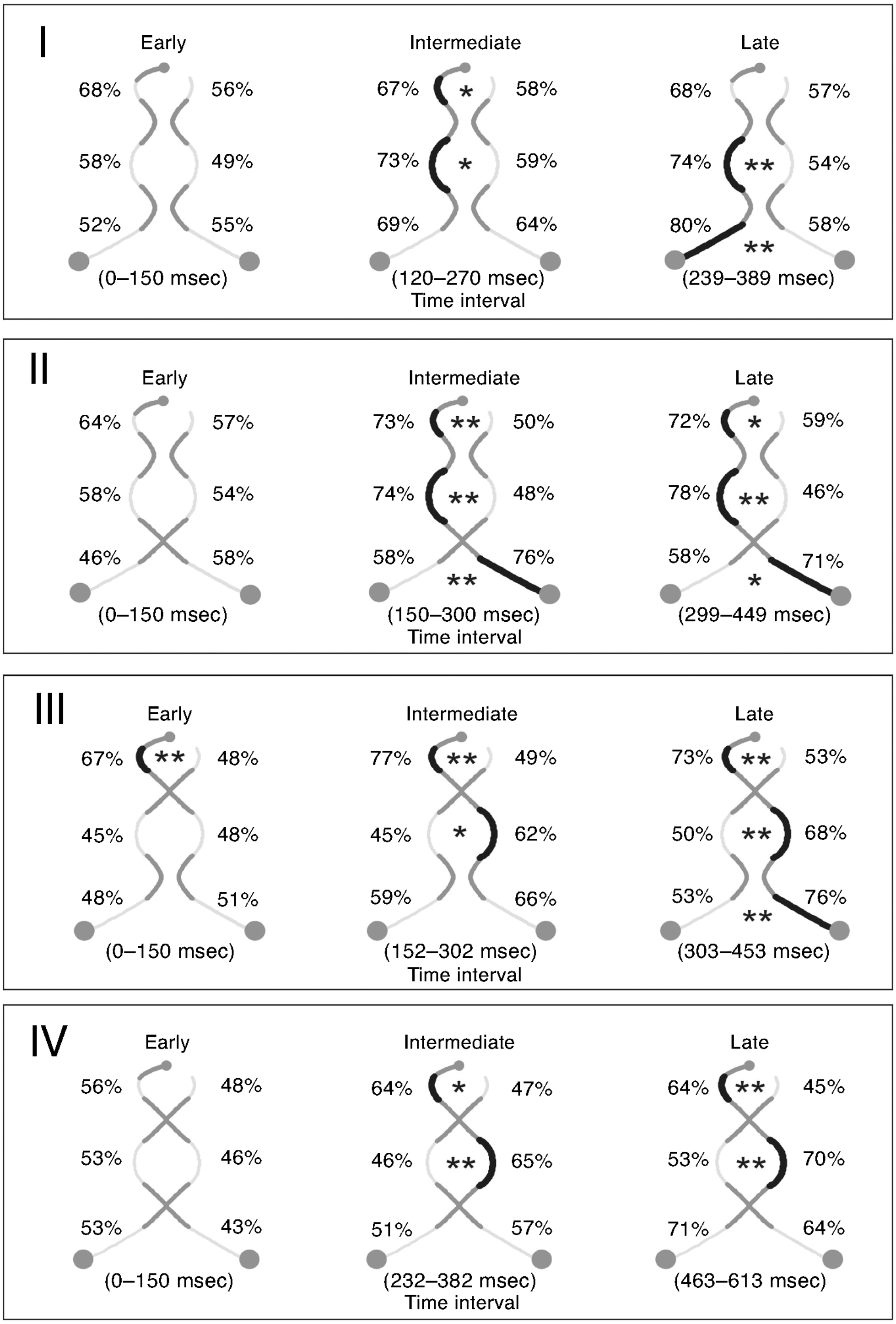

Figure 5. Percentages of correctly reported colors for the different stimulus categories (I–IV) at the three time intervals, pooled across subjects. Significant differences between performance on corresponding locations of the target and the distractor curves are indicated by a darker color. A * indicates a significant difference at the .05 level; a ** indicates significance at the .01 level.

trials remained for analysis. The results are summarized in Figure 5. Numbers within parentheses indicate the mean onset and offset times of the colors, averaged across subjects. To measure the spatial distribution of attention, performance on the color-naming task was compared between cue locations at corresponding locations on the target and distractor curves for each stimulus category and for each time interval. Significance was determined by using a Monte Carlo procedure (Foster & Bischof, 1991; Press, Flannery, Teukolsky, & Vetterling, 1986; Thompson, 1993; see the Appendix). For Stimulus Category I (Figure 5, upper panel), no significant difference was observed in the early interval, although the difference did approach significance for the upper location ($p < .06$). In the intermediate interval, performance at the upper and middle cue locations was better for the target curve than for the distractor curve ($p < .05$). In the late interval, performance was better at the middle and lower cue locations of the target curve ($p < .01$), but not at the upper location (although this difference approached significance; $p < .06$).

For Stimulus Category II (Figure 5, second row), no significant difference in performance between the target and the distractor curves occurred in the early interval, but again the difference at the upper location approached significance ($p < .07$). In the intermediate time interval, performance became better at the upper, middle, and lower cue locations on the target curve ($p < .01$). In the late interval, performance remained better at all cue locations of the target curve ($p < .05$, .01, and .05 for the upper, middle, and lower cue locations, respectively).

Performance for Stimulus Category III (Figure 5, third row) in the early interval was better at the upper location of the target curve ($p < .01$). In the intermediate time interval, performance was better at both the upper ($p < .01$) and middle ($p < .05$) cue locations of the target curve, and it was better at all its cue locations in the late interval ($p < .01$).

Finally, no significant differences in performance in the color-naming task occurred in the early interval for Stimulus Category IV (Figure 5, lower row). In the intermediate time interval, however, performance became significantly better for the upper ($p < .05$) and middle ($p < .01$) cue locations of the target curve, and these differences remained in the late interval (both ps $< .01$).

Presentation of the colored segments was followed by a mask, to avoid visual persistence of the presented colors (Phillips, 1974). This proved to be important, since color information that persists in a sensory buffer can be boosted by attention at a later point in time. Without the mask, a different pattern of results was obtained (data not shown). In that case, colors that were presented at lower segments of the target curve at early time intervals also were reported reliably, which suggests that they were indeed stored in a sensory buffer that was boosted when attention arrived at these segments at a later point in the tracing process. In the present experiment, performance in the color report task did not differ between the target and the distractor curves for the middle and lower locations in any of the stimulus categories in the earliest time interval and differed at the lower locations in only one of the four stimulus categories in the intermediate time interval. We may therefore conclude that the mask was effective in removing colors from this sensory buffer.

DISCUSSION

The pattern of reaction times in the primary task demonstrates that contour grouping on the basis of colinearity and connectedness is not always performed with unlimited capacity in parallel across the visual field. Reaction times increased significantly with each additional intersection between the target and the distractor curves, showing that contour grouping can be time consuming (see also Jolicœur et al., 1986, 1991; Roelfsema et al., 1999; Scholte et al., 2001).

One might expect that subjects become more efficient over trials if the same eight stimuli are used throughout the experiment, as was the case in the present paradigm. However, previous experiments have shown little improvement in tracing efficiency even after 100 consecutive trials with the same curves (Wolfe, Klempen, & Dahlen, 2000). Thus, contour grouping takes time, even if the stimuli are highly familiar.

The present curve-tracing task could, in principle, also be solved by a strategy that takes only the information inside the critical zones (gray in Figure 1) into account. One such strategy would be to count the number of intersections and to press the button on the same side as the connection to the fixation point if this number is even and to press the other button if it is odd. Previous results demonstrated that the pattern of reaction times observed in the primary task (Figure 4) are inconsistent with this strategy (Roelfsema et al., 1999). If subjects are forced to use only information in the critical zones, average reaction time increases substantially, and the pattern of reaction times is drastically different from that in Figure 4. The results obtained in the secondary task of the present study also exclude this strategy, by demonstrating that subjects direct their attention to contour segments of the target curve that are outside the critical zones.

Two attention models have been proposed, both of which can account for the delays observed during curve tracing (Figure 2). The first model employs a processing focus, which is shifted to successive segments along the target curve (McCormick & Jolicœur, 1991; Figure 2A). In this model, the processing focus does not need to linger at contour segments that were encountered earlier. The second model suggests that object-based attention is gradually spread over the target curve (Roelfsema et al., 2000; Figure 2B). According to this model, all the segments of the target curve are eventually labeled by attention, which thereby groups them together into a coherent representation. Thus, the spreading attention model predicts that attention remains on the initial segments of the target curve, whereas this is not required in the focal attention model (we note that the two models become identical if it is assumed that the processing focus leaves an attentional trace behind).

The results support the spreading attention model, since in three out of the four stimulus categories, performance at the initial segment of the color task remained better for the target than for the distractor curve, even during the late interval (Figure 5) (in the remaining stimulus category, there was a similar trend that just failed to reach significance; $p < .06$). If the results are collapsed across stimulus categories (Figure 6), it is evident that attention indeed gradually spreads along the target curve. Apparently, attention spreads from attended contour segments to other segments that are colinear and connected, until the end of the

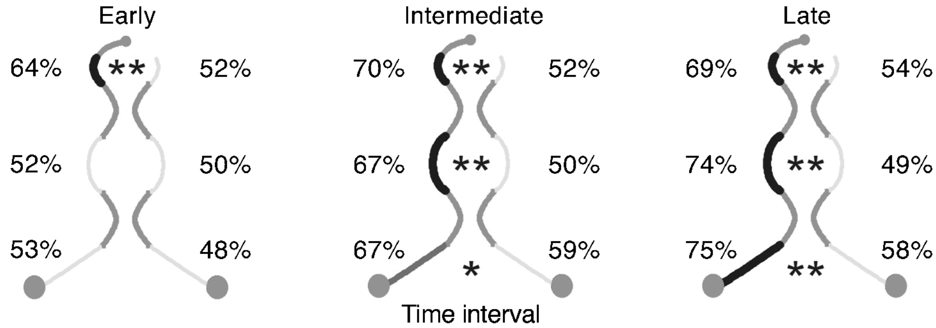

Figure 6. Mean percentages of correctly reported colors at the three time intervals, pooled across stimulus categories and subjects. A * indicates a significant difference between the performance on the target and the distractor curves at the .05 level; a ** indicates significance at the .01 level.

target curve is reached. We propose that attention labels these contour segments in order to integrate them into a coherent representation of the target curve.

This conclusion contradicts theories that assume that Gestalt grouping rules are applied preattentively (e.g., Treisman & Gelade, 1980) and may even seem to be at odds with data from other contour integration tasks, such as the so-called *pathfinder displays* studied by, for example, Field, Hayes, and Hess (1993; see also Hess, Beaudot, & Mullen, 2001; Kovács & Julesz, 1993). In the pathfinder task, a single figure that consists of colinear elements has to be detected on a background of distractor elements with random orientations. It may, therefore, be called a *figure–ground* segregation task. It can be solved by local operators that are sensitive to the degree of colinearity between neighboring image elements (see, e.g., Gigus & Malik, 1991). These operators could, in principle, be applied in parallel across the visual field. In contrast, curve tracing is a *figure–figure* segregation task, since the degree of colinearity does not differ between the target and the distractor curves. In this case, grouping requires an additional process that combines the local groupings between neighboring contour segments to form a coherent representation of an entire curve. The present results demonstrate that such a coherent representation is formed by attention, which labels all contour segments that need to be grouped together.

This view is partially consistent with the feature integration theory (Treisman & Gelade, 1980), which proposed a similar role for attention in grouping features of different domains, such as colors and orientations. However, our results are not entirely consistent with the feature integration theory for two reasons. First, in the feature integration theory, Gestalt criteria are applied preattentively, whereas in curve tracing they are also applied during attentive processing. We propose that in curve tracing, local groupings form preattentively but that attention comes into play whenever a correct global segmentation requires the joint evaluation of many of these local groupings. Second, in feature integration theory, attention can move from one location to another, but the possibility of a time-consuming spread of attention across a single object is not considered.

The present results are consistent with physiological data from the primary visual cortex of monkeys engaged in similar curve-tracing tasks. During curve tracing, neuronal responses in the primary visual cortex to the target curve are enhanced relative to responses evoked by the distractor curve (Roelfsema, Lamme, & Spekreijse, 1998). Furthermore, the response enhancement of neurons with a receptive field distal to an intersection is delayed relative to the response enhancement of neurons with a receptive field proximal to the intersection (Roelfsema & Spekreijse, 1999). This suggests that curve tracing is implemented in the visual cortex by the gradual spread of a firing rate enhancement among neurons that respond to various segments of a single curve. Numerous studies have reported enhanced firing rates in various visual cortical areas during tasks that require attention to be directed to one of several visual objects (e.g., Maunsell, 1995; Moran & Desimone, 1985), which suggests that this spreading rate enhancement is manifested at the psychological level as a gradual spread of attention across the object of current relevance.

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APPENDIX

Because the performance data of individual subjects in the secondary color report task are not normally distributed and the numbers of trials per cell differ substantially, we used a Monte Carlo procedure to analyze the significance of differences in performance in the color report task (Foster & Bischof, 1991; Press et al., 1986; Thompson, 1993). The null hypothesis stated that performance at a particular segment is similar for corresponding cue locations on the target curve and the distractor curve. Differences in performance between subjects, stimulus categories (I–IV), intervals (early, intermediate, and late), and color locations (upper, middle, and lower) were allowed in the null hypothesis. Suppose that t is a cue location on the target curve and that d is a cue location at the corresponding location on the distractor curve. In addition, suppose that the total number of responses of a Subject s for cue locations t and d at interval i are $Nt_{i,s}$ and $Nd_{i,s}$ and that $Ct_{i,s}$ and $Cd_{i,s}$ are the number of correct responses. According to the null hypothesis, we may pool the data across t and d, and a good estimate of performance that takes all data into account would be $(Ct_{i,s} + Cd_{i,s})/(Nt_{i,s} + Nd_{i,s})$. In other words, an unbiased estimate of the performance of this subject in this interval according to the null hypothesis is $Perf_{i,s} = (Ct_{i,s} + Cd_{i,s})/(Nt_{i,s} + Nd_{i,s})$. Because, according to the null hypothesis, performance is similar for t and d, the expected value of $Perf_{i,s}$ should equal the expected value of both $Ct_{i,s}/Nt_{i,s}$ and $Cd_{i,s}/Nd_{i,s}$. The expected value of $Ct_{i,s}/Nt_{i,s} - Cd_{i,s}/Nd_{i,s}$ should therefore be 0 for each Subject s. This implies that, in this interval, the expected value of the total td-difference $= \Sigma_s\ (Ct_{i,s}/Nt_{i,s} - Cd_{i,s}/Nd_{i,s})$, summed over subjects, should also be 0. For each stimulus category and interval, 10,000 experiments were simulated in which $Nt_{i,s}$ and $Nd_{i,s}$ responses were generated for each Subject s. In this simulation, the probability of a correct response was set to $Perf_{i,s}$ for both cue locations (t and d). This gives a distribution of 10,000 td-differences, generated according to the null hypothesis. The significance of a difference in performance between cue locations t and d was determined by comparing the experimental td-difference with the distribution of the 10,000 simulated td-differences. The significance of differences in secondary task performance between target and distractor curve at other cue locations was analyzed in the same way.

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