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Temporal constraints on the grouping of contour segments into spatially extended objects

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Abstract

The speed of contour integration was investigated in a task that can be solved by grouping contour segments into elongated curves. Subjects had to detect a continuous curve, which could be intersected by one or two other curves. At locations where these curves came in close proximity, the assignment of contour segments to the different curves could be based on collinearity. Reaction times exhibited a strong dependence on (1) the presence of intersections among curves; and (2) the context provided by the stimulus set from which individual stimuli were selected. Reaction times were shortest when grouping of contour segments depended on information at a single location in the visual field. In this condition, responses to stimuli containing an intersection were faster than responses to stimuli that did not. When responses were determined by information at spatially separate locations, responses were delayed, and every intersection increased the reaction time considerably. This result contrasts with earlier investigations which have suggested that contour integration on the basis of collinearity is performed pre-attentively but is in accordance with studies on curve tracing. We propose that the assignment of contour segments to equally coherent curves, a process which may be called figure–figure segregation, is a function of object-based attention. Moreover, the protracted reaction times for some of the stimuli indicate that spread of attention within an object costs time. This implies that object recognition is not always as fast as is sometimes assumed.

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

1. Introduction

Present theories of visual perception subdivide the processes underlying identification of objects in natural scenes in pre-attentive and attentive systems (Treisman & Gelade, 1980; Julesz, 1984; Posner & Presti, 1987; Allport, 1989; Cave & Wolfe, 1990; Kinchla, 1992). The pre-attentive system operates automatically and rapidly to segregate visual objects from background, whenever this distinction is possible on the basis of primitive image qualities. Pre-attentive processing takes place in parallel across the visual field, a property that accounts for its speed. Attentive processing, on the other hand, performs figure-ground segregation by selecting visual figures that are provided by the pre-attentive system, presumably one at a time (Treisman & Gelade, 1980; Bergen & Julesz, 1983; Eriksen & Yeh, 1985; Treisman & Gormican, 1988; Kinchla, 1992). Therefore, one of the defining characteristics of attentive processing is that it is time-consuming, and many studies have measured reaction-times to distinguish between pre-attentive and attentive performance

This distinction is corroborated by studies on texture segregation (Bergen, 1991). Whenever image elements of the figure differ in rather primitive qualities, like orientation, from the background, texture segregation is rapid and effortless (Olson & Attneave 1970; Treisman & Gelade, 1980; Julesz, 1981; Voorhees & Poggio, 1988). It is assumed that pre-attentive processing groups image elements with similar features automatically (Beck, 1966), and forms boundaries between figure and background where visual features change abruptly (Nothdurft, 1993). More complicated distinctions between image elements are not associated with an automatic segregation between figure and background, and

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this is taken as evidence that for these distinctions visual attention is required (Treisman & Gelade, 1980; Bergen & Julesz, 1983).

The importance of featural similarity for effortless perceptual grouping was, in fact, already recognized by the Gestalt psychologists in the first half of our century (reviewed by Rock & Palmer, 1990). The Gestalt psychologists have also delineated further grouping criteria, like collinearity and connectedness, 'good continuation' in their words (Koffka, 1935). Recent studies have confirmed that collinearity of image elements is indeed a potent grouping criterion (Field, Hayes & Hess, 1993). The detection of a group of collinear image elements among non-collinear distractors is performed effortlessly (Kovács & Julesz, 1993). This suggests that collinearity should be added to the list of grouping criteria available to the pre-attentive system. This conclusion is plausible from a computational point of view since fast, feedforward algorithms exist for the detection of contours that are defined by collinear line elements (Gigus & Malik, 1991).

However, contrasting results have been obtained in studies on curve tracing (Jolicoeur, Ullman & MacKay, 1986; Pringle & Egeth, 1988). In these studies, two equally coherent curves are displayed and subjects have to decide whether two crosses are lying on the same or on different curves. The time to decide whether two crosses are on the same curve increases monotonically with the distance between them, as measured along the curve. This suggests that some time-consuming mental operation tracks along the curve to group all contour segments that belong to it (Jolicoeur et al., 1986; Pringle & Egeth, 1988) The existence of such a visual routine was predicted by Ullman (1984). Thus, in some situations labeling the segments that belong to a single curve is time consuming.

In the present study subjects were required to detect which of two visual targets is connected to a fixation point by a continuous curve. All stimuli are highly similar, and the locations where variations occur are prespecified (Fig. 1). The task could be solved by a grouping operation that relies on collinearity. If this simplified curve tracing task is also associated with prolonged reaction times, it can be inferred that contour grouping on the basis of collinearity is not necessarily performed pre-attentively.

2. Experiment 1: The speed of contour grouping

The stimuli employed in the present experiment are shown in Fig. 1. They consisted of a fixation point, two (or three) curves, and two circular targets. One of the curves connected the fixation point to a target. We will refer to this curve as the target curve. In all stimuli there was a second curve that was connected to the other target, but not to the fixation point. We will refer to the second curve as the distractor curve. In some of the stimuli a third curve was present, which was neither connected to a target, nor to the fixation point. This third curve will be called an irrelevant curve. Subjects were instructed to press a button with their right hand if the fixation point was connected to the right target, and a button with their left hand if the fixation point was connected to the left target. The correct decision for each stimulus was influenced by variations along the path connecting the fixation point to one of the targets.

Within a session, stimuli were randomly selected from a set of eight stimuli. These stimulus sets differed between sessions. Stimulus sets differed in the number of locations at which the stimuli exhibited variations that were relevant to the response. We will refer to these locations as 'critical zones' (shaded areas in Fig. 1). In the first two stimulus sets (A1 and A2) there was a single critical zone. In the third set (B) there were two critical zones, and in the fourth set (C) there were three critical zones (Fig. 1). Subjects could perform tasks A1 and A2 by paying attention to a single critical zone, and these tasks therefore do not differ from a simple visual discrimination task. In contrast, in order to give a correct response upon presentation of stimuli from sets B and C, information present at different locations in the visual field needed to be integrated. A grouping operation which labels contour segments belonging to a single curve would be sufficient to solve the task. Such a grouping operation could rely on collinearity and connectedness of contour segments. Subjects could, in principle, press the left button whenever the fixation point and the left circular target are part of a single connected object, and press the right button when the fixation point and the right target belong to single object. Thus, if contour grouping in the present experiment is performed pre-attentively, reaction times should be uniformly short.

Reaction times to stimuli in set A1 and A2 will serve as a baseline against which the performance in the other two sets, which require integration of spatially separate information, can be compared. In order to have a similar number of stimuli in each set, sets A1, A2 and B were completed with additional stimuli in which a third, irrelevant curve was added. The correct response did not depend on the presence of this additional curve.

2.1. Methods

2.1.1. Subjects

Three subjects participated in the first experiment, two of which were naive with respect to the aim of the experiment. The third subject (PR) was one of the authors. All subjects had corrected to normal vision in both eyes.

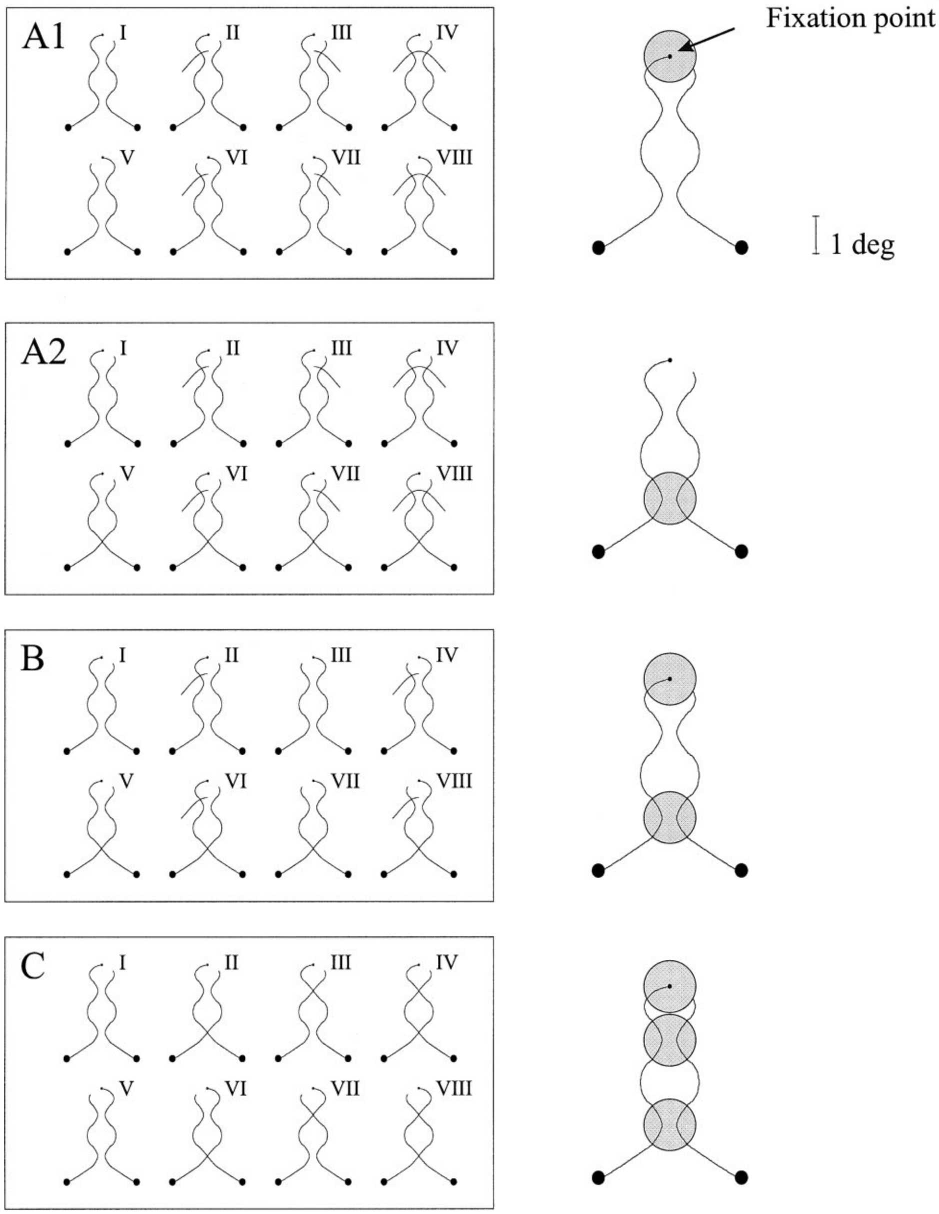

Fig. 1. (Left) The four stimulus sets from which stimuli were randomly selected. The fixation point is the small dot at the top of each stimulus. (Right) Schematics which illustrate the locations where stimulus sets exhibited variations that were relevant to the response ('critical zones'). There was a single critical zone for stimulus sets A1 and A2, two for set B, and three for stimulus set C.

2.1.2. Stimuli

Fig. 1 shows the stimuli used in the present study, which consisted of bright contours (the constituent contour segments were 3rd-order polynomials) with a width of 0.04° that were displayed on a Dell Ultrascan monitor, viewed from a distance of 115 cm. The frame rate of the monitor was 70 Hz. The luminance of the contours was 85 cd/m^2, and that of the background was 1.5 cd/m^2.

2.1.3. Procedure

Subjects had to fixate a point (0.15°) that appeared in the center of the screen. After 300 ms two (or three) curves were displayed for a period of 1 s. One of the curves connected the fixation point to one of two circular targets of 0.4° (Fig. 1). Subjects had to press a button on the side of the target which was connected to the fixation point. They were instructed to respond as soon as possible without making errors, and to maintain fixation until they had pressed one of the buttons. Auditory feedback was given after an erroneous response.

Subjects were tested in three sessions of approximately one hour, on different days. In the first session, they familiarized with the task, and reaction time data from this session were not included in the analysis. In a

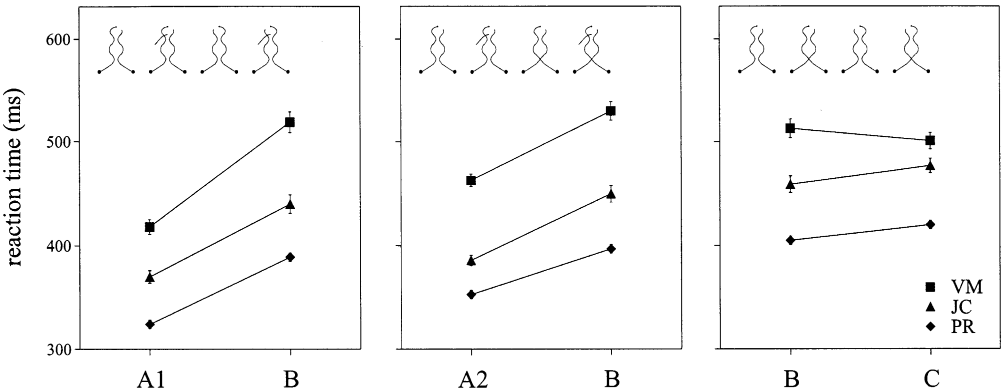

Fig. 2. Dependence of reaction times on the stimulus set in which stimuli were embedded. (Left) Comparison of reaction times of each of the subjects to stimuli that occurred both in set A1 and in set B. (Middle) Reaction times to stimuli common to set A2 and B. (Right) Reaction times to stimuli occurring in set B and C. Error bars indicate S.E.M. for each of the subjects.

single session four blocks of trials were performed, each of which contained approximately 180 trials. In a block of trials, stimuli were randomly selected from a set of eight stimuli. The first 40 trials of a block allowed the subjects to adapt to the change in the stimulus set, and reaction times from these initial trials were not evaluated. The order in which the different stimulus sets were presented was counterbalanced across subjects and across sessions.

In order to control for changes in eye position, eye movements were recorded in most, but not all sessions, with an infrared scleral reflection technique (IRIS, Reulen, Marcus, Koops, de Vries, Tiesinga, Boshuizen & Bos, 1988) with an accuracy of 3′.

2.2. Results and discussion

2.2.1. Reaction times in the case of 1, 2 and 3 critical zones

All subjects exhibited shortest reaction times for the stimuli in sets A1 and A2, which have a single critical zone (Fig. 2, Table 1). This effect is particularly obvious if reaction times are compared between stimuli that occurred both in set A1 and in B (stimuli I–IV of set B in Fig. 1). The introduction of a second critical zone in stimulus set B prolonged the reaction times by 79 ms, on average (Fig. 2). Three-way ANOVA, with set and stimulus as fixed, and subject as random variable, confirmed this main effect ($F_{1,2} = 49$; $P < 0.025$). The ANOVA did not reveal other significant effects. The significance of the difference between the sets was corroborated by planned within-subject comparisons, which yielded a highly significant dependence of reaction times on stimulus set in each of the subjects (in every subject $P < 10^{-6}$; rank-order test). Error rates to these stimuli were higher when they were presented as part of stimulus set B than when presented as part of set A1 (Table 2). This indicates that a speed-accuracy trade-off cannot account for the longer reaction times to stimuli when presented in the context of set B. Similar results were obtained when comparing reaction times between stimulus set A2 and B. Reaction times to stimuli I, II, V and VI of set B were on average 59 ms longer than the reaction times to the same stimuli in set A2 (3-way ANOVA; $F_{1,2} = 70$; $P < 0.025$) (Fig. 2). Again, planned within-subject comparisons confirmed the significance of this effect (in every subject $P < 10^{-6}$; rank-order test). Error rates were generally higher to stimuli in the context of set B than in the context of set A2 (Table 2), indicating again that a trade-off between speed and accuracy cannot account for the difference in reaction times. These results, taken together, indicate that the detection of a variation in the stimulus that is confined to a single location in the visual field is performed faster than a discrimination that is based on information dispersed across two locations in the visual field. The additional delay is presumably caused by a change of strategy, necessitated by the presence of information in multiple critical zones. A candidate strategy in the case of multiple critical zones is contour grouping, as was discussed above. When a third critical zone was introduced no substantial further lengthening of reaction times was observed. The average reaction time to stimulus I, II, V and VI of set C was only marginally (7 ms) longer than the reaction time to the same stimuli of set B (Fig. 2C). Three-way ANOVA did not yield a significant effect of stimulus-set ($F_{1,2} = 0.6$; $P > 0.05$). In contrast to the previous comparisons, however, a main effect occurred for the presented stimulus ($F_{3,6} = 7.8$; $P < 0.025$). This effect is related to a difference between reaction times to stimuli that did and that did not contain an intersection.

2.2.2. Effect of intersections between curves

Systematic differences were observed between reaction times to stimuli that contained intersections between the target and distractor curve, and stimuli that did not contain this type of intersection. Intersections

Table 1
Reaction times of the subjects for the stimuli in sets A1, A2, B and C

	Subject	I	II	III	IV	V	VI	VII	VIII
A1	JC	376 (75)	349 (45)	353 (45)	364 (55)	367 (76)	387 (60)	393 (85)	384 (53)
	VM	437 (53)	422 (75)	472 (87)	425 (56)	411 (85)	401 (83)	451 (135)	408 (98)
	PR	332 (43)	337 (58)	326 (42)	342 (51)	308 (36)	316 (29)	316 (34)	315 (37)
A2	JC	392 (45)	395 (45)	399 (48)	422 (68)	375 (76)	381 (50)	357 (44)	422 (101)
	VM	485 (67)	499 (56)	460 (52)	514 (54)	414 (49)	454 (59)	420 (52)	454 (105)
	PR	353 (34)	370 (30)	374 (45)	384 (30)	344 (57)	342 (43)	345 (46)	334 (38)
B	JC	439 (76)	464 (142)	433 (72)	421 (62)	444 (59)	451 (72)	518 (115)	497 (98)
	VM	565 (125)	587 (102)	444 (54)	479 (93)	472 (48)	494 (66)	568 (85)	608 (114)
	PR	387 (47)	400 (44)	384 (43)	381 (36)	406 (39)	393 (41)	440 (38)	444 (43)
C	JC	441 (54)	523 (68)	483 (74)	690 (162)	433 (48)	510 (83)	552 (72)	709 (115)
	VM	484 (69)	501 (51)	497 (44)	722 (131)	424 (46)	595 (85)	599 (95)	671 (73)
	PR	417 (52)	409 (36)	411 (25)	527 (57)	391 (32)	460 (45)	451 (40)	501 (39)

Numbers in brackets indicate standard deviation.

between the two curves that potentially connected the fixation point to one of the targets were relevant to the correct response, and will be referred to as R-type intersections. The effect of these intersections depended on the set in which stimuli were embedded. In the context of multiple critical zones (set B and C), reaction times to stimuli in which the two curves crossed each other were longer than reaction times to stimuli in which the respective curves did not cross (Fig. 3). In stimulus set B reaction times to stimuli in which the two curves had an R-type intersection (stimulus V–VIII of set B, see Fig. 1) were, on average, 30 ms longer than reaction times to the respective stimuli without an intersection. The significance of these effects was evaluated using a mixed 2-way ANOVA with presence or absence of an R-type intersection as fixed, and subjects as random variable. Thus, for this analysis reaction times were pooled across all stimuli that contained an intersection between the target and distractor curve, and compared with reaction times to all stimuli without such an intersection. Two-way ANOVA revealed a main effect of intersections ($F_{1,2} = 21$; $P < 0.05$). Planned within-subject comparisons confirmed significant effects of intersections for two of the subjects (JC and PR; $P < 10^{-4}$; rank-order test) but in the third subject (VM) this comparison failed to reach statistical significance ($P > 0.05$). However, in stimulus set C reaction times also exhibited a strong dependence on the number of R-type intersections (Fig. 3), corroborating the results obtained with stimulus set B. In each of the subjects reaction times were slowed considerably when a single and, in particular, when two intersections were present between the target and distractor curve. To analyze the significance of these effects, reaction times were pooled across stimuli without an intersection, across stimuli with an intersection at the first location, across stimuli with an intersection at the second location, and across stimuli with intersections at both locations (Fig. 3). Two-way ANOVA revealed a main effect of the intersections ($F_{3,6} = 18.4$; $P < 0.0025$). The average effect was a reaction time increase of 103 ms for each intersection, although the slopes differed greatly between subjects (range 55–133 ms per intersection). Moreover, planned within-subject comparisons confirmed that responses to stimuli without an intersection were significantly faster than responses to stimuli with a single intersection (in every subject $P < 10^{-6}$; rank-order test), and that the latter were significantly faster than responses to stimuli with two intersections (in every subject $P < 10^{-6}$; rank-order test).

The increase in reaction time caused by an R-type intersection depended on the set in which the stimuli were embedded. In stimulus set A2 reaction times to stimuli that contained an R-type intersection were, on average, 34 ms shorter than reaction times to stimuli that did not contain such an intersection (2-way ANOVA; $F_{7,14} = 4.8$; $P < 0.01$). Planned within-subject comparisons confirmed that in set A2 responses to stimuli with an intersection were significantly faster than responses to stimuli without an intersection (in every subject $P < 0.005$; rank-order test). This result indicates that the lengthening of reaction time due to intersections in stimulus set B and C were not caused by difficulties in the discrimination of intersections. Moreover, they support the hypothesis that subjects used a different strategy when relevant information was confined to a single critical zone.

In addition to the dependence on stimulus set, the effect of an intersection also depended on the identity of the curves forming the intersection. Intersections between the target and distractor curve (R-type) were associated with a larger increase in reaction time than

Table 2
Error rates in percent pooled across subjects for the stimuli in sets A1, A2, B and C

Set	I	II	III	IV	V	VI	VII	VIII	Total
A1	1 (0–3)	0	0	2 (0–3)	0	2 (0–7)	1 (0–3)	0	1 (0–2)
A2	5 (3–7)	2 (0–7)	4 (0–10)	1 (0–3)	3 (0–7)	3 (0–7)	7 (3–10)	4 (0–7)	4 (1–6)
B	10 (3–20)	2 (0–7)	4 (0–10)	10 (7–17)	6 (3–7)	8 (3–13)	8 (0–20)	4 (0–10)	7 (3–12)
C	7 (0–17)	6 (0–17)	9 (3–17)	9 (3–17)	7 (3–10)	3 (0–7)	8 (0–13)	7 (0–17)	7 (2–14)

Numbers in brackets indicate the range between subjects.

intersections with the third curve that was not connected to a target. We will refer to an intersection between the target curve and an irrelevant curve as a T-type intersection. The effect of T-type intersections can be estimated by comparing reaction times to stimulus I and II, and to V and VI of set B. The crossing with the irrelevant curve in stimulus II of set B increased the reaction time by 20 ms, on average. This is a small cost, when compared with the effect of an R-type intersection at approximately the same eccentricity. The effect of a relevant, R-type crossing at this eccentricity can be estimated by comparing reaction times to stimulus I and VII of set C. The R-type intersection at this eccentricity increased the reaction time by 67 ms, on average. Another between-set comparison confirmed the difference between the effect of R- and T-type intersections (Fig. 4). The T-type intersection in stimulus VI of set B increased the reaction times by 7 ms, whereas the R-type intersection in stimulus VIII of set C increased the reaction time by 159 ms, on average (difference between reaction times to stimulus V and VI of set B and between stimulus II and VIII of set C, respectively). Two-way ANOVA with stimulus as fixed, and subjects as random variable revealed a main effect of stimulus in the comparison of reaction times to the respective stimuli in set C ($F_{1,2} = 26$; $P < 0.05$), but no significant effect of the stimuli of set B ($F_{1,2} = 0.3$; $P > 0.2$).

Unfortunately, this comparison between R- and T-type intersections is based on a comparison between different stimulus sets. It should be noted that there was also a difference between sets B and C in the effect of a R-type intersection. R-type intersections in stimulus set B increased reaction times by 30 ms, whereas the average cost of a single R-type intersection at the same eccentricity in set C was 68 ms (Fig. 2). Therefore, we cannot exclude the possibility that a set-related effect contributed to the differences between R- and T-type intersections. Moreover, irrelevant curves were shorter than the relevant curves. At this point we cannot exclude the possibility that the small delay caused by T-type intersections is due the shorter length of the irrelevant curve. The difference between effects of T- and R-type intersections therefore requires a more thorough analysis. This will be taken up later (Sections 5 and 6).

2.2.3. Eye movements

Eye movement recordings were performed in each of the subjects during at least one of the sessions. Saccades and eye blinks occurred in a small minority (2–4%) of the trials. The results presented here were pooled across sessions with and without eye movement recordings. However, when data analysis was confined to the trials without eye movements or eye blinks, the results were indistinguishable from those presented here (data not shown).

2.2.4. Strategy differences between subjects

After the last session, subjects were invited to describe how they solved the task. Two subjects (VM and PR) had the impression that they grouped contour segments that constitute the path from the fixation point to the target. They reported to perceive the spatially extended object that connected the fixation point to the relevant target. However, the third subject (JC) reported a drastically different solution for the task. After the initial training, he had adopted a strategy in which he counted the number of R-type intersections. If this number was even he pressed the button at the side on which a contour was attached to the fixation point, and when this number was odd he pressed the other button. Remarkably though, the reaction times of this subject were within the range of the other subjects, and exhibited all the dependencies that were described above. For example, even in this subject reaction times to stimuli of set A2 which contained an intersection, were shorter than reaction times to stimuli of the same set which did not, whereas the converse was true for stimulus set B and C (Table 1, Fig. 3).

The report of subject JC illustrates a difficulty in the interpretation of the present results. It is unclear whether reaction times are determined by the speed of contour integration, or rather by time constaints on a different strategy for solving the present task, like counting the number of intersections. Nonetheless, it is remarkable that this task which can, in principle,

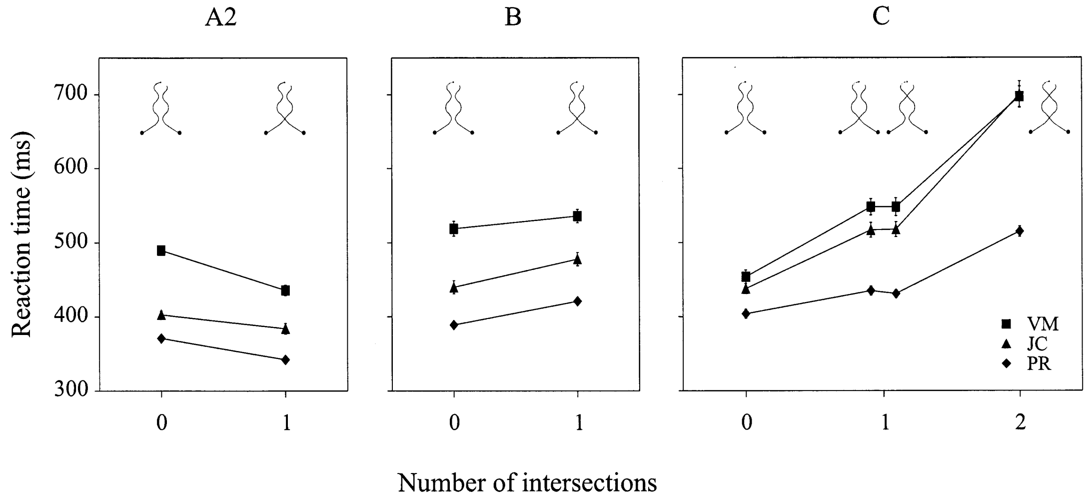

Fig. 3. Reaction times depend on the number of intersections between the curves that potentially connect the fixation point to one of the targets. (Left) Reaction times to stimuli containing zero and one intersection when embedded in stimulus set A2. (Middle) Reaction times to stimuli containing zero and one intersection in the context of set B. (Right) Dependence of reaction times on the number and location of intersections of stimuli contained in set C. Error bars indicate S.E.M. for each of the subjects. The insets illustrate the stimuli. For stimulus set B and C, reaction times were pooled across the stimuli shown, and their mirror images.

be solved by a grouping operation linking collinear contour segments is associated with prolonged reaction times. Let us, for the sake of the argument, assume that such a grouping operation exists, and that it takes place pre-attentively. If so, the strong dependence of reaction times on the number of intersections would call for an additional time consuming process which 'reads out' the segmentation results. There are two alternative explanations which are much more parsimonious.

According to the first explanation, subjects solve the task by paying attention to the critical zones, which contain necessary and sufficient information for the solution of the task. Prolonged reaction times are caused by time-consuming shifts of visual attention between the critical zones. According to this interpretation, contour integration does not occur, for example because it is an unreliable strategy in the present task. If the only information used is confined to the critical zones, it would be predicted that removal of contour segments outside these zones has little effect on reaction times.

According to the second alternative explanation, contour grouping does occur, but is an attentive, time-consuming process. Contour integration could account for the present results, if it slows down at locations where two curves intersect. This explanation implies that subjects should benefit from the contour segments outside the critical zones, because these segments are essential for the integration all segments that belong to a curve. In Section 3 we will therefore investigate the dependence of reaction times on the presence of contour segments outside the critical zones, in order to investigate whether contour integration is involved in the present task.

3. Experiment 2: The effect of non-varying contour segments

In the present experiment, the aim is to investigate whether contour segments outside the critical zones influence the pattern of reaction times[1]. Influences from non-varying image elements on reaction times have been observed previously, in studies on visual discrimination and visual search. Pomerantz, Sager and Stoever (1977), for example, investigated the performance of subjects who were required to discriminate between a single left-open and right-open brackets, (and). When these stimuli were accompanied by a second, nonvarying bracket, the stimuli () and)) were obtained, and performance improved. This improvement was called the 'configural superiority effect' (Pomerantz et al., 1977). Pomerantz and Pristach (1989) suggested that configural superiority occurs if varying and non-varying contours can be grouped together in a configuration that provides features that are more discriminable than the distinguishing contours presented in isolation. In this view, stimuli () and)) can be distinguished on the basis of closure, but (and) must be distinguished on the basis of a less salient feature.

Inclusion of non-varying image elements in a display may also speed up visual search for a target among distractors, in particular when these additional elements allow for grouping of distractors in larger chunks (Donnelly, Humphreys & Riddoch 1991; Wolfe & Bennett, 1997). We infer that if contour grouping is involved in the present paradigm, a configural effect is to

[1] We are grateful to an anonymous reviewer for suggesting this experiment.

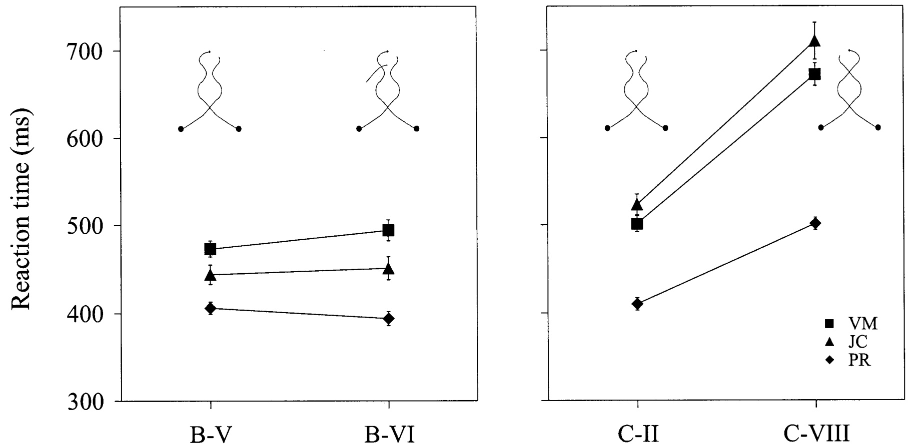

Fig. 4. Comparison of the effect of relevant and irrelevant intersections. (Left) The effect of an irrelevant, T-type intersection can be estimated by comparing reaction times to stimulus V and VI of set B. (Right) The effect of the addition of an R-type intersection at approximately the same eccentricity was estimated by comparing reaction times to stimulus II and VIII of set C. Error bars indicate S.E.M. for each of the subjects. Insets show the respective stimuli. Note that stimulus V of set B is identical to stimulus II of set C.

be expected from the contour segments outside the critical zones. The absence of such a configural effect, on the other hand, would constitute strong evidence that subjects solve the task by a different strategy, which is solely dependent on information inside the critical zones, like counting the number of intersections.

In order to study the effects of the non-varying contour segments, an additional set of stimuli was constructed by removing all contours from set C that are outside the critical zones. This novel set of stimuli OS (omitted segments) is shown in Fig. 5a. If there is a configural superiority effect, it should be revealed by comparing reaction times between stimuli of set C and set OS.

3.1. Methods

3.1.1. Subjects

Four naive subjects participated in the experiment. All subjects had corrected to normal vision in both eyes.

3.1.2. Stimuli

Two sets of stimuli were used. The first was set C of Experiment 1, which is shown in Fig. 1. The second set (set OS; omitted segments) is shown in Fig. 5a. Set OS was derived from set C by removing all contour segments outside the critical zones. The targets were also removed, but the fixation point was not.

3.1.3. Procedure

The procedure with set C was identical to the procedure of Experiment 1. However, the instructions had to be changed for set OS. Subjects were instructed to respond according to the location of the contour segment adjacent to the fixation point. If there were no intersections or if there were two intersections they were instructed to press the button on the side of this contour segment, but if there was a single intersection they were instructed to press the opposite button. Visual fixation had to be maintained until the response.

Subjects were tested in three sessions. In the first session, they familiarized with one or the other task. Reaction time data from this session were not included in the analysis. In the second and third session 240 trials were obtained with set OS and 240 trials with set C. The order in which the different stimulus sets were presented was counterbalanced across subjects. Eye position was controlled with EOG, and trials in which eye movements or blinks occurred were excluded from analysis.

3.2. Results and discussion

Reaction times of the individual subjects to set C and set OS are shown in Fig. 5c, d, and reaction times that were pooled across subjects are shown in Fig. 5b. On average, reaction times to the stimuli of set C were 91 ms shorter than reaction times to stimuli of set OS. A benefit from the contour segments outside the critical zones was obtained for each of the four subjects, and did not depend on the order in which the two tasks were performed. Three-way ANOVA, with task (C or OS) and stimulus as fixed variables, and subject as random variable confirmed this main effect ($F_{1,3} = 10.8$; $P < 0.05$). The second significant effect revealed by ANOVA was an interaction between stimulus and task ($F_{3,9} = 24$; $P < 0.001$). This interaction reflects a pronounced difference between tasks in the dependence of reaction time on the number of intersections. The dependence of reaction time on the number of intersections in set C reproduces the result obtained in Section

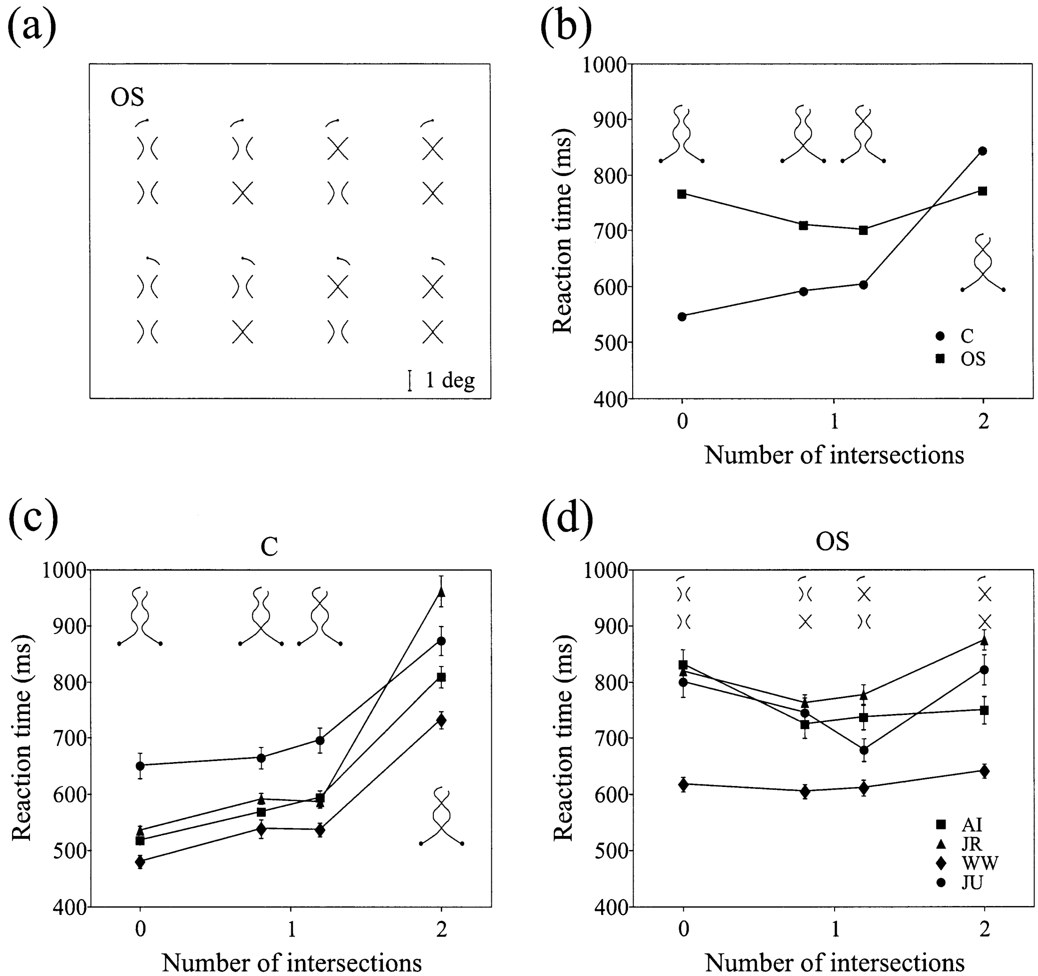

Fig. 5. Dependence of the reaction time on the presence of contour segments that do not differ between stimuli. (a) Stimulus set OS (omitted segments) derived from set C by removing contour segments which are identical for all stimuli. (b) Reaction times, averaged across subjects to stimuli of set C (●) and set OS (■). Insets show the respective stimuli of set C, but it should be noted that reaction times were averaged across stimuli and their mirror images. (c) Reaction times of the individual subjects to stimuli of set C. (d) Reaction times of individual subjects to stimuli of set OS.

2. Reaction times were prolonged for stimuli that contained intersections. The average increase in reaction time caused by each intersection amounted to 149 ms (range between subjects, 112–213 ms). Reaction times to stimuli of set OS were more homogeneous. Nonetheless, a separate 2-way ANOVA on the reaction times to stimuli of set OS also revealed a systematic difference in reaction times between stimuli ($F_{3,9} = 4.6$; $P < 0.05$). Responses to stimuli of this set with a single intersection were about 60 ms faster than responses to stimuli without intersections and to stimuli with two intersections (Fig. 5b) (Tukey's HSD test, $P < 0.001$ for all pairwise comparisons). One of the subjects reported that he had learned all stimuli by heart. In contrast, the other three subjects reported that they solved the task by first checking whether there was a single intersection. If so, they pressed the button opposite to the contour segment close to the fixation point, and if not, they pressed the other button. This strategy appears to be reflected by the pattern of reaction times. We will not elaborate further on this effect, however, because it is beyond the scope of our study.

The results demonstrate a remarkably strong configural superiority effect caused by the contour segments outside the critical zones. This indicates that the task is solved by a mechanism that utilizes information from beyond the critical zones. The non-varying contour segments of set C were associated with a shortening of reaction time by more than 221 ms for the stimuli without an intersection, and by 109 ms for the stimuli with a single intersection. Thus, the data suggest that the original task (set C) is solved by a contour integration mechanism. Responses to the stimuli of set C with two intersections were delayed by 73 ms relative to responses to the corresponding stimuli of set OS (Fig. 5b). A separate 2-way ANOVA for the stimuli with two intersections, with subjects as a random and task (C or OS) as a fixed variable, revealed that this

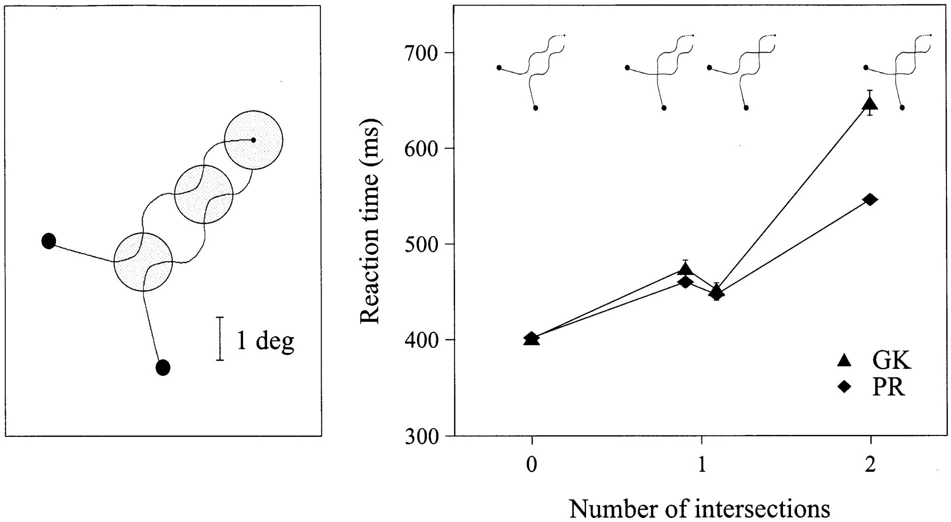

Fig. 6. Dependence of reaction times on the number of intersections when stimuli were rotated by 45°. (Left) Illustrated are the critical zones of the modified stimulus set C. In this stimulus set all contour segments appear in the lower left quadrant of the visual field. (Right) Dependence of reaction times on the number and location of intersections contained in the modified set C. The insets illustrate the stimuli, data were pooled across the stimuli shown and their mirror images. Error bars indicate S.E.M. for each of the subjects.

increase in reaction time to the respective stimuli of set C was significant ($F_{1,3} = 55$; $P < 0.01$). If the contour integration mechanism and the strategy that is solely based on information from the critical zones were carried out simultaneously and without interference, then it would be predicted that the mechanism that comes up first with the correct response determines the reaction time. Thus, this 'horse-race model' can be rejected, because the responses to the stimuli of set C with two intersections are delayed relative to the responses of the corresponding stimuli of set OS.

The results of Experiment 1 and 2, taken together, demonstrate that intersections among curves are associated with a considerable reduction in the speed of contour integration. This is consistent with earlier studies, which indicated that curve tracing slows down when other contours come in close proximity of the curve that has to be traced (Jolicoeur, Ullman & Mackay, 1991). This slowdown would account for the delays caused by intersections, since the curves touched each other when they intersected but stayed well separated when they did not.

However, the data described so far are also consistent with an alternative explanation for the slowdown of contour integration at intersections. R-type intersections in Experiments 1 and 2 occurred exactly at the vertical meridian. Therefore, stimuli that contained intersections differed from stimuli that did not, in that segments of the target curve were located in both visual hemi-fields. The increased reaction times for these stimuli might reflect additional time costs associated with the integration of contour segments that are represented in different cerebral hemispheres. A difference between time constraints on perceptual processes occurring in one and in two visual hemifields would not be unprecedented. It has been shown, for example, that when focal attention needs to shift across the vertical meridian additional time is required compared to when it needs to shift between two positions at the same side of the vertical meridian (Hughes & Zimba, 1985; Rizzolatti, Riggio, Dascola & Umiltá, 1987; but see Egly & Homa, 1991). In Experiment 3 it will be investigated whether temporal constraints on interhemispheric communication can account for the slowdown of contour integration at intersections.

4. Experiment 3: stimuli confined to a single quadrant of the visual field

Two subjects were tested in a modified paradigm in which the stimuli were rotated by 45°, so that all contour segments were located in the lower left quadrant of the visual field (Fig. 6). If the increased reaction times to stimuli that contain an intersection are related to the integration of contour segments on both sides of the vertical meridian it is expected that reaction times are more homogeneous in this modified paradigm.

4.1. Methods

4.1.1. Subjects

Two subjects participated in Experiment 3. The first subject (PR) had also been tested in Experiment 1, and was one of the authors. The second subject (GK) was naive with respect to the aim of the study.

Table 3
Reaction times of the subjects for the rotated stimuli in sets A1, A2, B and C

Set	Subject	I	II	III	IV	V	VI	VII	VIII
A1	GK	360 (49)	358 (75)	340 (36)	369 (57)	360 (37)	375 (42)	378 (67)	367 (71)
	PR	319 (33)	313 (37)	315 (33)	329 (31)	324 (45)	318 (32)	326 (54)	351 (52)
A2	GK	396 (61)	387 (39)	407 (47)	402 (50)	406 (85)	403 (72)	444 (98)	431 (82)
	PR	373 (45)	368 (57)	376 (40)	398 (51)	372 (53)	379 (56)	378 (48)	378 (43)
B	GK	428 (60)	437 (53)	425 (44)	442 (54)	522 (61)	576 (116)	505 (88)	517 (106)
	PR	375 (47)	402 (68)	401 (23)	396 (34)	460 (43)	465 (41)	446 (46)	461 (49)
C	GK	405 (47)	481 (72)	459 (42)	643 (102)	397 (22)	465 (62)	443 (67)	650 (93)
	PR	395 (33)	451 (34)	459 (45)	543 (47)	408 (29)	469 (35)	435 (37)	549 (37)

Numbers in brackets indicate standard deviation.

4.1.2. Stimuli and procedure

Both subjects were tested with rotated versions of the stimuli of set A1, A2, B, and C of Experiment 1 (Fig. 6). The procedure was identical to that of Experiment 1. Eye position was controlled with the infrared scleral reflection technique (IRIS, Reulen et al., 1988).

4.2. Results and discussion

Average reaction times that were obtained with stimulus set C of the modified paradigm are shown in Fig. 6, and reaction times to the other stimulus sets are shown in Table 3. Again, the reaction time exhibited a strong dependence on the number of intersections. Two-way ANOVA revealed a main effect of the location of intersections ($F_{3,3} = 12.1$; $P < 0.05$). The average effect was an increase of 98 ms in the reaction times for each intersection. Planned within-subject comparisons confirmed that responses to stimuli without an intersection were significantly faster than responses to stimuli with a single intersection (in both subjects $P < 10^{-6}$; rank-order test), and that the latter were significantly faster than responses to stimuli with two intersections (in both subjects $P < 10^{-6}$; rank-order test).

These results show that R-type intersections, which are not located at the vertical meridian, are associated with an increase in reaction time of a similar magnitude as was observed in Experiments 1 and 2. This indicates that the increase in reaction times caused by intersections cannot be attributed to delays in the communication between the two hemispheres. Previous experiments on curve tracing showed that its speed is reduced when distracting contours are close to the curve that should be traced (Jolicoeur et al., 1991). The delays associated with intersections are consistent with these results, since the two curves remained only well separated in stimuli without intersections.

5. Experiment 4: Relevant and irrelevant intersections

The results of Experiment 1 showed that subjects take advantage of foreknowledge about the occurrence of intersections at particular locations and about their potential relevance. However, the evidence is inconclusive with respect to the question whether it is the contour integration mechanism that uses this foreknowledge. The strongest set effect was obtained when comparing reaction times to stimuli of set A1 and A2 on the one hand, and to stimuli of set B on the other (Fig. 2). However, in set A1 and A2 there was a single critical zone, and therefore, these tasks did not differ from simple discriminations in which contour integration need not be involved. A second result suggesting that contour integration uses foreknowledge was a relatively small effect on reaction times of T-type intersections, i.e. intersections between the target curve and an irrelevant curve (Fig. 4). However, this result was based on a comparison between stimuli of different sets. Thus, it is unclear whether the difference between the effect of R- and T-type intersections would also hold when the respective stimuli are part of the same set. Moreover, irrelevant curves of Experiment 1 were shorter than relevant curves. It remains to be excluded that the effect of an intersection depends on the length of the curves that form the intersection. In the present experiment we therefore investigated reaction times to stimuli of a single set IC (irrelevant curves). This set contained 16 stimuli, eight of which were identical to the stimuli of set C, and the other eight contained an additional, irrelevant curve with a length that is comparable to that of the other two curves (Fig. 7). The irrelevant curve crossed the target curve (T-type intersection) as well as the distractor curve. We will refer to intersections between the irrelevant and the distractor curve as D-type intersections.

5.1. Methods

5.1.1. Subjects

Four naive subjects participated in the experiment.

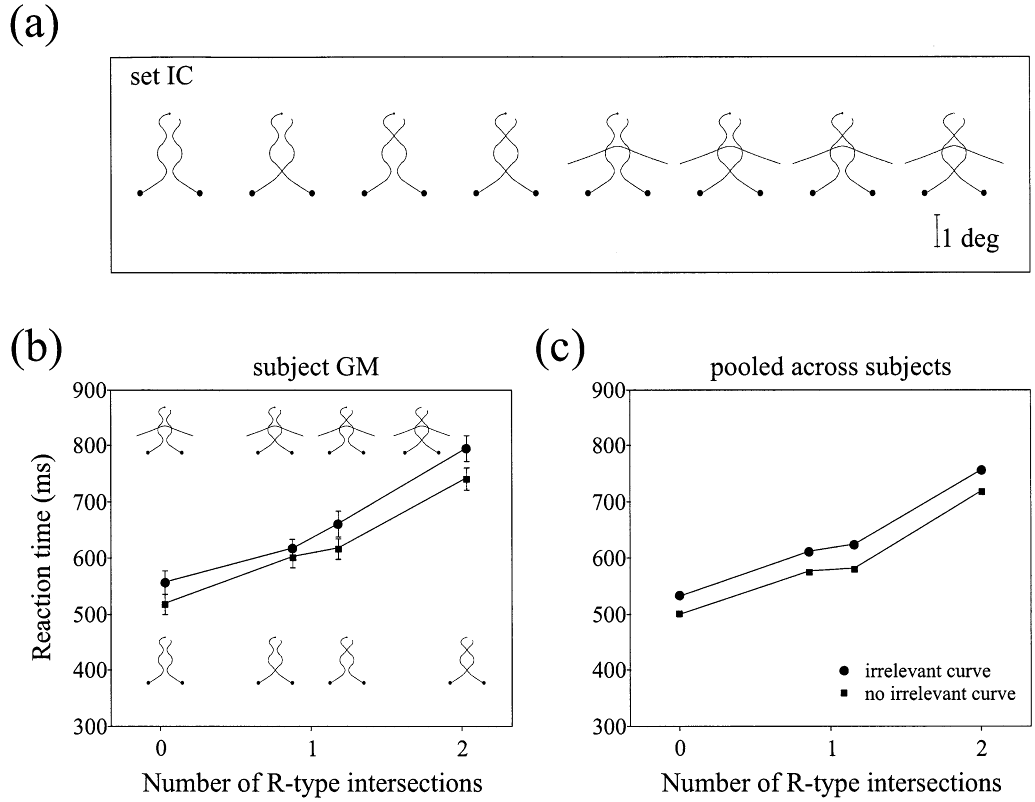

Fig. 7. Within-set comparison of delays associated with relevant and irrelevant intersections. (a) Stimuli of set IC. The actual set was composed of the stimuli shown and their vertical mirror images. (b) Reaction times of a representative subject, GM. (c) Reaction times averaged across the four subjects.

All subjects had corrected to normal vision in both eyes.

5.1.2. Procedure

The procedure was identical to that of Experiment 2. Stimuli were presented 60 times, and response times were pooled across pairs of stimuli that were mirror images of each other. Eye position was controlled with EOG, and trials in which eye movements or blinks occurred were excluded from analysis.

5.2. Results and discussion

Fig. 7b shows reaction times of a representative subject, GM. Reaction times to the stimuli without an additional curve were comparable to reaction times to stimuli of the original set C. Indeed, reaction times exhibited a strong dependence on the number of R-type intersections (112 ms per intersection, in this subject). In contrast to the results of Experiment 1, however, the irrelevant curve was associated with a further increase in reaction time by 42 ms.

Fig. 7c shows reaction times that were averaged across subjects. The average delay caused by a R-type intersection amounted to 111 ms (range between subjects, 93–127 ms). The irrelevant line of set IC was also associated with an increase in reaction time by 37 ms, on average. Thus, the irrelevant (T- and D-type) intersections are associated with a delay that is a factor three shorter than the delay associated with an R-type intersection. Nonetheless, the increase in reaction time caused by the irrelevant curve was consistent across subjects (range between subjects, 14–57 ms). In order to investigate the significance of this effect, a 3-way ANOVA was carried out, with subject as a random variable, and stimulus (location of the relevant intersections) and presence of an irrelevant curve as fixed variables. This analysis revealed a main effect of the irrelevant curve ($F_{1,3} = 16.3$; $P < 0.05$). The increase in reaction time associated with R-type intersections comprised the second main effect, which was highly significant ($F_{3,9} = 82$; $P < 0.001$), in accordance with the results of Experiments 1–3. The interaction between R-type and irrelevant intersections was not significant ($F_{3,9} = 16.3$; $P > 0.5$), which indicates that the slowdown of the response caused by irrelevant intersections was relatively constant across stimuli (Fig. 7, range between stimuli, 33–42 ms).

The results of this experiment support the conclusion of Experiment 1 that the effect of R-type intersections on reaction time is larger than the effect of T- and D-type intersections. However, in Experiment 1 T-type intersections appeared to have virtually no effect on reaction times, whereas the present experiment uncovered a substantial and consistent effect. This discrepancy can be attributed to differences in design between the experiments. In Experiment 1 reaction times had to be compared between stimuli of different sets, and it could not be excluded that a set effect contributed to the results. Moreover, irrelevant curves in Experiment 1 were substantially shorter than irrelevant curves of the present experiment, which were of approximately equal length as the relevant curves.

An additional result supports the difference between the effect of relevant and irrelevant intersections on reaction times. A comparison between the effect of the two R-type intersections suggests that the delay caused by the first relevant intersection (80 ms) is shorter than the delay associated with the second intersection (140 ms). In order to evaluate the significance of this difference, an additional 4-way ANOVA was carried out, in which the presence of an R-type intersection at the upper location and an R-type intersection at the lower location were treated as separate fixed variables. Subjects and presence of the irrelevant curve were the other two variables of the ANOVA. In this analysis, a supra-additive effect of the two R-type intersections should show up as a significant interaction between them. The interaction between the effect of the upper and lower R-type intersection on reaction time revealed a trend, which did not quite reach statistical significance ($F_{1,3} = 6.8$; $P = 0.08$).

However, the results of all 12 subjects that were tested in Experiments 1–4 with stimulus set C, taken together, provide evidence in support of this trend (this can be confirmed by comparing the delay associated with the first and second R-type intersection in Figs. 3, 5 and 6). A single R-type intersection located at the lower position (Fig. 1, stimulus II and VI of set C) was associated with an average delay of 64 ms (12 subjects). This delay did not differ significantly from the delay of 67 ms associated with a single R-type intersection at the higher location (Fig. 1, stimulus III and VII of set C) (Wilcoxon signed ranks test, $P > 0.5$, $N = 12$). However, the increase in reaction time associated with an intersection at the lower position, in the presence of an intersection at the highest position, was significantly larger (Wilcoxon signed ranks test, $P < 0.005$, $N = 12$), and amounted to 178 ms. Similarly, the delay associated with an intersection at the highest position in the presence of an intersection at the lowest position was also 181 ms, which is sigificantly larger (Wilcoxon signed ranks test, $P < 0.005$, $N = 12$) than the delay associated with a single intersection at the higher critical zone. In contrast, Fig. 7 shows an effect of irrelevant intersections, which was remarkably constant across stimuli, and did not depend on the number of R-type intersections. Indeed, ANOVA did not reveal a trace of interaction between R-type and irrelevant intersections, as was discussed above. The differential effect of R-type and irrelevant intersections supports the conjecture of Experiment 1 that subjects take advantage of foreknowledge about the composition of the set of stimuli.

The residual delay of about 40 ms associated with the irrelevant curve could be caused by an interference with the contour integration mechanism. This interference would be compatible with the configural superiority effect of Experiment 2. Since contour segments outside the critical zones speed up responses, it would be expected that intersections outside these zones may interfere with performance. However, the delay associated with the irrelevant curve need not be caused by a specific interference with contour integration. Kahneman, Treisman and Burkell (1983), for example, showed that the presence of an irrelevant image component is associated with a delay in a word naming task, even if this image component was easily disciminable as a non-word. In their terminology, the presence of a distractor may attract some visual attention, and therefore, this distractor needs to be filtered out. In our task, 'filtering out' of an irrelevant curve could also be responsible for the delay. An additional experiment was carried out in order to investigate whether the delay associated with an irrelevant curve was caused by an interference with contour integration, or rather, by the mere presence of an additional image component.

6. Experiment 5: Irrelevant intersections and irrelevant curves

The previous experiment demonstrated that irrelevant curves are associated with a small, but consistent increase in reaction time. The present experiment aims to distinguish between two possible causes for the delay. The first potential cause is an interference with a process that groups of contour segments into spatially extended objects. According to this hypothesis, grouping of contour segments that belong to the target curve is somewhat impaired by the addition of an irrelevant intersection. This hypothesis implies that the irrelevant curve should cause a larger delay when it intersects with the target curve, which connects the fixation point to one of the targets, than when it intersects with the distractor curve. In contrast, the 'filtering' hypothesis predicts that an additional irrelevant image component causes a delay that is relatively independent of its exact location. Therefore, the performance of subjects was investigated with a new set of stimuli (Fig. 8) (set EI, eccentric irrelevant curves). Set EI comprised 24 stimuli, 16 of which contained an irrelevant curve. In eight

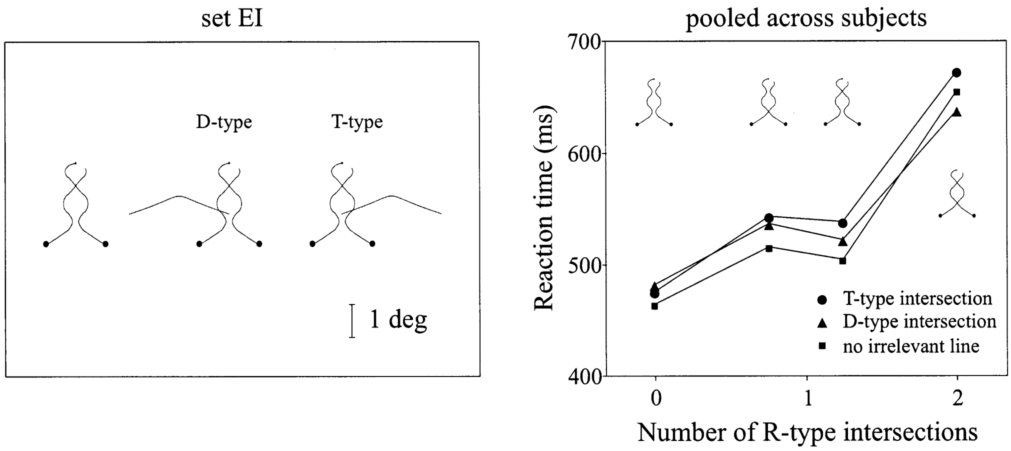

Fig. 8. Delays associated with R-, T- and D-type intersections. (Left) Example stimuli of set EI. The irrelevant curve either crossed the target curve in a T-type intersection, or the distractor curve, in a D-type intersection. (Right) Reaction times averaged across the four subjects.

stimuli the irrelevant curve crossed the target curve (T-type intersection), and in the other eight stimuli it crossed the distractor curve (D-type intersection).

6.1. Methods

The methods were identical to those of Experiment 4. The stimuli of set EI were generated by adding an additional curve to the stimuli in set C (Fig. 8). Four naive subjects participated in the experiment. All subjects had corrected to normal vision in both eyes.

6.2. Results and discussion

Fig. 8 shows examples of stimuli in set EI. For each of the stimuli of set C, two additional stimuli were generated. One of these stimuli contained a T-type intersection, and the other contained a D-type intersection. The average delay associated with T-type intersections amounted to 23 ms, and the delay associated with D-type intersections amounted to 10 ms. The significance of these effects was assessed using a 3-way ANOVA, with condition (no irrelevant curve, T- or D-type intersection) and stimulus (location of R-type intersections) as fixed, and subjects as random variable. This analysis revealed a main effect of condition ($F_{2,6} = 7.3$; $P < 0.05$). Post-hoc testing revealed a significant difference between the delay associated with T- and D-type intersections (Tukey's HSD test; $P < 0.001$). The delays associated with T- and D-type intersections were also significant, when compared to stimuli without an irrelevant curve (Tukey's HSD test; $P < 0.001$ and $P < 0.05$, respectively). The second main effect was associated with the R-type intersections ($F_{3,9} = 18.3$; $P < 0.001$). R-type intersections contributed an average delay of 91 ms per intersection, thus reproducing the results of Experiments 1–4.

T-type intersections contributed a delay that was relatively constant across stimuli (range between stimuli, 12–33 ms), in accordance with the results of Experiment 4. The delay associated with D-type intersections exhibited a more erratic dependence on the stimulus, varying from a decrease in reaction time by 16 ms for the stimulus with two intersections, to an increase by 20 ms for the stimulus with a single intersection at the lower critical zone. These differences between stimuli could not be interpreted, however, since the interaction between relevant and irrelevant intersections was not significant ($F_{6,18} = 7.3$; $P > 0.2$).

The finding that T-type intersections are associated with a longer delay than D-type intersections suggests that at least part of the delay is caused by an interference with contour integration. Contour integration is a possible strategy in the present task, because the correct response can be determined by a process that integrates segments of the curve that connects the fixation point to the target. The configural superiority effect of Experiment 2 indicated that contour segments outside the critical zones have a beneficial effect on performance. Therefore, it was expected that irrelevant contours outside the critical zones might also interfere with performance, in particular, if they intersect with the target curve. The difference between the effects of T- and D-type intersections is consistent with this view. It indicates that the target curve is treated differently by the visual system than the distracting curve. However, D-type intersections were also associated with a small delay of about 10 ms. This may reflect a small, aselective 'filtering cost' (Kahneman et al., 1983).

7. General discussion

The present results show that a visual discrimination task which can, in principle, be solved by a grouping operation linking collinear contour segments into spatially extended objects is associated with prolonged reaction times. The task could also be solved by a different strategy, based solely on information present inside the critical zones. However, such a strategy can be ruled out, because a large configural superiority effect occurred for contour segments outside the critical zones. In contrast, the hypothesis that contour grouping is involved does account for this configural superiority effect. We are unaware of other mechanisms that would exhibit a dependence on contour segments outside the critical zones, and provide a solution for the present task. A contour integration mechanism would also account for the difference in delays associated with T- and D-type intersections. T-type intersections occur when an irrelevant curve crosses the target curve. This should produce more interference than a D-type intersection, which is an intersection between two irrelevant curves, for which contour integration need not take place.

Reaction times exhibited a rather complex dependence on the type of visual stimulus, as well as on the context that was determined by other stimuli of a set. In task A1 and A2 the correct response was determined by information at a single critical zone, and reaction times were shortest. These tasks did not differ from simple visual discriminations, and can be used as a baseline against which performance in the other tasks can be compared. In the presence of multiple critical zones, reaction times to stimuli were prolonged by at least 60 ms. This delay is presumably due to a change of strategy, related to the necessity of integrating information from distinct positions in the visual field. We presented evidence that contour grouping is a likely candidate mechanism for this integration, and therefore, we conjecture that the contour grouping operation requires an additional 60 ms, in our task. The hypothesis that subjects change strategy in the presence of multiple critical zones is corroborated by a difference in the effect of intersections. In case of a single critical zone (set A2), stimuli with an R-type intersection were associated with faster responses than stimuli without such an intersection. This is in line with a study by Treisman and Gormican (1988) who found that it takes more time to detect non-intersecting line segments among intersecting distractors than to detect intersecting segments among non-intersecting distractors. In the case of multiple critical zones, R-type intersections were associated with considerable delays. These delays do not depend on the alignment of intersections with the vertical meridian, which indicates that delays in integration of information that is represented in different hemispheres cannot account for the increases in reaction time.

Intersections are likely to confront the mechanism that groups contour segments into spatially extended objects with additional complexity. The grouping operation can only use collinearity as a grouping criterion at an intersection, but can also rely on connectedness at all other locations. Intersections do not cause contour grouping to break down completely, however, since the configural superiority effect also occurred for stimuli with a single intersection (Fig. 5). Moreover, the finding of faster responses to stimuli with intersections in the context of set A2 indicates that enhanced complexity is not an inherent property of intersections.

An alternative, non-exclusive explanation for the delays associated with intersections can be derived from earlier studies on curve tracing. These studies demonstrated that reaction times depend on the distance that subjects needed to trace, as measured along the curve (Jolicoeur et al., 1986; Pringle & Egeth, 1988). Importantly, Jolicoeur et al. (1991) showed that tracing speed is reduced when other contours come in close proximity of the curve that has to be traced. This could also account for the delays caused by intersections. The finding that the second R-type intersection causes a larger delay than the first also seems to be related to these earlier findings. Jolicoeur et al. (1986, 1991) noted that the reaction times, in some cases, exhibit a supralinear dependence on the distance that should be traced. This resembles the supralinear interaction of R-type intersections.

7.1. Is detection of collinearity pre-attentive?

The contour segments that formed the target curve could be grouped together on the basis of collinearity and connectedness. The prolonged reaction times for some of the stimuli may therefore seem to contradict earlier studies suggesting that collinearity yields pre-attentive grouping of oriented image elements (Field et al., 1993; Kovács & Julesz, 1993). It might be suggested that contour grouping also occurred pre-attentively in our task, but that delays were caused by a difficulty in 'reading out' segmentation results. We note that this assumption is unattractive, and non-parsimonious. The assumption is unattractive, because it could be made in all tasks showing prolonged reaction times, including visual search. This would imply that reaction times are a useless measure for the distinction between pre-attentive and attentive mechanisms. It is also non-parsimonious, since it attributes the differences in our task and previous tasks to an unknown mechanism for reading out segmentation results.

As a second approach to the resolution of the apparent discrepancy, it might be argued that contour grouping occurs pre-attentively, except at the intersections[2]. At the intersections contour grouping is deprived of

[2] We thank an anonymous reviewer for this suggestion.

connectedness as a grouping criterion. This might cause a breakdown of contour grouping, and necessitate the recruitment of visual attention. However, in most of the previous studies on curve tracing the curve that had to be traced stayed well separated from other curves (Jolicoeur et al., 1986; Pringle & Egeth, 1988). Nonetheless, in these studies the reaction time depended approximately linearly on the distance that had to be traced along the curve. Thus, even when connectedness is available as a grouping criterion at all locations, contour integration need not take place pre-attentively. Furthermore, Jolicoeur (1991) demonstrated that tracing speed is gradually reduced, when the spacing between the curve that should be traced and other curves decreases. This is evidence against a dichotomy between pre-attentive and attentive contour grouping. Moreover, the configural superiority effect of Experiment 2 also occurred for stimuli with a single intersection. This indicates that contour grouping did not break down in the presence of R-type intersections, as was discussed above.

We would rather attribute the discrepancy to another difference between our task and curve tracing tasks on the one hand, and the tasks employed in studies suggesting pre-attentive contour grouping on the other hand. Specifically, in previous tasks of collinearity detection (Field et al., 1993; Kovács & Julesz, 1993) subjects were required to detect a group of approximately collinear image elements on a background of randomly oriented elements. These studies indicate that a coherent figure defined by collinear image elements readily stands out from randomly oriented background elements. Indeed, even the detection of low contrast image elements is facilitated when they are flanked by approximately collinear elements (Polat & Sagi, 1994; Kapadia, Ito, Gilbert & Westheimer, 1995). Physiological evidence corroborates facilitatory interactions among neurons encoding collinear line elements. For example, neuronal responses to line elements that are flanked by approximately collinear line elements are enhanced in the primary visual cortex (Nelson & Frost, 1985; Kapadia et al., 1995).

The task of the present study and earlier curve tracing tasks (Jolicoeur et al., 1986; Pringle & Egeth, 1988) differ in that there is no need to segregate coherent contours from an unstructured background. The stimuli of the present task, for example, contained two or three equally coherent curves on a homogeneous background. The response was presumably based on the grouping of contour segments belonging to the target curve. This implies that the division of contour segments among equally coherent figures costs additional time, especially when the respective figures are overlapping. Thus, whereas earlier tasks provided evidence for the existence of a pre-attentive mechanism which groups collinear line elements in order to segregate figure from ground, the present results together with earlier results on curve tracing (Jolicoeur et al., 1986; Pringle & Egeth, 1988) provide evidence for the failure of the same mechanism to segregate equally coherent figures from each other. This conclusion is also plausible from a computational point of view. Feedforward algorithms exist for the detection of contours defined by collinear line elements among randomly oriented background elements (Gigus & Malik, 1991). These algorithms are sensitive to the degree of collinearity among line elements, and are therefore likely to fail in the present task, since the degree of collinearity did not differ between curves.

A final difference between the present study and previous studies on collinearity detection is that in these earlier studies the oriented image elements that needed to be grouped together were spatially separate and disconnected. In the present study all segments that belonged to one of the contours were connected. It seems unlikely, however, that this difference can account for the protracted reaction times of the present study, since connectedness is an additional grouping criterion, which should have facilitated rather than prohibited contour grouping (Rock & Palmer, 1990).

In search tasks in which the presence of a particular target item among distractors needs to be detected, a strong dependence of reaction time on the number of distractors is usually taken as evidence for the involvement of visual attention. It is assumed, for example, that an attentional focus ‘visits’ the image elements, one or a few at a time, until a target item is found (Treisman & Gelade, 1980; Posner & Presti, 1987; Treisman & Gormican, 1988). In the present study we observed a strong dependence of reaction time on the number of locations of relevant stimulus variation and on the number of intersections between curves. We wish to consider three hypotheses that invoke different forms of visual attention.

7.2. Is visual attention involved in the present paradigm?

7.2.1. Involvement of focal attention

The first hypothesis is that focal attention needs to be directed to the critical zones in order to resolve whether the curves do or do not intersect. When there is a single critical zone, as in set A1 and A2, visual attention can be directed to it, and there is no need for redirecting the focus of attention during the session. In contrast, when there are multiple critical zones, movements of focal attention are necessary in every trial, and this would explain why reaction times are longer. Moreover, locations of stimulus variation that do not affect the correct response need not to be visited by the attentional focus. This would explain why intersections with the irrelevant curve (T- and D-type intersections) had a relatively small effect on reaction times. The overall pattern of reaction times can, however, not be explained by time consuming shifts of an attentional focus. The results demonstrate that in the context of multiple loci of stimulus variation, intersections between curves cost more time than when the same curves do not cross each other. This cannot be explained by movements of the attentional focus, since the focus would have to move to all critical zones, irrespective of the presence of an intersection. Moreover, the introduction of the third critical zone did not lengthen reaction times to the same extent as the introduction of the second (Fig. 2). If the pattern of reaction times would depend solely on movements of an attentional focus, then the reaction time should increase proportionally to the number of critical zones. When attention moves in a straight line from one critical zone to the next, it is also difficult to explain the differences between the delays caused by T- and D-type intersections. This hypothesis also fails to explain why the removal of contour segments outside the critical zones prolongs the reaction time ('configural superiority effect').

7.2.2. Curve tracing by moving the focus of attention over the target curve

A second hypothesis that would account for the lengthening of reaction times caused by the intersections has been put forward by McCormick and Jolicoeur (1991). They suggested that curve tracing might be carried out by a movement of focal attention along the entire curve (not just between the critical zones). According to their proposal, the focus would be rescaled during this tracing process. A large focus would suffice to trace in image regions where curves are widely separated, whereas the 'attentional beam' should be narrowed at locations where curves are in close proximity, in order to restrict it to segments belonging to a single curve.

This proposal would account for the configural superiority effect, since the contour segments outside the critical zones are important for guiding the focus from one intersection to the next. It has been shown previously that shifts of attention between locations of a single object are faster than between locations of different objects (Egly, Driver & Rafal, 1994). Moreover, this hypothesis elegantly accounts for the reduced tracing speed at locations where curves are close together, since a smaller attentional beam needs to be shifted more often in order to trace a curve of fixed length (McCormick & Jolicoeur, 1991). However, at intersections it is impossible to avoid the presence of multiple curves within the attentional focus. Thus an additional process, which should depend on collinearity, would be necessary to allow the focus to cross an intersection.

D-type intersections are at a location that need not be visited by the moving focus, and this would explain why they are associated with a shorter delay than T-type intersections. However, the difference in delay caused by T- and R-type intersections implies that the curve tracing process is sensitive to high level foreknowledge. Tracing should speed up in image regions where no relevant variation is expected. There is also a finding that is harder to account for by a movement of focal attention over the entire target curve. The addition of the first R-type intersection to the stimuli was associated with a shorter delay than the addition of the second. This would imply that the speed of the focus is not solely determined by the information enclosed by it.

7.2.3. Involvement of object-based attention

As a third hypothesis with respect to the engagement of visual attention we wish to consider the possibility that object-based attention is involved in the present paradigm. There is good evidence that visual attention can be directed to a coherent perceptual object, even when this object is spatially overlapping with another object (Rock & Gutman, 1981; Duncan, 1984). Patients with a lesion in the parietal cortex can exhibit extinction of one of two spatially overlapping visual objects (Farah, Wallace & Vecera, 1993; Humphreys, Romani, Olson, Riddoch & Duncan, 1994). However, grouping criteria like similarity of color, and connectedness can prevent extinction in such patients if they link the respective image components into a single coherent object (Farah et al., 1993; Humphreys & Riddoch, 1993; Mattingly, Davis & Driver, 1997). Also in healthy individuals, visual attention has a tendency to spread from attended image regions to image elements with a similar color or motion or to elements that are linked to these regions by good continuation (Driver & Baylis, 1989; Kramer & Jacobson, 1991; Baylis & Driver, 1992, 1993). These results, taken together, suggest that object-based attention is guided by the Gestalt criteria of perceptual grouping, and that it can be invoked in order to disentangle spatially overlapping objects. Our task would have been solved as soon as subjects had been able to direct attention to the entire target curve. A proportion of the subjects reported that their subjective impression was indeed that the target curve stands out from the other curves (the reader may verify that it is possible to direct attention to one of the curves by scrutinizing Fig. 1). A strategy based on object-based attention depends on contour segments outside the critical zones and is, therefore, supported by the configural superiority effect. Such a strategy would also predict the difference between the effects of T- and R-type intersections on the one hand, and D-type intersections on the other, because only D-type intersections, which are between the distractor curve and an irrelevant curve cannot interfere with the spread of attention within the target curve. The large difference in delay associated with T- and R-type intersections, however, should be attributed to the influence of foreknowledge.

A hint on how this foreknowledge might speed up reaction times can be derived from earlier studies on the effects of distracting information in visual identification tasks. Tipper, Weaver, Cameron, Brehaut and Bastedo (1991) showed that directing attention to a particular image components takes more time, if this component had to be ignored on an earlier trial. The inhibitory influence on the ignored image component was found to be stable over many seconds, and even across intervening stimuli. In the present task, such a prolonged inhibition of the irrelevant curve would be beneficial, since it never became relevant on a subsequent trial. In contrast, segments of the distractor curve typically became part of the target curve on a subsequent trial. The irrelevant curve at a T- and D-type intersection could have been inhibited across trials, but the two curves that met in an R-type intersection could not. Thus, a prolonged attention-related inhibition of the irrelevant curve could explain the difference in delay between T- and R-type intersections.

Object-based attention is also consistent with the supralinear interaction of the two R-type intersections, although it does not provide a strong prediction in this respect. According to the grouping criterion of connectedness, every intersection provides some evidence that the two curves are, in fact, part of a single object. Thus attention may tend to 'leak' from the target curve into the distractor curve at an intersection (Kramer & Jacobson, 1991). In the case of two intersections, there is even a closed compartment in the stimulus, which provides additional evidence that the two curves are part of a single object. Therefore, it might be speculated that two intersections are associated with a strong spread of attention from the target curve into the distractor curve.

We have recently carried out an experiment that strongly supports the involvement of visual attention in curve tracing (Scholte, Spekreijse & Roelfsema, 1998). Subjects were tested in a dual-task paradigm with the stimuli of set C. The primary task was identical to the task of the present study. Some of the contour segments were colored however, and the secondary task was to report one of these colors. Colors of the target curve were reported more reliably than colors of the distractor curve. This enhanced performance for colors of the target curve was observed for contour segments outside the critical zones. These results provide strong support for our conjecture that segments of the target curve are are attended by the subjects, and in addition, supports our conjecture that attention is not solely directed to the critical zones.

It should be noted, however, that the distinction between the hypothesis that object-based attention is involved and the hypothesis that there is a focus moving along the entire curve is rather subtle. Both hypotheses predict that all segments belonging to the target curve are attended at some point in time, and that segments of the distractor curve are not. The only difference is the order in which the various segments of the target curve are attended, which is in parallel for the object-based attention hypothesis, and one at a time for the moving focus. We have recently performed a study on the neurophysiological correlates of curve tracing in awake monkeys using stimuli that were similar to the ones of the present study (Roelfsema, Lamme & Spekreijse, 1998). Responses of neurons in the primary visual cortex to segments of the target curve were enhanced relative to the responses to the distractor curve. This is consistent with the view that the target curve is attended, because physiological studies on the correlates of visual attention agree that neural responses to attended image components are enhanced relative to responses to unattended image components (Wise & Desimone, 1988; Maunsell, 1995). During curve tracing, enhancement of neuronal responses in area V1 occurred simultaneously for segments of the entire curve that connected the fixation point to the correct target (Roelfsema, Lamme & Spekreijse, 1998). Thus, the physiological data are in support of the object-based attention hypothesis.

These results, taken together, indicate that object-based attention is involved in curve tracing, in order to group spatially separate image elements into a coherent object representation. One of the first theories in which attention was suggested to be important for the assignment of visual features to a single object representation is the feature integration theory of Treisman and coworkers (e.g. Treisman & Gelade, 1980). According to feature-integration theory, features are integrated into a coherent object as soon as focal attention is directed to the object's location in the visual image. The process of shifting the focus between different objects is considered to be a rate-limiting step in feature-integration theory, and the emphasis is on integration of features in different domains, such as color, motion, texture, and shape. Our observations are largely consistent with feature-integration theory, but also suggest a number of important modifications. First, attention is not necessarily focal, but can be simultaneously directed to spatially separate image regions that belong to a single object (Duncan, 1984). Second, the selectivity of attention can only be guaranteed if its distribution depends on Gestalt criteria, such as collinearity and connectedness (Kahneman & Henik, 1981; Duncan, 1984; Kramer & Jacobson, 1991; Wolfe & Bennett, 1997). Third, attention is also invoked in order to label responses to elementary features in a single domain: spatially separate contour segments. Fourth, the process of spreading attention to all segments of a single curve is time consuming, in particular when this curve intersects with another curve. Thus, the spread of attention within a coherent perceptual object costs time (Roelfsema & Singer, 1998), just as the redirection of focal attention between different objects (Posner, 1980; Treisman & Gelade, 1980).

7.3. How fast is object recognition?

The delays that occur during the assignment of contour segments to perceptual objects should affect other visual processes, like object recognition, which depend on the outcome of these grouping operations. It should be noted that the number of locations that contained information relevant to the solution of the task was not an intrinsic property of the stimuli, but depended on the other stimuli of the set. This implies that the optimal strategy with shortest reaction times could only be applied as soon as the entire context determined by the other stimuli was appreciated by the subjects. Thus, the longest reaction times obtained in our restricted experimental context provide a lower bound for the duration of the perceptual processes which underlie the processing of similar stimuli in more natural environments (for example during electrical wiring).

There is, however, also considerable evidence for rapid recognition of simple objects by the visual system. Biederman (1987), for example, showed that an exposure of 100 ms suffices for the visual recognition of many figures. Similarly, Rolls and Tovée (1994) have suggested that presentation times as short as 20 ms can be sufficient for the recognition of a face. Physiological evidence supports a rapid cortical analysis of visual shape. In the inferotemporal cortex, an area that is essential for visual recognition, neurons are found which are selective for rather complicated shapes like human faces (Perrett, Mistlin & Chitty, 1987; Tanaka, 1995). Tovée, Rolls, Treves and Bellis (1993) showed that the early responses of these face selective neurons, which occur after a latency of about 100 ms, contain significant information about the identity of a face. Taken together, this evidence suggests that very little processing time is required for the rather complicated transformations necessary for the identification of objects that may be as complicated as a face (Tovée, 1994). Thus, neurons of the inferotemporal cortex seem to encode about everything there is to know about the identity of a visual object as soon as they start to fire. Based on this evidence, these authors speculated that it is unlikely that object recognition depends on time consuming grouping operations (Rolls & Tovée, 1994; Tovée, 1994). The present results, on the other hand, strongly suggest that the recognition of visual objects can be delayed substantially. Each stimulus set contained a limited number simple stimuli which could, in principle, be discriminated very rapidly. Indeed, when there was only a single location of stimulus variation reaction times were rather short. In contrast, when information from different locations in the visual field needed to be integrated for a correct decision, reaction times could be prolonged by up to 250 ms. Thus, these results seem to rule out the possibility that the early (within 150 ms) responses of neurons at higher stages of the visual cortical processing hierarchy contain sufficient information to solve the task. In other words, it seems unlikely that neurons of the inferotemporal cortex would encode the solution for the present paradigm as soon as they start to fire.

8. Concluding remarks

The finding that reaction times can be rather long in a task that can be solved by grouping on the basis of collinearity and connectedness demonstrates that these grouping criteria are not necessarily applied pre-attentively. When the present results and earlier results on grouping on the basis of collinearity (Field et al., 1993; Kovács & Julesz, 1993) are considered together, they suggest that grouping on the basis of collinearity is only pre-attentive in tasks in which it suffices to detect a group of collinear image elements among randomly oriented background elements. In contrast, the same process is not pre-attentive when oriented image elements need to be divided among multiple coherent objects, a process which we call figure–figure segregation. Thus, other 'pre-attentive' grouping criteria may also have to be re-evaluated, since they may exhibit a similar task dependence (Joseph, Chun & Nakayama, 1997).

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