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Self-terminating Processing in Curve Tracing

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Several possible operations on visual curve tracing were investigated using elementary stimuli without interweaving curves. Experiment 1 required subjects to determine whether a line segment was connected or disconnected by one or two gap(s). The effects of line complexity, gap redundancy, two-point distance, and gap distance were assessed. Mean response time for both ***gap*** and ***no-gap*** trials increased linearly with two-point distance (i.e., linear distance between the ends of the line segment). Furthermore, two-point distance interacted with line complexity. Therefore, response time increased with the distance ***along the curve***, consistent with the notion of "curve tracing"(Ullman, 1984). In the ***gap*** trials, however, mean response time increased linearly with gap distance (i.e., distance between a central point and a gap). Furthermore, mean response time for double-gap trials was faster than that for single-gap trials. Using a half circle with a gap and two Xs, Experiment 2 tested whether the curve tracing operation is carried out by an exhaustive or by a self-terminating process. Again, mean response time in ***same*** trials increased linearly with the distance between two Xs. However, mean response time in ***different*** trials remained unaffected by the distance between two Xs. Taken together, effects of gap distance and gap redundancy are best explained by a self-terminating curve tracing process.

The perception of spatial relations among various objects plays an important role in visually guided manipulation such as painting, drawing or even picking up an object. People experience no difficulty in determining which object is to the left, which is above, which is inside, or which is outside another object. These simple tasks may seem to require no explanation. However, when the processes entailed in the perception of spatial relations are examined more closely, the mechanisms involved are rather complex and require detailed investigation. According to Ullman(1984), the perception of spatial relations among objects is accomplished by one or more "visual routines." Each routine is an assembly of elementary operations or processes, and the assembly of those operations is driven by visual context. Each elementary operation results in a base representation, and these representations are integrated by a certain visual routine. According to Ullman, determining how and which visual routines are used in a given task and which assembly of elementary operations is applied is an important step in studying space perception and object recognition.

There are many approaches to the study of visual routines. One of them is to investigate the phenomenon called "curve tracing"(Ullman, 1984). For example, suppose you are presented with a display containing several curved lines and Xs (see Figure 1).

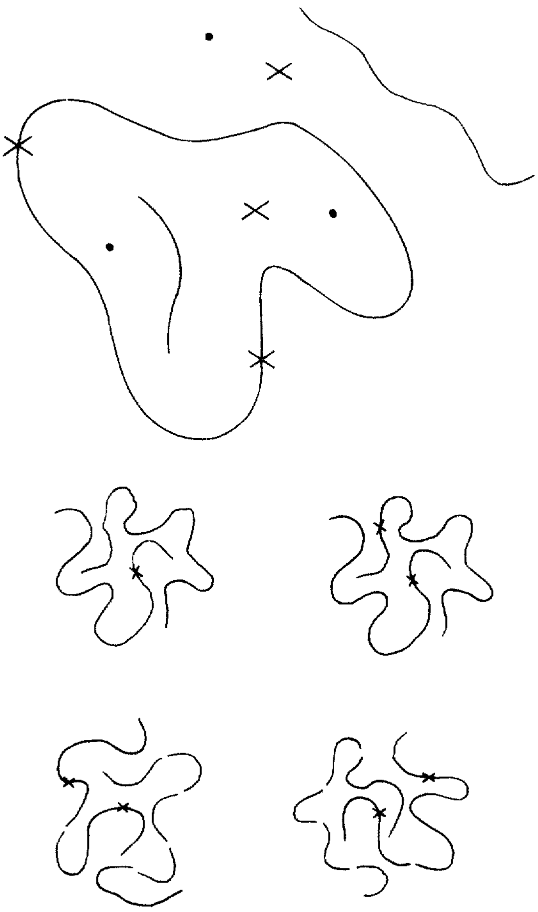


Figure 1. Stimulus examples from Jolicoeur, Ullman, and Mackay(1986). Upper figure was modified for illustration. Middle two figures are their stimuli from Experiment 1, and the lowest two are those from Experiment 2.

The task required is to determine whether there are two Xs on the same line. To do this task, several elemental operations appear necessary: (1) the detection of a curve, (2) the detection of both Xs, and (3) the judgment of whether the two Xs are both on the curve. Because there are always two Xs in the display, the mere detection of two Xs does not provide enough information about whether they lie on the same curve. Instead, the task may require the observer to trace along the curve to determine whether the two Xs lie on the same curve.

A crucial question here is that what kinds of basic operations are involved in the task. Specifically, is the task carried out in a parallel fashion or not? Phenomenologically, the task is so easy that it appears to be done almost immediately and effortlessly. However, if more time is required with longer curves than with shorter curves, the notion of serial curve tracing would be supported.

Jolicoeur, Ullman and Mackay(1986) carried out two experiments to examine possible basic operations in the curve tracing task. Experiment 1 required subjects to determine whether two Xs lie on the same curve or not. RT increased linearly with the distance between the Xs along the curve, even though the physical distance between two Xs was held constant. This result suggests that subjects, starting from one X, traced along the curve until they found another X. In their Experiment 2, subjects decided as quickly as possible whether the section of a curve marked by two Xs had a small gap or not. Again, RT increased with increasing the distance between two Xs along the curve. Furthermore, the tracing rates for both *gap* trials and *no-gap* trials were about the same, that is, subjects traced entire curve even when they found a gap before reaching the peripheral X. Therefore, it was suggested that curve tracing operation is carried out in an exhaustive manner. If curve tracing were self-terminating (i.e., subjects stopped tracing a curve when they find a gap), then the ratio of the slopes from *no-gap* and *gap* trials should have been 2:1. The reason is that subject would spend half the time tracing the *gap* trials compared to *no-gap* trials, provided that the average distance between the central X and a gap in the *gap* condition is half the length of the curve in the *no-gap* condition. The notion of exhaustive curve tracing was strengthened by the result that the distance along the curve between the fixation point and a gap had no effect on RT.

The stimuli used by Jolicoeur et al. were carefully constructed to rule out the effect of retinal eccentricity (see Figure 1) by keeping the physical distance between the two Xs. Thus the visibility of each peripheral X is the same regardless of the variations in the distance *along the curve.* However, careful examination suggests that the stimuli may have favored an exhaustive curve tracing process. For example, since one of the Xs was always in the fixation point, subjects may have inadvertently traced the curve to check another X. Furthermore, there may have been uncertainty about which direction subjects should trace because the curves were so closely interwoven that central portion of the display was more complex than peripheral portion. The existence of the portion of distractor curve attached to the central X also may have made subjects more difficulty deciding the right direction of curve tracing. These facts might have forced subjects to adopt a backward-tracing strategy. Specifically, subjects might have traced the curve from the peripheral X to the central X, cancelling any effect of gap distance that might otherwise have appeared.

Using elementary stimuli, Pringle and Egeth(1988) conducted four experiments to determine whether curve tracing takes place even for simple stimuli (see Figure 2). Each stimulus consisted of two curves (arcs of a circle) on which two Xs were marked. The task required subjects to decide as quickly as possible, if the two Xs lie on the same or different curves. The stimuli were constructed so there were no interweaving curves. Neither of Xs were located at the fixation point, eliminating the possible demand characteristics of the experiments of Jolicoeur et al. (1986). If curve tracing is required with these rather simple stimuli, then curve tracing could be regarded as a basic operation.

Pringle and Egeth found that mean RT for *same* trials increased with the distance separating Xs, suggesting that even processing the simple stimulus requires curve tracing. For *different* trials, however, mean RT *decreased* with the distance between Xs,

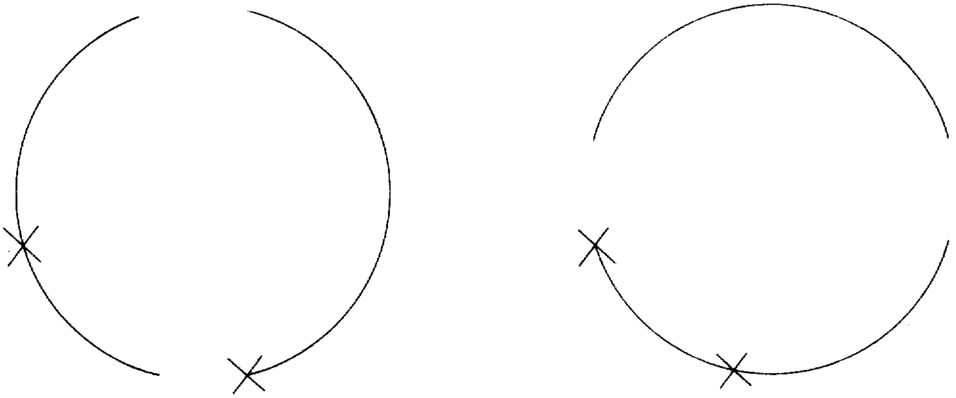


Figure 2. Stimulus examples from Pringle and Egeth(1988), Experiment 1.

suggesting that performance on *same* trials and on *different* trials may involve different processing components. It was suggested that in the *same* trials the evidence strongly favored curve tracing, while *different* trials were apparently solved on the basis of judgmental processes presumably operating in parallel with curve tracing.

In summary, this line of research suggests that when subjects are required to determine whether two Xs lie on the same curve, curve tracing may be required. However, while curve tracing seems to be serial in nature, it is not clear whether curve tracing operation could be done in an exhaustive manner or self-terminating manner. The reason is that the task as well as the stimuli used in those previous studies may have been insufficient for a clear examination of the mechanisms of curve tracing. Specifically, in the *different* trials, it is not obvious how to define the distance between two Xs (e.g., Jolicoeur et al. 1986, Experiment 1). It follows that the *same* and *different* trials cannot be compared adequately, leaving unanswered the question of exhaustive vs. self-terminating process. Second, there are few experiments designed to determine whether curve tracing is required in the processing of extremely simple stimuli such as a single line. Therefore, it is not clear whether exhaustive curve tracing is an elemental operation over a wide range of stimulus characteristics. Manipulating the line complexity would provide another method for exmining the effects of distance along the curve while controlling the confounding effects of retinal eccentricity.

In the present study, we replicated the experiments of Jolicoeur et al.(1986) and Pringle and Egeth(1988) using even simpler stimuli. In addition, we attempted to examine the specific nature of the curve tracing operation. Specifically, manipulating gap distance should illuminate whether curve tracing takes place in an exhaustive or self-terminating manner. In addition, effects of gap redundancy may shed light on whether curve tracing occurs in parallel or serial manner.

EXPERIMENT 1

Experiment 1 required subjects to determine as quickly as possible whether there were any gaps on the line segment specified by two red points, one of which presented on the fixation point was defined as a *starting point*, the other on either side of line segment was defined as a *variable point*. In order to estimate distance effect independent of retinal eccentricity, we manipulated line complexity (*line*, *sine*, *compound*) with two-point distance (*short* vs. *long* distance). In addition, gap redundancy (*single* vs. *double gap*) and gap distance (i.e., the distance between the *starting point* and gap, *near gap* vs. *far gap*) were manipulated to test the modes of processing. Therefore, there would be several models that predict various possible outcomes, depending on the assumptions of serial vs. parallel and exhaustive vs. self-terminating processes.

Prediction of parallel models

There are several versions of the parallel model that must be considered. According to the limited-capacity parallel model, gap detection operations are carried out simultaneously over the entire display (we call this model a *"pure parallel model"*). Here, by "limited-capacity" we mean that the amount of processing resource decreases with increasing stimulus size. This parallel model does not assume curve tracing operates along the curve because the curve tracing always implies a serial nature of processing. The other version of the parallel model assumes there are two serial curve tracing operations that simultaneously proceed, but the starting point and the direction of tracing are opposite to one another. Specifically, subjects might start from both the starting point and from the variable point concurrently, and trace inward until they find a gap. This model can be called a *"parallel tracing model"*. or a *"concurrent serial model"*. Also, this kind of model be called as a *"mixed model"*, since the model incorporates both the parallel and serial nature of processing. If a redundancy gain is observed, this would be evidence for either version of the parallel processing models. Note that we define a gap-redundancy effect by the difference in RT between the *single-near gap* and *double gap* trials, excluding *single-far gap* condition. The reason for excluding *far gap* trials in assessing redundancy gain was to eliminate the confounding effect of retinal eccentricity.

The two parallel models predict different patterns of results regarding the effects of line complexity, two-point distance, and gap-distance. The "pure parallel model" predicts that line complexity should have no effect, and should not interact with two-point distance or with gap distance.

In contrast, the "parallel tracing model" predicts that curve tracing time increases with increasing line complexity and with two-point distance. Note that this is the same pattern predicted by a serial self-terminating model. However, gap distance would not affect RT, because the distance between the starting point and the near gap is the same as the distance between the variable point and the far gap (see Figure 3) Therefore, a parallel model assumes that the gap distance effect can only be attributed to the differences in retinal eccentricity between the near gap and far gap conditions, but not to the differences in tracing time between the two conditions. Furthermore, according to the parallel tracing model, any effect of gap redundancy would be due to the variance of completion time of the two simultaneous tracing operations. Therefore, if the variance of the tracing completion time is larger in the *long* condition than in the *short* condition, then a larger gap redundancy effect should be obtained in the *long* condition than in the *short* condition.

The two parallel models mentioned above both assume self-terminating processes. However, both of these parallel models can be revised to assume exhaustive processing. Both parallel exhaustive models predict no effects of gap redundancy, no effects of gap distance, and no interactions among the variables.

Prediction of serial models

The two types of serial models, exhaustive and self-terminating curve tracing, both predict no effect of gap redundancy, assuming subjects always start curve tracing from the starting point. Unfortunately, it is possible that a subject's actual starting point may vary from trial to trial. In this case, serial self-terminating processing could yield a redundancy gain. The reason is that the average distance to be traced is shorter in the *double gap* condition than in the *single near gap* condition. A strong effect of two-point distance and its interaction with line complexity could constitute evidence for a serial self-terminating process.

If curve tracing is serial, but *exhaustive* in nature, then the average slope of the *no-gap* trials should not be different from that of the *gap* trials. Remember that Jolicoeur et al. obtained this result, supporting exhaustive curve tracing (Jolicoeur et al., 1986, Experiment 2). Finally, a serial exhaustive tracing model predicts no significant effect of gap-distance nor an interaction of gap-distance with line complexity.

Method

Subjects

Eighteen undergraduates at The Johns Hopkins University participated as a part of credit for a class in Psychology. All had normal or corrected-to-normal vision.

Stimuli

The viewing distance was roughly 70 cm, the entire display subtended 13.65°×1.23°. The stimuli were constructed to minimize pattern complexity, and to eliminate interweaving curves (see Figure 3). There were three levels of line complexity, a straight *line*, a *sine curve* (.18 cycles per degree of visual angle), and a compound curve created by summing two sine waves of different frequency (.18 cycle/deg and .75 cycle/deg). Each line or curve was drawn in blue. In the center of each curve was a red square(.2°×.2°) that served as a starting point. Another red square, serving as a variable point, appeared unpredictably on either the left or the right side of the curve. The portion of the curve opposite the variable point was referred to as the distractor curve. On both the target and distractor sections of the curve, there were either one gap, two gaps, or no gap. Each gap subtended .2° of visual angle. The positions and number of gaps for the two sections of the curve were assigned independently of one another.

The two-point distance in each condition was 2.78° in the *short* condition, and 5.54° in the *long* condition. However, the distances *along the curves* were different across the line complexity. The ratios of distance along the line or curve to two-point distance for *line*, *sine curve*, compound curve were 1 ; 1.16 ; 1.34 respectively. The distance between the starting point and the nearest gap was either 1/3 (*near-gap* condition) or 2/3 (*far-gap* condition) of the two-point distance. A '+' sign was used as a fixation point (.2°×.2°).

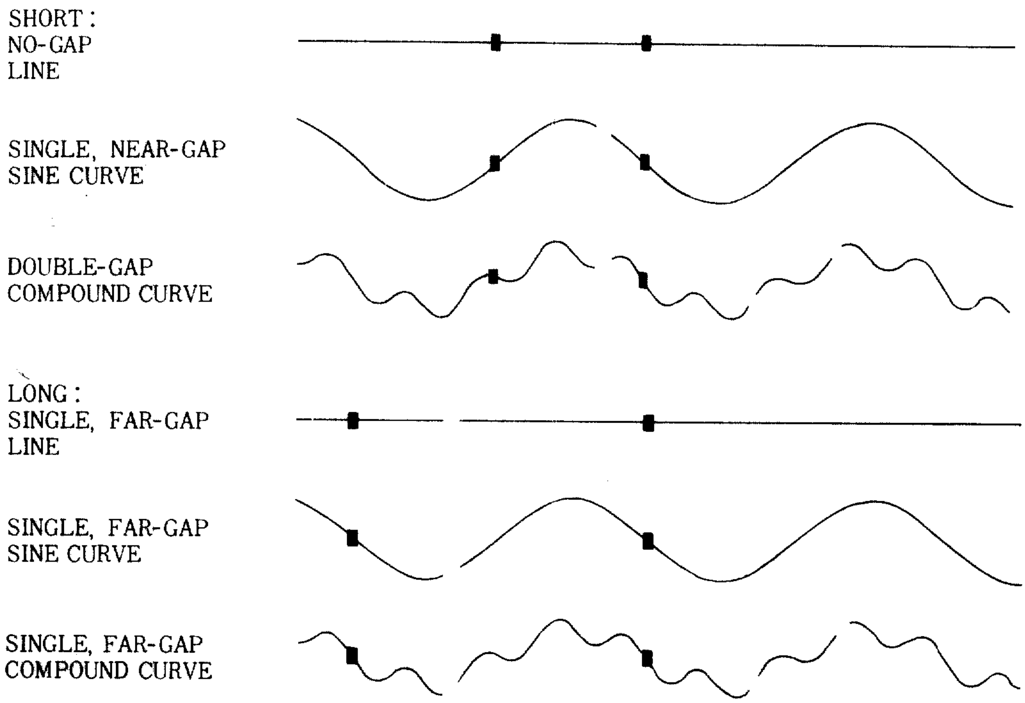


Figure 3. A prototype of the stimuli used in Experiment 1. Upper three figures are Short distance condition, and Lower three are Long distance condition. First of them is Simple Line with no-gap condition, second is Sine curve with single-near-gap condition, third panel is Compound curve with double-gap condition.

Apparatus

An IBM PC/AT computer driving a NEC Multisync EGA display was used for the display presentation and reaction time measurement. A two-button box was attached to the computer for gathering subjects' responses.

Design

A three-way repeated-measures design was used: the three factors were line complexity(*line, sine curve, compound curve*) x response type(*gap* vs. *no-gap*) x two-point distance(*short* vs. *long*). Of the *gap* trials, half were *single-gap* trials, half were *double-gap* trials. Of the *single-gap* trials, half were *near-gap* trials, and half were *far-gap* trials. Therefore, the gap distance variable was nested within the *single-gap* condition, and gap redundancy was nested within the *near-gap* condition. Line complexity was blocked. All other variables were intermixed randomly within each block. The order of the blocks was counterbalanced using a Latin Square design. The order of blocks as well as trials was randomized. Each subject participated in 6 blocks each consisting of 8 practice trials and 64 experimental trials.

Procedure

The task was to determine whether the line between two squares was connected or not. Subjects responded by pressing either the middle or the index finger of their dominant hand. The response key assignments of the two alternative responses were counterbalanced across subjects. Each trial begin with the presentation of fixation point which remained on the screen for .5sec. After .5sec of a blank field, the stimulus display was presented and it remained on the screen until subjects responded. Subjects were instructed not to move their eyes from the fixation point until they pressed the response button.

Results

Errors

Correct responses within three standard deviations of the mean within each block, distance, and gap vs. no-gap conditions for each subject were included in the analysis. The total error rate was 4.7%. An analysis of variance revealed that the errors in the *single gap* conditions were higher than in the *double-gap* conditions, $F(1,17)=4.37$, $p<.05$. No other significant main effects or interactions involving error rates were observed.

Reaction time

Figure 4 shows mean RT as a functon of line complexity, two-point distance, and response type. An ANOVA for those three variables revealed that the main effect of line complexity, $F(2,34)=32.71$, $p<.001$, two-point distance, $F(1,17)=93.77$, $p<.001$, and their interaction, $F(2,34)=14.13$, $p<.001$, were

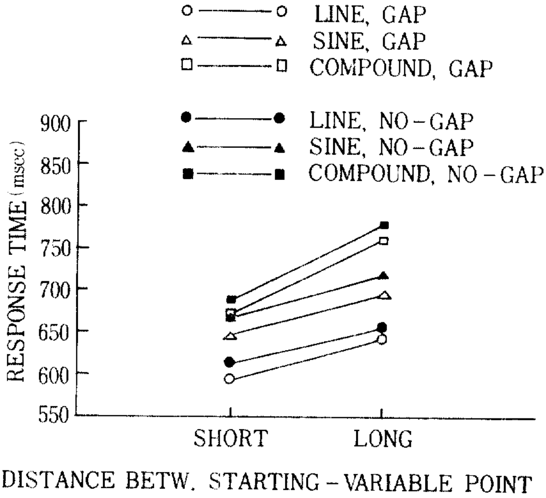


Figure 4. Mean Gap and No-gap RT as a function of the distance between the starting point and the variable point, and the Line complexity in Experiment 1.

significant. In addition, RT for *no-gap* trials were slower than *gap* trials, $F(1,17)=5.39$, $p<.05$. However, response type did not interact with any other variables.

Figure 5 shows the effects of gap redundancy on mean RT as a function of line complexity and two-point distance in the *near-gap* trials. A separate ANOVA for these variables in the near-gap condition revealed that the main effect of gap-redundancy was highly significant $F(1,17)=35.81$, $p<.001$. The effects of line complexity, $F(2,34)=15.70$, $p<.001$, and two-point distance, $F(1,17)=31.49$, $p<.001$, along with their interacion, $F(2,34)=3.93$, $p<.05$, were significant. Gap-redundancy did not interact with any other variable.

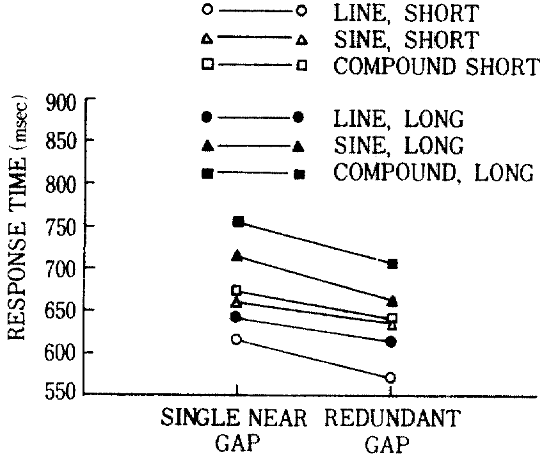


Figure 5. Mean Gap RT as a function of the Gap-redundancy, Two point distance, and the Line complexity in Experiment 1.

Figure 6 shows effects of gap-distance on mean RT as a function of line complexity, and two-point distance in the *single gap* trials only. A separate ANOVA for the variables showed that the main effect of gap-distance, $F(1,17)=12.57$, $p<.01$, its interaction with line complexity, $F(2,34)=3.70$, $p<.05$, and the interaction between gap distance and two-point distance, $F(1,17)=12.19$, $p<.01$, attained significance.

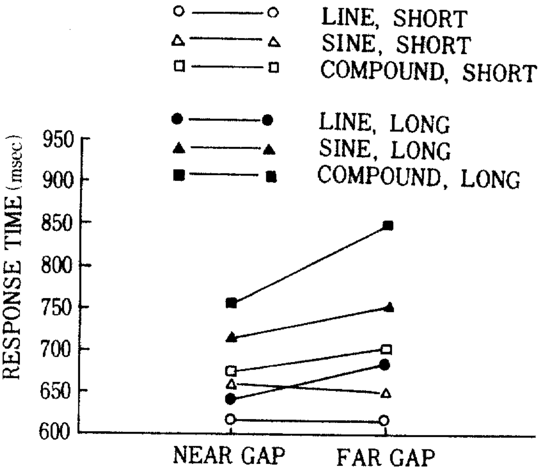


Figure 6. Mean Gap RT as a function of the distance between the starting point and the nearest gap, Line complexity, and two-point distance in Experiment 1.

Discussion

Distance effect

The result that mean RT increased with increasing two-point distance (see Figure 4) seems to support the curve tracing hypothesis (Jolicoeur et al., 1986) which states that the subject traces along the curve to determine the presence / absence of a gap. If subjects detect a gap in a purely parallel manner, there would not have been a significant effect of two-point distance. One might argue that the parallel tracing model discussed above can account for these results. However, without additional complication, this version of parallel model cannot explain the interaction between gap-distance and line complexity (see Figure 6), because the model predicts that RT for the *near-gap* condition would not be different from the RT of the *far-gap* condition. Furthermore, the significant interaction between two-point distance and line compexity (see Figure 3) rules out the possible confounding effect of retinal eccentricity, since the physical distance between two points were the same across the different levels of line complexity.

The lack of interaction between two-point distance and response type (Figure 4) replicates the similar results of Jolicoeur et al.(1986), suggesting that curve tracing operates in an exhaustive manner. If subjects stopped tracing as soon as they found a gap, that is, with a self-terminating process, then the average slope of *gap* trials should be less than that of *no-gap* trials. However, an exhaustive tracing model has difficulties in explaining the gap-distance effect, the interaction between gap-distance and line complexity, and the interaction between gap-distance and two-point distance(see Figure 6). If subjects traced the *entire* curve regardless of the detection of a gap, there should have been no effect of gap-distance. The gap-distance effect obtained is a function of the gap-distance *along the curve*, since the interaction between gap-distance and line complexity rules out explanations based on differences in retinal eccentricity. In any event, we are left to explain two apparently contradictory results in that one aspect of the results supports an exhaustive model while another aspect of the results supports a self-terminating model.

However, it seems that the only model that can explain the gap-distance effect and its interaction effect with line complexity is a self-terminating model. Moreover, there are several data patterns that are inconsistent with an exhaustive model. First, the redundancy gain obtained in this experiment cannot be explained by an exhaustive model(this is discussed in a later section). Second, there is some evidence that the comparison between the positive response and negative response is not always appropriate if the two responses have different processing components (Pringle & Egeth, 1988). More concretely, in the *no-gap* trials there were no gaps, whereas in the *gap* trials there were either a *single gap* or *double gap*. In the *single gap* condition, there were either *near-gap* or *far-gap* trials. Therefore, the lack of difference between slopes of *gap* and *no-gap* trials might be due to some kind of averaging

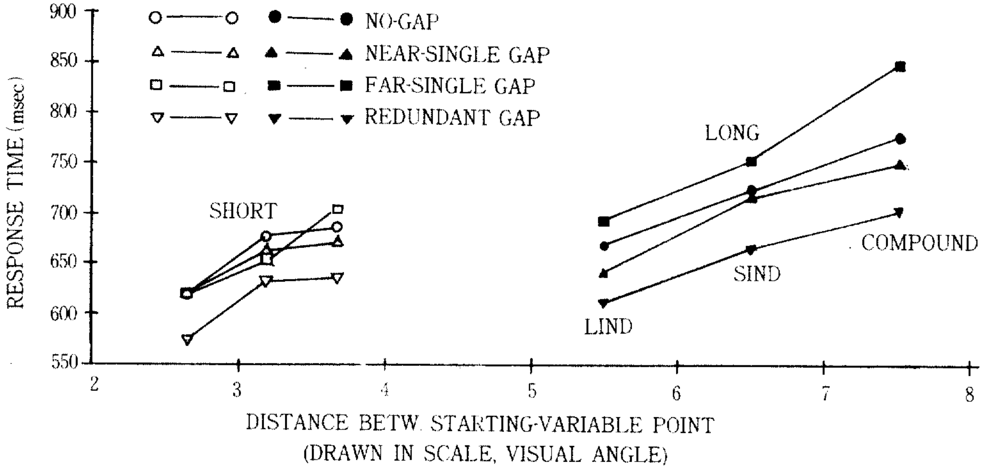


Figure 7. Mean RT as a function of the distance along the curve between the starting point and the variable point, Gap vs. No-gap, Gap redundancy, and the distance between the starting point and the nearest gap. Physical distance between two points is the same within each graph.

artifact if the RT patterns in the *gap* trials are heterogeneous (i.e., slow *far-gap* RTs combined with fast *near-gap* RTs). Thus, if there is any difference in the curve tracing rate across the different levels of the two-point distance in the *gap* trials, this could be taken as evidence against the exhaustive model.

Figure 7 shows mean RT as a function of distance *along the curve, in the no-gap, single near-gap, single far-gap*, and *double gap* conditions. Note that the distance shown here was measured along the curve, not the linear distance between the starting and variable points. The purpose of this scaling was to estimate the rate of curve tracing more precisely. If curve tracing is exhaustive in nature, then the slopes for each condition should not be different from one another. However, while the average slope for *no-gap* trials was 72 msec per degree in visual angle, the slope for *double gap* trials and that for *single near-gap* trials were 61 msec / degree, and the slope for *single far-gap* trials was as high as 90 msec / degree. Because the distance along the curve was the same across each graph, the exhaustive curve tracing hypothesis predicts that tracing rate of *single near-gap* trials would not different from that of *single far-gap* trials. To test this hypothesis, the regression coefficients for each subject in the *single gap* condition were calculated, then were subject to t-tests. The regression coefficient between the *near gap* and *far gap* conditions was significantly different, $t(1,35) = -2.03$, $p < .05$, rejecting the hyothesis. Alternatively, this pattern of results can be easily explained by self-terminating curve tracing. Indeed, *gap* trials may have several additional processing components not involved in the *no-gap* trials. For example, the processing and rechecking of gap may require additional processing time in the *gap* trials but not in the *no-gap* trials. In contrast, on half of the *no-gap* trials, there was no gap on the distractor curve either. In these trials, subjects may not trace the curve at all. Instead, subjects may use a kind of matching process(Posner, 1978) which might have helped them respond without tracing the curve. Therefore, unlike the classical visual search paradigm(e.g., Treisman & Gelade, 1980), it is inapropriate to compare positive vs. negative trials.

It is interesting to assess the average rate of curve tracing. It turned out that the rate of curve tracing in the no-gap trials was about 14° / sec. The tracing rate estimated here is less than the 40° / sec estimated by Joliceour et al.(1986). The difference might be due to the difference in the gap size, or to the absence of interwoven curves, or to the relatively large visual angle of entire display in the present experiment.

The interaction between gap-distance and two-point distance stems from the fact that the gap-distance effect was mainly observed in the *long* distance condition, but not in the *short* condition (see Figure 6). Thus, it is suggested that within a *short* range, parallel processing is dominant, while within a *long* range serial curve tracing is required (see Pashler, 1987, for a similar argument in the visual search task).

Redundancy gain

The effect of *gap redundancy* suggest the involvement of a certain kind of parallel processes. Because there were no discrete items that could be examined sequentially, it is plausible to assume that the curve tracing process entails several parallel sub-proceses so that within a certain range, a parallel processing is favored. However, there could be an alternative explanation for the effect of gap redundancy, that is, a *"random-favored-position hypothesis"*(e.g., Van der Heijden, La Heij, & Boer, 1983). Assume that on certain trials for a given subject, the subject may start tracing curve from a variable point to starting point. This kind of strategy can be called *"backward tracing"*. If the result was a mixture of forward and backward tracing, then gap redundancy is statistically inevitable, because the redundancy defined here is the difference in RT between the *single, near gap* condition and *double gap* conditions.

In order to test this hypothesis, we divided the RTs for each of the *single* and *double gap* trials into two halves, a fast subset and a slow subset(in this analysis, we included both the *near-gap* and *far-gap* conditions). The fast subset was the set of RT data that is less than the median of each *single-gap* and *double-gap* trials ; the slow subset was the rest of the data. If the redundancy gain is the result of the favored-position artifact, then the amount of redundancy gain in the slow subset should be larger than that in the fast subset. The reason is that on any given trial in the *single gap* condition, subjects may have traced only half of the gap distance, while in the *double gap* condition subjects will always find a gap within the same amount of time, regardless of which point was used as a starting point (see Figure 3). In fact, the redundancy gain in the fast subset was 32 msec, whereas the redundancy gain in the slow subset was 62 msec, suggesting that some subjects do have a favored variable point as a starting point for tracing the curve. An analysis of variance with *gap redundancy* and *fast-slow* subset revealed that the two variables were interacted significantly, $F(1,17)=8.43$, $p<.01$.

A reasonable amount of redundancy gain observed in the fast subset suggests that a certain contribution of parallel processing was also involved. However, the lack of interaction between *gap redundancy* and other variables (i.e., line complexity, or two-point distance) strengthens the conclusion that curve tracing itself is not accomplished by a parallel process. Also, the tracing rate of *single gap* trials was the same as that of *double gap* trials, suggesting that gap-redundancy did not affect the tracing rate or slope. Instead, gap-redundancy affected the overall intercept, suggesting the contribution of a parallel processing component which is independent of the curve tracing process. It should be added that whatever strategy or mechanism is responsible for the effect of *gap redundancy,* this effect cannot be explained by exhaustive curve tracing, because the exhaustive processing model predicts *redundancy cost,* not a redundancy gain. Taken together, only the serial self-terminating model with parallel sub-processes could explain the entire pattern of results from this experiment.

EXPERIMENT 2

There were complications in Experiment 1 that prevented certain kinds of analyses. First of all, all variable points are not the same distance from the fixation point so that the effects of two-point distance obtained in Experiment 1 were confounded with retinal eccentricity, even though effects of line complexity could be used to eliminate these confounding effects. Second, because the display was present until subjects responded, Experiment 1 did not rule out the role of eye movement on curve tracing. Therefore, Experiment 1 could not unambiguously separate covert curve tracing from overt eye tracking.

In Experiment 2, we presented to subjects a half circle containing a central gap and two Xs(see Figure 8). Thus, all positions of gap, Xs, and curve portion were equidistant from the fixation point. One of the Xs was always positioned next to the central gap, while the other X was randomly presented on the curve. Assume that subjects always start at the central X. According to the self-terminating curve tracing model, the X-X distance would not increase tracing time in the *different* trials, since the gap is always positioned next to the terminal point, so that subjects need not trace the curve at all. In contrast, if RT increases with increasing distance between the Xs in the *different* trials, an exhaustive tracing model would be supported. However, another possibility is that subjects may start at a peripheral X. If this is the case, both kinds of serial model predict increasing function of RT with increasing the X-X distance.

To prevent eye movement, exposure duration was set at 150 msec. If the curve tracing is independent of eye movement, RT should increase with the X-X distance where eye movement was not possible. In addition, gap size was increased to .81° to make the task more easy.

Another purpose of Experiment 2 was to replicate the result of Pringle and Egeth (1988). One peculiar result of their experiments was that RT decreased with X-X distance in the *different* trials, a result that could not be interpreted as curve tracing. One explanation they offered is that a judgmental process was involved in the *different* trial. One related point is that their display always contained two gaps in a whole circle. This fact may have encouraged subjects to use alternative strategies other than curve tracing. Therefore, it is interesting to see if the decreasing function would still be obtained even with a half circle with a gap.

Method

Subject

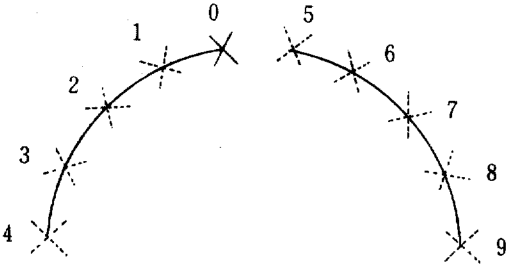
Twelve psychology graduate students in The Johns Hopkins University participated in Experiment 2. All had normal or corrected-to-normal vision.

Apparatus

Displays were presented on a Hewlett-Packard 1345A digital display module which was controlled by an IBM AT computer. The computer was also used for collecting RT and error data. The display scope was mounted into one channel of an Iconix four-channel tachistoscope to maintain the viewing distance. A second channel in the tachistoscope was dimly illuminated to reduce the contrast of the display. A two-button response box attached to a game port of the computer was used for gathering subjects' responses.

Stimuli

A half circle(diameter of 5.71° visual angle from the viewing distance of 70cm) with a gap(.81°) in the center of the half circle and two Xs made by crossing two short lines(.46×.46 degree) were drawn. One of the Xs(terminal X) was always on the either side and directly adjacent to the gap, and the other X(variable X) was positioned according to each level of X-X distance (see Fig. 8). In the *same* condition, in which the two Xs were on the same curve, there were four levels of X-X distance. In the *different* curve condition, there are five levels of X-X distance. One unit of X-X distance subtended roughly .81 degree of visual angle. A small diamond pattern was used as a fixation point (.4×.4 degree).



0 : Terminal Point
1-4 : Possible locations of variable point in the Same trial
5-9 : Possible locations of variable point in the Diff. trial.

Figure 8. A prototype of the stimuli used in Experiment 2. A solid X is terminal X, and is always next to a central gap. Dotted Xs are possible positions of variable X, depending on the particular level of X-X distance.

Design

Each subject served one practice block of 36 trials and six experimental blocks of 82 trials. The first 10 trials for each experimental block were for practice. Seventy-two experimental trials were divided into 32 *same* trials and 40 *different* trials according to each X-X distance (4 levels in the *same* trials, 5 levels in the *different* trials), positions of curve (4 possible positions), positions of terminal point(2 possible positions). The order of presentation of trials for each block was randomized so that no subjects saw the same sequence of displays again.

Procedure

Subjects were instructed to respond "same" or "different" as quickly as possible while maintaining accuracy above 90%. Mapping of response type onto left / right hand was counterbalanced across the subject. On each trial, after an 800 msec presentation of fixation, followed by a 200 msec blank field, a semi-circle containing a gap and two Xs was presented for 150 msec, which was finally replaced by a 2-sec blank field. The computer beeped when an error was made. Any latency exceeding 1500 msec was regarded as an error. After a two-second inter-trial interval, the next trial began. Subjects were allowed to rest between blocks. An entire session lasted about 40 minutes.

Results

Error data

Overall error rate was 10%. This was higher than expected, presumably due to the brief 150 msec presentation of each display. Two separate ANOVAs for *same* trials and *different* trials for the error data showed that error patterns were not associated with any major variables, such as response type or X-X distance. Therefore, there was no indication of a speed-accuracy trade-off.

Response time

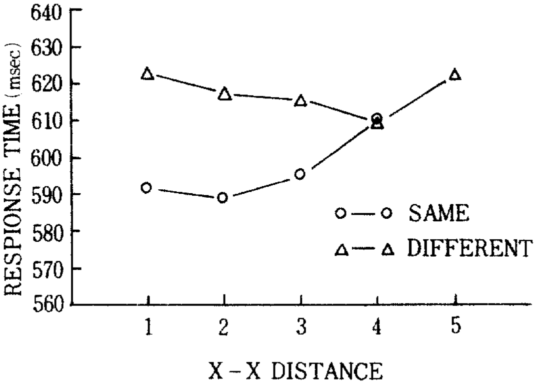


Figure 9. Mean RT as a function of X-X distance and response type. Unit of each level of distance is 1 degree.

Figure 9 shows mean RT as a function of X-X distance and response type.

An ANOVA for mean RTs in the *same* trials revealed that the effect of X-X distance was significant, $F(3, 33)=5.405$, $p<.01$. A trend analysis showed that a linear component, $F(1, 33)=11.414$, $p<.01$, along with a quadratic component, $F(1, 33)=4.79$, $p<.05$, was highly significant. The result of an ANOVA for *different* trials showed no significant effect of X-X distance, $F(4, 44)<1$. After deleting of the longest level in the different condition to equate the number of level for *same* and *different* trials, a two-way ANOVA was done to check an interaction between response type and X-X distance. While none of the main effect were significant, the interaction between those two factors was significant, $F(3,33)=3.662$, $p<.05$.

Discussion

The significant effect of the X-X distance in the *same* trials suggests that subjects actually traced the curve in order to respond correctly. This pattern of result replicates the result of Pringle and Egeth(1988). Interestingly, RTs for X-X distance unit 1 and 2 in the *same* trials were almost the same, 591 msec and

589 msec, respectively. This result suggests that within a relatively short distance, subject may process the connectedness of the curve between two Xs in a parallel manner.

Unlike the result of Pringle and Egeth(1988, Experiment 1), who reported the decreasing function of X-X distance on ***different*** trials, the X-X distance had no effect on ***different*** trials in Experiment 2. Making the stimuli half-circles seems to have caused a drastic change from the results of Pringle and Egeth(1988). Because a gap was always positioned next to the terminal X, a self-terminating model predicts that in ***different*** trials subjects do not need to trace the curve toward the variable X. Therefore, the result that ***different*** RT remained unchanged with increasing X-X distance provides evidence for a self-terminating curve tracing.

Curve tracing rate estimated for the ***same*** trials of Experiment 2 was 167 degree per second, compared to 14 degree for the ***no-gap*** trials of Experiment 1. One possible reason for such a fast tracing rate is due to the large gap size, .81 degree, compared to .2 degree in Experiment 1. Therefore, beside the line complexity, gap size is evidently an improtant variable affecting the efficiency of curve tracing.

General discussion

Results of experiments reported here can be summarized as follows. First, significant effects of two-point distance in Experiment 1 and effects of X-X distance on ***same*** trials in Experiment 2 support the notion of curve tracing. Thus, when subjects are required to determine whether a designated portion of line/curve is continuous or disconnected by a gap, curve tracing evidently is required. Second, curve tracing time increased linearly as a function of the distance along the curve to be traced. Third, effects of gap distance obtained in Experiment 1 and no effect of the X-X distance on ***different*** trials in Experiment 2 suggest that curve tracing is carried out by a self-terminating process. Thus, subjects evidently stop tracing the curve as soon as they find a gap. Fourth, effects of gap redundancy observed in Experiment 1 and the result of Experiment 2 in which distances 1 and 2 did not differ in response time suggest some contribution of parallel processing in those experiments. However, it should be added that the parallel process is independent of curve tracing itself, since the effect of gap redundancy was additive to other variables. Finally, curve tracing occurs even when eye movement is not possible(Experiment 2).

In summary, our results suggest that even in the simplest stimuli(e.g., line segments), a curve tracing operation is required to detect the presence of a gap. Line complexity provided a way to examine the effect of distance along the curve on curve tracing while the effects of the ***gap-distance*** and the ***gap-redundancy*** undermine the hypothesis proposed by Jolicoeru et al.(1986) that curve tracing is exhaustive. Rather, a model that assumes self-termination upon the detection of gap can account for the results better.

We found that curve tracing rates varied across experiments. While this diversity may be due to the differences of stimulus variables, such as gap size, entire stimulus size, stimulus complexity, etc., it could also reflect the shape and size of the curve tracer itself. The curve tracer is similar to an attention spotlight, the size and shape of which may change depending on stimulus conditions. Like the feature integration theory of attention proposed by Treisman and Gelade(1980), within the range of the curve tracer parallel processing may occur, while each successive movement of the curve tracer entails serial processing.

Further research should shed light on the nature of curve tracing more precisely. Specifically, in what sense is curve tracing different from eye tracking? Is the curve tracing operation different from attention movement or mental scanning or even mental rotation? Does curve tracing occur in a continuous manner or in a discrete, saccadic manner? Is the tracing rate constant in a given trial, or does it change over time?

In addition, further studies should address the following questions: (1) If it turns out that there are parallel sub-processes involved in the curve tracing task, how do these processes contribute to curve tracing operation? (2) What kind of elemental operation is entailed in the curve tracing operation? (3) What are the relationships among these elemental operations? (4) How in the curve tracing routine related to other visual routines such as coloring, boundary trecking, inside-outside decisions, feature-integration processes, and 3-D perception? and (5) What are the universal elemental operations shared with curve tracing and other visual routines?

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곡선 추적하기에서의 자기종료적 처리과정

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서로 얽히지 않은 기본 선분 패턴들을 사용하여 시각적으로 제시된 곡선의 추적에 관여하는 기본 처리과정들이 무엇인지를 두 실험을 통해서 밝히고자 하였다. 실험 1의 피험자들은 한 선분이 연속적인지, 아니면 하나 또는 두 틈때문에 불연속적인지를 빨리, 정확히 판단해야했다. 선분의 복잡성, 틈의 중복성, 두 점 거리 및 틈 거리(gap distance)의 효과가 검토되었다. 선분에 틈이 있는 시행과 그렇지 않은 시행 모두에 있어서 평균 반응시간은 두 점 거리, 즉 해당 선분의 끝에서 끝 간의 직선 거리와 함께 선형적으로 증가하였다. 두 점 거리는 선분의 복잡성과 상호작용하였다. 곡선에 따라 거리와 더불어 반응시간이 증가한다는 이러한 결과는 Ullman(1984)의 곡선 추적하기(curve tracing)가설과 일치한다. 그러나 틈이 있는 시행의 평균 반응시간은 틈 거리, 즉 중앙점과 틈 간의 거리와 함께 선형적으로 증가했다. 틈이 둘이 있는 시행의 경우 그 반응시간은 틈이 하나 있는 시행의 반응시간 보다 훨씬 빨랐다. 틈이 하나 있고 두개의 X가 있는 반원을 사용한 실험 2는 곡선 추적하기 과정이 소진적(exhaustive)인지 자기종료적(self-terminating)인지를 검토하였다. 이 실험에서도 동일 시행의 평균 반응시간은 두 X들 간의 거리와 더불어 선형적으로 증가한 반면, 상이 시행의 경우 그 평균 반응시간은 이 거리의 영향을 전혀 받지 않았다. 두 실험의 결과들을 종합해 보면, 틈 거리와 틈 중복성의 효과는 자기종료적 곡선추적하기 과정에 의해 가장 잘 설명된다.