Predicting the shape of distance functions in curve tracing: Evidence for a zoom lens operator

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Jolicoeur, Ullman, and MacKay (1986) showed that the time to confirm that two dots are on the same curve increases monotonically, but nonlinearly, as the curve distance between the two dots increases. These displays contained two curves and two dots. On *same* trials, the two dots were on the same curve (target curve), while the other curve served as a foil (distractor curve). The monotonically increasing effects of curve distance on response times for *same* trials suggested that the intervening curve segment was traced. In the present investigation of the source of the nonlinearity in these distance functions, it was hypothesized that differences in the distractor curves may have allowed a curve tracing operator with zoom lens properties to widen its receptive field while tracing parts of certain target curves. The wider receptive field may have allowed faster tracing over certain segments, owing to a reduced number of shifts required by the operator to scan the curve. The consequence of training certain segments of the curve more quickly than other segments of the curve would be a nonlinear effect of distance. A new set of stimuli was created for testing this hypothesis directly. Fairly linear distance effects were found for stimuli that contained a distractor curve that constrained the breadth of the postulated curve tracing operator, whereas stimuli that contained a distractor curve that could allow for a larger receptive field yielded nonlinear distance functions. The results are compared with the predictions of three quantitative models: pixel-by-pixel tracing; Jolicoeur, Ullman, and MacKay's (1991) bipartite operator; and a new zoom lens model, analogous to the zoom lens model of visual attention. The results were fit best by the latter model, in which tracing is accomplished by tracking the curve with a variably sized local operator.

Ullman (1984) has suggested that the spatial relations between objects in a visual display are perceived through the implementation of visual routines that operate on early visual representations. A *visual routine* is an ordered assembly of basic visual operations, such as covert and overt shifts of the processing focus, the indexing of locations for further processing, bounding surfaces for selective processing, boundary tracing, and the marking of surfaces and locations that have already been processed. In the present study, we are concerned with the boundary or curve tracing operation, which has been studied extensively by Jolicoeur and his colleagues (Jolicoeur, 1988; Jolicoeur & Ingleton, 1991; Jolicoeur, Ullman, & MacKay, 1986, in press; McCormick & Jolicoeur, in press). The variable manipulated in these studies was whether or not two dots appeared on the same curve in a display consisting of two or more nonintersecting curves. The results consistently showed monotonically increasing response times as a function of the curve distance between the two dots, which has been taken as evidence that the curves were traced, at a limited rate, in order to verify the spatial relation.

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The Curve Tracing Operator and Shifts of Visual Attention

McCormick and Jolicoeur (in press) provided evidence in support of the notion that visual attention and curve tracing are intimately related. In that study, attention was directed to a curve by briefly increasing the luminance of the curve. The effect of distance interacted with the manipulation that directed visual attention. This interaction, within an additive factors approach (Sternberg, 1969, 1975), suggests that attention and curve tracing may be part of a common stage of processing.

A number of reasons suggest to us that the curve tracing operation may involve shifting the locus of visual attention. The effects of distance in the curve tracing task suggest that a local operator is required to trace, or move along, the curve in order to maintain continuity and to ensure that the correct curve is processed. This operator could be unique to tracing, but it seems more parsimonious to suppose that it could also be a component of a more general attentional system. Whether this is the case, however, remains an empirical issue.

Visual attention is often considered to be analogous to a "spotlight which enhances the efficiency of detection of events within its beam" (Posner, Snyder, & Davidson, 1980, p. 173). Eriksen and his colleagues have proposed a variation of the spotlight metaphor, which they call the zoom lens model (Eriksen & Hoffman, 1972; Eriksen & Rohrbaugh, 1970; Eriksen & St. James, 1986).

The zoom lens model of visual attention holds that the spatial extent of the scope of the beam can be controlled by the observer in response to his or her computational goals or to characteristics of the stimulus. A finite amount of resources can be allocated over a varying amount of spatial area. In research on the spatial structure of visual attention, the zoom lens model has continued to gain support (e.g., McCormick & Klein, 1991; Shepherd & Müller, 1989). Jolicoeur et al. (in press) have proposed that the spatial extent of the curve tracing operator could be variable and could depend on a number of display properties, one of which is the proximity of other curves.

Nonlinear Distance Functions

One consistent and potentially problematic finding in research on curve tracing is that of nonlinear distance effects for the intertwining stimuli first employed by Jolicoeur et al. (1986). The typical function for these curve patterns is displayed in Figure 1. These results are for *same* trials collapsed across all the experiments reported by Jolicoeur and Ingleton (1991). It can be seen from this graph that the distance function over the first three distances appears to be linear, but that the response time for the fourth distance increases more sharply than would be expected from a linear extrapolation from the first three distances. As Pringle and Egeth (1988) have remarked, this nonlinear function makes determining the rate of tracing rather difficult. One clue about the source of the nonlinearity is that it only occurs with the intertwining stimuli (e.g., Jolicoeur & Ingleton, 1991; Jolicoeur et al., 1986; McCormick & Jolicoeur, in press, Experiments 2 and 3) and not with other stimuli used to

Figure 1. Mean *same* response times collapsed across the experiments reported by Jolicoeur and Ingleton (1991). Note—Overall pattern size was manipulated in this experiment, so that curve distance is expressed relative to the overall pattern size (see Jolicoeur & Ingleton).

Figure 2. Three examples from the stimulus set developed by Jolicoeur and Ingleton (1991). The spotlight in each example represents the receptive field of the postulated tracing operator. (A) A curve pair in which up to three potential second dot locations can be encompassed simultaneously within the receptive field of the operator without also encompassing part of the distractor curve. (B) A curve pair in which up to two potential second dot locations can be encompassed within the receptive field of the operator. (C) A curve pair in which only one potential second dot location can be encompassed within the receptive field of the operator.

investigate tracing, such as parallel lines or concentric circles (e.g., Jolicoeur, 1988; Jolicoeur et al., in press; McCormick & Jolicoeur, in press, Experiment 1; Pringle & Egeth, 1988). Because the curve tracing operations employed in all of these studies probably involved the same processes, a likely source of the nonlinearity might lie in differences between the stimuli that were used. Our purpose in the present study was to elucidate a potential cause of these nonlinear effects of distance found with certain stimuli but not with others. We hope to do so by providing a theoretically motivated account of the nonlinearity, which we will support by gaining experimental control over the phenomenon.

The stimulus set first used by Jolicoeur et al. (1986) and modified by Jolicoeur and Ingleton (1991) consisted of nine pairs of curves that had been developed to meet a number of constraints outlined below. Eight of these curve pairs were used as experimental stimuli, and one pair was used exclusively for practice. Three examples from the Jolicoeur and Ingleton stimulus set are given in Figure 2. Each pair consisted of two intertwining but nonintersecting curves. One curve passed through the spa-

tial location of the fixation stimulus (a dot centered on the monitor screen) where one target dot always occurred. For a *same* trial, the second dot was presented on this curve, which we call the target curve. For a *different* trial, the second dot was presented on the other curve (which did not pass through the location of the fixation stimulus), and we will call this curve the *distractor* curve. Each possible target dot position had part of the distractor curve within approximately 1° of visual angle. The curve distance between two dots was a multiple of a constant base distance (e.g., in Jolicoeur & Ingleton, 1991, in the small display condition, one unit of curve distance corresponded to 2° of visual angle, and the potential dot locations could be 2° , 4° , 6° , or 8° of curve distance apart), but the absolute Euclidean distance between two dots did not vary. The final constraint was that for half the curves the first lobe of the target curve (approximately 2 or 3 units of curve distance; see Figure 2) had a portion of the distractor curve on the inside (see Figure 2C), whereas the other four curves had part of the distractor curve on the outside of the first lobe (see Figures 2A and 2B).

The same stimulus set was used by McCormick and Jolicoeur (in press) in the attentional cuing experiment mentioned earlier. In this study, the target curve, the distractor curve, or both curves were flashed briefly, prior to the presentation of two dots requiring a *same*-curve or *different*-curve response. The results for the neutral condition (both curves were flashed briefly) for *inside* curves (i.e., the distractor curve is located on the inside of the target curve; see Figure 2C) and *outside* curves (i.e., the distractor curve is located on the outside of the target curve; see Figures 2A and 2B) are presented in Figure 3. The difference in the results across these two types of curves is striking. For the inside curves, the effects of distance are fairly linear, whereas for the outside curves, there is an exaggeration of the nonlinear trends reported in earlier work.

We propose a zoom lens model of the curve tracing operator that can account for the observed difference between inside and outside distractors. In this model, the curve is traced with an operator that has a variable size receptive field, starting at the first dot (the one at the spatial location of the fixation stimulus) and terminating when and if a second dot is found on that curve. We assume that a certain amount of processing is required at the old location before the operator can shift its receptive field to a new location. One goal of this processing is to determine whether the line segment is "safe" to trace—that is, whether or not there is a single curve within the receptive field of the operator. A problem arises when there are two different curves within the receptive field. Shifting under these conditions could result in moving the receptive field to the wrong curve. This problem is avoided by requiring that there be only one curve within the receptive field of the operator prior to a shift. When this condition is met, it is safe to shift the processing region. Jolicoeur et al. (in press) have suggested an algorithm in which the length of the curve passing through the recep-

Figure 3. Mean response times from the neutral condition of McCormick and Jolicoeur (1991), Experiment 2. Open circles represent the results from curve pairs with an inside distractor curve; closed circles represent the results from curve pairs with an outside distractor curve.

tive field of the operator is independent of the processing time required to decide that it is safe to make a shift. This method is discussed in greater detail in the General Discussion section.

One way in which the zoom lens operator could determine whether or not there is only one curve within its receptive field would be to use a process that can detect terminators (i.e., the end of a curve) and closed objects within the receptive field and a process to detect and count the number of intersections of curves with the perimeter of the receptive field. This information is sufficient for determining whether or not it is safe to make another shift. If there are more than two intersections of curves with the perimeter of the receptive field, it is possible that there is more than one curve within the receptive field. If terminators are detected within the receptive field of the operator and there is more than one intersection of a curve with the perimeter of the receptive field, there may be more than one curve within the receptive field of the operator. In addition, if a closed object is detected within the receptive field of the operator, it may not be safe to shift, because there is a risk that the operator could shift the receptive field to the boundary of the closed object instead of the curve that is being traced. For the stimuli employed by Jolicoeur et al. (1986) and Jolicoeur and Ingleton (1991), this would not be a problem (the only closed objects are the target dots). For these stimuli, a sufficient condition that would indicate that it was safe to make a shift would occur when there were only two intersections of a curve with the perimeter of the receptive field and there were no terminators within the receptive field. When

this condition is met, there can only be one curve passing through the receptive field of the operator. The only other condition that would be of interest would occur when there was only one intersection of a curve with the perimeter of the receptive field and there was only one terminator detected within the receptive field. This condition would indicate that the end of the curve had been reached.

In the present model, we assume that if more than one line is found within the receptive field of the operator, a zooming operation will act to reduce the size of the receptive field. This zooming should continue until there is only one line within the receptive field. After determining that it is safe to shift the receptive field and that the second dot has not been found, a tangent to the curve might be calculated in order to determine which direction to shift next. The receptive field would shift to a new segment of the curve that also included a small region of the previously processed segment. This overlap is necessary in order to avoid zooming in on the wrong curve when more than one curve falls within the new processing region. Under these conditions, the operator would zoom in on the receptive field toward the location of the overlap until there was only one curve, which included a piece of the previously processed line segment, within the receptive field. Just as the receptive field of the operator can zoom in on only one curve, we assume that it can zoom out, maximizing the size of the processing region. However, the size of the receptive field is bounded by the constraint that there can only be one curve (which includes a piece of the previously processed line segment) contained within it. This type of processing would continue until the second dot was found or the end of the curve was reached.

Thus far we have described five main subprocesses that the curve tracing operation might involve: (1) processing that can determine whether or not there is only one curve within the receptive field of the operator; (2) a zoom process that can vary the breadth of the receptive field of the operator until an optimal size is reached such that there is (still) only one curve within the receptive field; (3) a process to determine whether or not the second dot has been located; (4) calculating the direction of the next shift if another shift is necessary; (5) shifting the receptive field to a new region that contains part of the previously processed curve segment. Although many aspects of this model remain underspecified, we believe that these conditions are sufficient for successful curve tracing and that the model can be further simplified into two general types of processes: (1) processing within the receptive field of the operator (checking for a single line, checking for a dot), and (2) processes involved with moving along the line (calculating the direction of the next shift, shifting, and zooming).

We hypothesize that these two types of processing contribute to the distance effects in curve tracing tasks. First, there is a certain amount of time that is likely devoted to the processing performed within the receptive field of the operator. The time required for this processing to oc-

cur is likely to vary with each shift of the receptive field, owing to variations in the complexity (e.g., parafoveal eccentricity, luminance, curvature, etc.) of the stimulus that can be contained within this processing region of the operator. However, in the long run we would expect that this processing time would be distributed about some mean and that with every new shift to the receptive field additional processing time would be required. As curve distance between the two dots increases, the number of shifts required to trace the segment increases, and with each shift new processing must be performed. It follows that the total time spent processing stimuli within the receptive field of the operator should be some function of the number of shifts that are required for the curve to be traced. Furthermore, because increases in curve distance are likely to increase the number of shifts required for the curve to be traced, we would expect the total time spent processing stimuli within the receptive field of the operator to be intimately related to curve distance.

The other factor affecting the time required to trace the curve between two dots is the time required for the shifting and the zooming of the receptive field of the operator. As with the processing that is required within the receptive field, the total time required to shift and zoom would also be related to the curve distance between the two dots. As curve distance increases, so does the number of shifts, and consequently, the total time required for shifting and zooming increases.

The model predicts that the time required for tracing a curve segment consists of both the total time spent processing information within the receptive field of the operator and the total time spent shifting and zooming the receptive field. The total time required by both of these processes can be estimated by counting the number of shifts the operator needs to trace the curve segment. That is, the total time needed for each process should be a linear transformation of the number of shifts, and the total time required for tracing a curve segment should be some linear transformation of the number of shifts. The model can be quantified simply by counting the number of shifts that would be made by the zoom lens operator while tracing a given curve segment. Later, in the General Discussion, we will discuss in more detail how this quantification can be implemented and tested with multiple regression techniques. For now, we want to point out that the model predicts that an operator with a large receptive field would trace more quickly than an operator with a small receptive field because the former requires fewer shifts to trace a curve than does the latter. In addition, the model can account for nonlinear distance effects in the following way: For outside curve pairs, multiple dot locations on the target curve can be encompassed simultaneously within the receptive field of the operator (see Figure 2A) without also encompassing portions of the distractor curve. For inside curve pairs, encompassing multiple locations cannot be done without also encompassing portions of the distractor curve, which results in the need for employing a smaller receptive field (see Figure 2C). We hy-

pothesize that the small distance effects over the first three locations for the outside curves are due to a larger receptive field in which a larger region of the curve is contained within the processing region of the curve tracing operator.

In the model outlined above, we have purposely avoided a process that traces a line segment within the receptive field operator. If it were the case that tracing also occurred within the receptive field of the operator, we would be tempted to ask how this tracing was accomplished and then likely hypothesize another operation used to track the curve passing through the receptive field of the primary operator. This secondary operator might then need a tertiary operator for the same reasons, and this tertiary operator would need an operator with a smaller receptive field to trace within its processing field, and so on, ad infinitum. The proposed model avoids this infinite regress by relying on processes other than tracing to determine that there is only one line within the receptive field of the operator. Thus we expect relatively uniform processing times whenever the two dots and the intervening line can be contained within the receptive field of the operator without encompassing any part of the distractor curve. If one can determine that there is only one line within the receptive field of the tracing operator and that there are also two dots within the receptive field, each of which fall on a curve, a *same-curve* response can be initiated. Furthermore, the time required to make this response will be independent of the curve distance between the two dots, unless increasing curve distance has some effect on the processing time required to determine that there is only one curve within the receptive field of the operator. However, because the conditions that need to be checked are probably not very sensitive to the size of the receptive field of the operator, and because we do not consider tracing within the receptive field to be a necessary part of this process, we expect small or null effects of distance within the processing region of the operator.

As stated earlier, for the inside distractor curve pairs, multiple dot locations cannot be contained within the receptive field of the operator without also encompassing part of the distractor curve. A tracing operator with a smaller receptive field must be employed, which requires more shifts to traverse a curve segment than an operator with a larger receptive field would require. As previously discussed, our model suggests that distance effects are due to shifting the receptive field of the operator. For outside distractors, Locations 1, 2, and sometimes 3 can be processed in a single step; for inside distractors, increasing distance is more likely to be associated with an increase in the number of shifts of the receptive field. Thus, the model predicts more linear distance effects for inside distractors than for outside distractors. This processing account would also explain why tracing rates from other types of stimuli tend to be linear. For example, consider tracing a line contained in a series of parallel lines. In this task, a constant separation of target from distractor curves is maintained, and our model would predict that

the size of the receptive field of the operator would not vary from shift to shift. Thus, we would expect the relationship between curve distance and the number of shifts to be linear. That is, because the receptive field of the operator is not changing size, if it takes three shifts to trace 3° of visual angle, then it should take six shifts to trace 6°, seven shifts to trace 7°, and so on, as long as the separation between the two dots, relative to the separation of the two lines, is such that the two dots cannot be encompassed simultaneously within the receptive field of the operator.

The only assumption that we make about the shape of the receptive field is that its perimeter is convex. Jolicoeur et al. (in press) have suggested further that it may be oval in shape. In Figure 2, the receptive fields are ovals, in order to demonstrate that with the convexity constraint multiple dot locations can be incorporated simultaneously within the receptive field for some curves but not for others. How the tracing operator achieves this spatial distribution is not our primary concern in the present paper. The main observation is that outside curves allow the receptive field to be larger, whereas inside curves constrain the receptive field to a smaller size. Because a larger processing region, as suggested by Jolicoeur et al. (in press), can trace the curve faster (i.e., with fewer shifts) than a smaller one, we expect shallower distance functions for the early portions (i.e., Locations 1 and 2, and possibly Location 3) of outside curve pairs (Figures 2A and 2B) than for inside curve pairs (Figure 2C).

Reanalysis of the Jolicoeur and Ingleton (1991) Data

To assess further the processing account of the nonlinear distance effects outlined in the previous section, we performed a post hoc analysis on the data set from the experiments reported by Jolicoeur and Ingleton (1991). Figure 2 shows three examples of the stimuli. Figure 2A is an outside curve pair where, at most, three dot locations can be encompassed by an expanded receptive field without also including portions of the distractor curve. In the Jolicoeur and Ingleton stimulus set, there were two outside curve pairs like this one. Figure 2B is also an outside curve pair, but in this example only two dot locations can be encompassed without also including portions of the distractor curve. There were two outside curve pairs such as this one in the stimulus set. The remaining four curve pairs were inside pairs like that shown in Figure 2C.

The results of this breakdown are presented in Figure 4. An analysis of variance (ANOVA) performed on these data yielded significant main effects of curve type [$F(2,190) = 25.30$, $MS_e = 11,666.0$, $p < .01$] and distance [$F(3,285) = 81.26$, $MS_e = 26,072.1$, $p < .01$], as well as an interaction between these two variables [$F(6,570) = 13.40$, $MS_e = 9,704.0$, $p < .01$]. This interaction was also evident in polynomial contrasts. The linear component of distance interacted with distractor type [$F(1,95) = 5.23$, $MS_e = 7,492.3$, $p < .03$], as did the quadratic component of distance [$F(1,95) = 5.61$,

Figure 4. Mean response times in the Jolicoeur and Ingleton (1991) study collapsed across all the experiments and broken down into three curve pair types. Points labeled "1" represent the results from inside curve pairs; points labeled "2" represent outside curve pairs that allow, at most, two locations to be encompassed within the receptive field of the tracing operator without also encompassing part of the distractor curve; points labeled "3" represent outside curve pairs that allow up to three locations to be encompassed within the receptive field of the tracing operator without interference from the distractor curve. Note—Overall pattern size was manipulated in this experiment, and thus curve distance is expressed relative to the overall pattern size (see Jolicoeur & Ingleton).

$MS_e = 8,339.1, p < .02$]. What is most important about these results is the nature of the interactions. As can be seen in Figure 4, the distance effects for inside curve pairs (labeled "1") appear more linear than the distance effect for outside curve pairs. The outside curves that allowed, at most, two locations to be encompassed simultaneously without any distractor portions (labeled "2") showed equal performance at these two locations with substantial distance effects manifested at Locations 3 and 4. The outside curves that could allow up to three locations to be encompassed by the receptive field without including any distractor curve (labeled "3") have a U-shaped function with little difference between performance at Location 1 and Location 3. These results are consistent with our hypothesis that the nonlinearity observed in curve tracing tasks with intertwining stimuli is due to an interaction between the stimuli and the size of the receptive field of the curve tracing operator. In Experiment 1, we test our hypothesis directly by manipulating whether a target curve is paired with an inside or an outside distractor curve.

EXPERIMENT 1

Experiment 1 was a curve tracing task like that used by Jolicoeur et al. (1986) and Jolicoeur and Ingleton

(1991). Additional stimuli were developed from the stimulus set created by Jolicoeur and Ingleton in order to test the predictions of the model outlined above. Recall that the original stimulus set consisted of four inside curves in which the distractor curve passed along the inside of the first lobe of the target curve (see Figure 2C) and four outside curves in which the distractor curve passed along the outside of the lobe of the target curve (see Figures 2A and 2B). However, all eight of these stimuli had different target curves. The curve set used in the present experiment was created by taking each target and distractor pair developed by Jolicoeur and Ingleton and creating a new set by duplicating the target curve and creating a new distractor curve: an inside distractor if the original distractor was outside of the first lobe, and an outside distractor if the original distractor was inside of the first lobe. The entire stimulus set is shown in Appendix A. Thus, nine new curve pairs were created that would allow a direct evaluation of the effects of the type of distractor (i.e., inside vs. outside) while holding target curves constant. That is, in the new stimulus set, each target curve occurs in the context of both an inside and an outside distractor curve, whereas in the original set, each target curve appeared with either an inside or an outside distractor. The predictions were straightforward: If the nonlinearity observed in earlier curve tracing experiments was due to an adjustable or a zoom lens curve tracing operator, the inside distractor curve set should yield fairly linear distance functions, and the outside distractor curve set should yield nonlinear functions.

Method

Subjects

Seven female and 5 male undergraduates at the University of Waterloo were paid \$4 for their participation. All were right-handed and had normal or corrected-to-normal vision.

Materials

The stimuli were adapted from Jolicoeur and Ingleton (1991). A description of these display has been given elsewhere (Jolicoeur & Ingleton, 1991; McCormick & Jolicoeur, in press). The stimuli were made up of two nonintersecting curves. One curve passed through the spatial location of the fixation stimulus used to begin a trial; one dot always occurred at this location. Intersecting points of the two curves with an imaginary circle centered at fixation determined the potential second dot locations. In this manner, the Euclidean distance (2.3° visual angle) between the two dots remained constant while the curve distance between the two dots varied (in *same* trials). There were four potential second dot locations on the target curve (the curve passing through fixation). The curve distance between dot locations was approximately 3° .

For *different* trials, the second dot occurred on the distractor curve. Curve distance was undefined, but potential dot locations were constrained in the following manner. The terminus of the target curve was defined as the end of the target curve that one would reach by tracing outward from fixation through all the potential *same* trial dot locations. For the stimuli used in the present experiment, this is the end of the target curve that is farthest (in curve distance) from the first dot location (i.e., the dot that occurs at the spatial location of the fixation stimulus). Location 1 was arbitrarily defined to occur 3° from the end of the distractor curve closest to the terminus of the target curve. As for *same* trials, there were four

possible dot locations for different trials that were separated by approximately 3° of curve distance, and the Euclidean distance between the second dot location and fixation (the first dot location) was 2.3° .

The present stimulus set was adapted from this existing set of eight pairs of target and distractor curves (in addition, another pair was developed from the practice curve set used in the original studies). We refer to the convex region of curve that passes through the first dot location or first two dot locations as the first lobe. Each curve has two of these lobes. Four of the original pairs had been constructed so that the distractor curve passed along the outside of the first lobe of the target curve and the other four so that the distractor passed along the inside of the first lobe (see Figure 2). For each original target curve, a new distractor curve was constructed. An outside distractor was constructed if the original pair contained an inside distractor curve, and an inside distractor was constructed if the original pair contained an outside distractor curve.

The 18 curve pairs that were used are displayed in Appendix A. Two pairs (one inside and one outside) based on the practice stimulus used by Jolicoeur and Ingleton (1991) served as practice stimuli in the present experiment. The remaining 16 curve pairs were used as experimental stimuli. The curves and dots were presented in white on a black background. The experiment was controlled by an Amiga 1000 computer, and the stimuli were displayed on an Amiga color monitor.

Procedure

A subject sat facing the computer monitor with viewing distance controlled by a chinrest placed 140 cm from the video screen. The room was dimly lit. Each trial began with a fixation dot presented for 750 msec. This dot was replaced by the two curves and the two dots, which remained on the screen until the subject responded. The subjects were informed that one dot would appear at the spatial location of the fixation stimulus and that they should respond "same" if the second dot was on the same curve or "different" if the second dot was on the other curve. They were also instructed that their response times and accuracy would be recorded and that they should respond as quickly, but also as accurately, as they could. Half of the subjects responded "same" by pressing a response button with the right hand and "different" by pressing a response button with the left hand; the other half of the subjects responded "same" with the left hand and "different" with the right hand. The inter-trial interval was 2 sec.

Each session began with a block of 48 practice trials. The subjects were required to respond correctly on at least 43 of these trials in order to go on to the experimental trials. Only 1 subject failed to perform at this level on the first block but succeeded on the second attempt.

There were three blocks of 128 experimental trials. Within each block, all possible combinations of conditions occurred once: 2 responses (*same*, *different*) $\times$ 4 dot locations $\times$ 16 curve pairs. The order of trials within a block was randomly chosen without replacement but was constrained so that no particular condition could occur in more than four consecutive trials. The total time spent in the experiment was approximately 30 min.

Results

Response Times

Outliers. The data for each subject were broken down into 48 cells (2 responses $\times$ 3 repetitions of the stimuli $\times$ inside or outside curve $\times$ 4 distances). Within a cell, the mean and standard deviation were calculated after the shortest and longest response times were temporarily removed. Each of these response times was examined to see if it fell within four standard deviations from the mean.

If not, it was permanently excluded. The process continued until no further response times were permanently removed. Any temporarily removed response times were then added back to the cell and the mean calculated. This outlier analysis resulted in the exclusion of 4.5% of the *same* response trials and 4.0% of the *different* response trials.

Same responses. The response time results are presented in Figure 5. These data were subjected to a repeated measures ANOVA that included distractor type (inside or outside) and distance as within-subjects factors. The main effect of distance was significant [$F(3,33) = 21.17$, $MS_e = 46,990.1$, $p < .01$], as were both the linear component of distance [$F(1,11) = 21.49$, $MS_e = 124,984.4$, $p < .01$] and the quadratic component of distance [$F(1,11) = 45.11$, $MS_e = 6,460.3$, $p < .01$]. Curve pairs that had an inside distractor were responded to more slowly than curve pairs that had an outside distractor [$F(1,11) = 17.21$, $MS_e = 21,166.3$, $p < .01$]. In addition, distance interacted with distractor type [$F(3,33) = 3.01$, $MS_e = 7,634.2$, $p < .05$]. Differences between the slope of the distance function for inside and outside curves were reflected by the interaction of the linear component of distance with distractor type. The slopes for the two conditions differed significantly [$F(1,11) = 10.07$, $MS_e = 3,784.5$, $p < .01$], with outside distractor curves yielding a shallower slope on the average (25.4 msec/deg) than inside distractor curves (32.2 msec/deg). The interaction of distractor type with

Figure 5. Mean response times and percent error rates for Experiment 1 for *same* and *different* responses. Open circles represent the results from inside distractor curve pairs; closed circles represent the results from outside distractor curve pairs.

the quadratic component of distance was not significant [$F(1,11) = 1.75$, $MS_e = 13,812.9$, $p > .20$].

As can be seen in Figure 5, the difference between inside and outside distractors, although significant, is not as well delineated as it was in the reanalysis of the Jolicoeur and Ingleton (1991) data (see Figure 4). One possible explanation for this difference is a confounding effect of multiple stimulus presentations. Recall that each target curve appeared with an inside and an outside distractor curve and that both of these pairs were presented three times (i.e., once in each of the blocks) for each dot location. Thus the subject saw any particular target curve a total of 48 times. These repeated exposures may have had some effect on the distance functions. A repeated measures ANOVA that included the variable of trial block (three levels) supported this notion. In the left panel of Figure 6 are shown the results for inside curves for each block (or third) of the experimental trials; in the right panel are shown the corresponding results for outside curves. In the first block of trials, the inside curves yielded nearly linear effects of distance. However, across blocks, the results became increasingly nonlinear. The pattern of the distance effects for outside curves, however, did not change substantially with practice. The three-way interaction of practice with distractor type and distance only

approached significance in the omnibus ANOVA [$F(6,66) = 1.72$, $MS_e = 7,341.6$, $p < .13$]. However, the three-way interaction of practice with distractor type and the linear component of distance was significant [$F(2,22) = 5.82$, $MS_e = 4,167.6$, $p < .01$], suggesting that the slope of the linear effect of distance changed differentially for inside and outside distractors across blocks. The three-way interaction of practice with distractor type and the quadratic component of distance was not significant ($F < 1$).

A trend analysis was performed on each of the six distance functions presented in Figure 6. The linear component of distance was significant for each function [all $F_s(1,11) > 9$, all $p_s < .01$]. However, the quadratic component of distance was significant for all functions except for the first block of inside distractors ($F < 1$), reflecting nonlinearity in all the functions except for this one condition. An analysis was performed on the three blocks of inside distractor curves. The interaction between practice and distance was significant [$F(6,66) = 2.65$, $MS_e = 8,276.0$, $p < .03$]. In the trend analysis, however, practice interacted with only the linear component of distance [$F(2,22) = 5.17$, $MS_e = 8,702.1$, $p < .02$], and not the quadratic component of distance [$F(2,22) = 1.15$, $MS_e = 7,240.4$, $p > .30$]. An analysis was also performed on just the outside distractor set. This analysis

Figure 6. Mean response times and percent error rates for Experiment 1 for each experimental block. The left panel displays the results from inside distractor pairs; the right panel displays the results from outside distractor pairs. Open circles represent the results from the first block of experimental trials, gray-filled circles represent the results from the second block of trials, and black-filled circles represent the results from the third and final block of trials.

did not yield a significant interaction between practice and distance, nor did it yield any interactions between practice and the polynomial trends of distance (all $ps > .30$).

Different responses. Because distance was defined arbitrarily for *different* trials, the data from this response condition are presented in Figure 5 collapsed across the four dot locations. These data were subjected to a repeated measures ANOVA that included distractor type and block as within-subjects factors. There was a significant main effect of distractor type [$F(1,11) = 10.49$, $MS_e = 142,640.0$, $p < .01$], such that inside distractor curves resulted in slower responses than did outside distractor curves. There was a main effect of practice as well [$F(2,22) = 15.72$, $MS_e = 164,227.8$, $p < .01$]. However, these two variables did not interact ($F < 1.0$).

Error Rates

Same responses. The error rates are presented at the bottom of Figures 5 and 6. These data were subjected to a repeated measures ANOVA with the same model as that used for the response times. There was a main effect of distance [$F(3,33) = 9.84$, $MS_e = 113.8$, $p < .01$], the linear component of which was significant [$F(1,11) = 11.69$, $MS_e = 215.1$, $p < .01$], as was the quadratic component [$F(1,11) = 9.10$, $MS_e = 88.27$, $p < .02$]. There was also a significant effect of block (see Figure 6) [$F(2,22) = 4.01$, $MS_e = 14.42$, $p < .04$].

An analysis was performed on each of the six distance functions presented at the bottom of Figure 6. For inside distractor curves, there was a significant effect of distance in the first block [$F(3,33) = 3.94$, $MS_e = 54.45$, $p < .02$]; the linear component of this distance effect was also significant [$F(1,11) = 6.83$, $MS_e = 41.82$, $p < .03$], but not the quadratic component ($p > .18$). There were no significant effects involving distance in the second block (all $ps > .13$). However, the effect of distance was significant in the third block [$F(3,33) = 8.58$, $MS_e = 32.41$, $p < .01$]. The quadratic component of this distance effect was significant [$F(1,11) = 6.79$, $MS_e = 30.05$, $p < .03$], as was the linear component [$F(1,11) = 13.57$, $MS_e = 41.82$, $p < .01$].

For outside distractors, the effect of distance was significant in the first block [$F(3,33) = 3.65$, $MS_e = 43.23$, $p < .03$]. The quadratic component of this distance effect approached significance [$F(1,11) = 4.13$, $MS_e = 38.14$, $p < .07$], as did the linear component of the distance effect [$F(1,11) = 4.77$, $MS_e = 59.49$, $p < .06$]. In the second block, there was a significant effect of distance [$F(3,33) = 6.73$, $MS_e = 36.48$, $p < .01$]. The quadratic component of this distance effect was significant [$F(1,11) = 6.77$, $MS_e = 30.79$, $p < .03$], as was the linear component of distance [$F(1,11) = 7.09$, $MS_e = 71.13$, $p < .03$]. The effect of distance was also significant in the third block [$F(3,33) = 3.72$, $MS_e = 71.52$, $p < .03$]. The quadratic component of this distance effect approached significance [$F(1,11) = 3.87$, $MS_e = 53.83$, $p < .08$], as did the linear component of the distance effect [$F(1,11) = 4.46$, $MS_e = 131.95$, $p < .06$].

An analysis was performed on just the inside distractor curves. There was a significant effect of practice [$F(2,22) = 4.51$, $MS_e = 15.80$, $p < .03$] and distance [$F(3,33) = 6.25$, $MS_e = 74.44$, $p < .01$]. The linear component of distance was significant [$F(1,11) = 9.17$, $MS_e = 123.82$, $p < .02$], and the quadratic component of distance approached significance [$F(1,11) = 4.35$, $MS_e = 57.59$, $p < .07$]. There was a significant interaction between practice and distance [$F(6,66) = 2.56$, $MS_e = 19.46$, $p < .03$], which was reflected in the trend analysis by a significant interaction between practice and the linear component of distance [$F(2,22) = 3.76$, $MS_e = 18.31$, $p < .04$]. There were no other significant effects or interactions (all $ps > .13$).

An analysis was also performed on the outside distractor condition. There was a significant effect of distance [$F(3,33) = 6.09$, $MS_e = 107.10$, $p < .01$]. The linear component of distance was significant [$F(1,11) = 6.49$, $MS_e = 207.65$, $p < .03$], as was the quadratic component [$F(1,11) = 6.50$, $MS_e = 87.99$, $p < .03$].

Different responses. The error results for *different* responses are presented in Figures 5 and 6. A repeated measures ANOVA that included the variables of distractor type and block was performed on the error data but revealed no significant effects. However, both main effects approached significance [$F(1,11) = 4.71$, $MS_e = 26.06$, $p < .06$, for distractor type, and $F(2,22) = 2.75$, $MS_e = 54.14$, $p < .09$, for block].

Discussion

The type of distractor stimulus had a strong modulating effect on curve tracing performance. As predicted, the distance effects with inside distractors were more linear than the distance effects with outside distractor curves. This aspect of the data is clearest in the first block of trials. Regressing distance on response time in these conditions yielded an $R^2 = .99$ for inside distractors and an $R^2 = .76$ for outside distractors. These results provide strong support for the notion that the nonlinearity in the results of studies done with intertwining stimuli was due to the construction of the distractor stimuli (e.g., Jolicoeur et al., 1986). More specifically, the results are consistent with a tracing operator that has a variable size receptive field. The apparent reduction in the size of the distance effect over the first two or three dot locations for the outside distractor stimuli and the linear distance function for inside distractor curves are both predicted by a tracing mechanism sensitive to the proximity of distractor curves. Furthermore, unlike the reanalyses presented earlier, these results were obtained from a direct empirical manipulation.

Repeated exposure to the stimuli had an effect on the linearity of the distance functions for inside curve pairs. In the first block of trials, response time increased linearly with distance. Across Blocks 2 and 3, however, there was a flattening of the response time function over the first two or three dot locations. These practice effects were not predicted by any of the models outlined in the introduc-

tion and were not as strong in the reanalysis of the Jolicoeur and Ingleton (1991) data. However, the stimuli used by Jolicoeur and Ingleton differed from the stimuli used in the present experiment in that each target curve in the Jolicoeur and Ingleton study was presented with either an inside distractor or an outside distractor, but never with both. In addition, Jolicoeur and Ingleton presented their stimuli at two different orientations, which may have acted like doubling the stimulus set, thereby reducing exposure. In the present experiment, each target curve was presented with both an inside distractor and an outside distractor, and the stimuli were presented at only one orientation. A second experiment was designed with inside and outside distractor curves treated as a blocked variable, in order to reexamine or eliminate the effects of repeated exposure found in the present experiment.

EXPERIMENT 2

In Experiment 2, half the subjects were presented with only inside distractors for the first half of the experiment and only outside distractors for the second half of the experiment. The remaining subjects were presented with only inside and only outside distractors in the reverse order. Recall that in the Jolicoeur and Ingleton (1991) study, repeated exposure had little or no effect on the linearity of the distance effects for inside distractor curves. If this null effect was due to having the target curves appear in only one type of distractor context (either inside or outside), then presenting only inside distractor curves for the first half of the experiment should eliminate the effects of repeated exposure that were observed in the previous experiment. Thus, the first half of the experiment could be used as a direct test of distractor type differences without any of the potential confound of the effects of repeated exposure.

It might also be possible to determine whether or not the effects of repeated exposure observed in Experiment 1 are transferable from one set of stimuli (outside distractors) to another set of stimuli (inside distractors) when the two stimulus sets are not presented randomly within a block of trials. If it is possible for such transfer to take place, then when the inside distractor stimulus set is presented as the second block of the experiment, the distance effects should resemble the nonlinear distance effects observed for the outside distractor set in the first half of the experiment.

Finally, if blocking the distractor type variable does not yield any evidence for an effect of repeated exposure either across or within blocks, the data can be collapsed across the practice variable and the block variable, and these results can be compared with predictions made by the zoom lens operator model outlined earlier.

Method

Subjects

Fourteen female and 10 male students at the University of Waterloo were paid \$4 for their participation. The subjects were randomly assigned to one of two groups. One group was presented with only

inside distractor curves for the first half of the experiment and only outside distractor curves for the second half of the experiment. The other group was presented with the distractor types in the reverse order.

Materials and Procedure

Except for the blocking of the distractor type variable, the materials and procedure for Experiment 2 were identical to those in Experiment 1.

Results

Response Times

Outliers. The recursive procedure for removing outliers in Experiment 1 was again used to remove outliers in the present experiment. This resulted in the exclusion of 4.95% of *same*-curve responses and 5.02% of *different* responses.

Same responses. The results for *same* responses are presented in Figure 7. The data was subjected to a repeated measures ANOVA that included order of distractor type presentation (inside for the first half or outside for the first half) as a between-subjects factor and distractor type (inside or outside), curve distance, and practice (three exposures per block) as within-subjects factors. The analysis revealed main effects of distractor type [$F(1,22) = 65.52$, $MS_e = 46,220.5$, $p < .01$], practice [$F(2,44) = 24.88$, $p < .01$], and distance [$F(3,66) = 54.75$, $MS_e = 32,869.0$, $p < .01$]. The linear component of the distance effect was significant [$F(1,22) = 80.26$,

Figure 7. Mean response times and percent error rates for *same* and *different* responses in Experiment 2. Circles represent the results from inside distractor pairs; squares represent the results from outside distractor pairs. Open symbols were used when a condition was presented in the first half of the experiment; closed symbols were used when a condition was presented in the second half of the experiment.

$MS_e = 62,413.6$, $p < .01$], as was the quadratic component [$F(1,22) = 15.85$, $MS_e = 23,520.0$, $p < .01$].

The only significant interaction involving practice occurred between distance and practice [$F(6,132) = 2.82$, $MS_e = 7,816.6$, $p < .02$] (all other $ps > .16$). This interaction was likely due to a larger distance effect in the first block of trials than in the last two blocks of trials. There was a significant interaction between distractor type and distance [$F(3,66) = 8.51$, $MS_e = 7,993.0$, $p < .01$]. Distractor type interacted with both the linear component of distance [$F(1,22) = 11.16$, $MS_e = 9,538.9$, $p < .01$], reflecting the fact that the slope of the distance function for inside curve pairs was steeper than the slope of the distance function for outside curve pairs (31.9 msec/deg vs. 23.7 msec/deg, respectively); distractor type also interacted with the quadratic component of distance [$F(1,22) = 10.47$, $MS_e = 6,013.5$, $p < .01$], reflecting the characteristic flattening of the distance function over the first two or three dot locations of outside distractor curves.

A trend analysis was performed on just the inside distractor curves. The cubic component of the distance effect was significant [$F(1,23) = 6.25$, $MS_e = 3,708.9$, $p < .02$], as were both the quadratic component [$F(1,23) = 11.28$, $MS_e = 4,103.9$, $p < .01$] and the linear component [$F(1,23) = 76.29$, $MS_e = 15,908.6$, $p < .01$]. A trend analysis was also performed on just the outside curves. The quadratic component of the distance effect was significant [$F(1,23) = 36.26$, $MS_e = 7,750.8$, $p < .01$], as was the linear component [$F(1,23) = 65.0$, $MS_e = 9,971.1$, $p < .01$].

The interaction between order of distractor condition and distractor type was significant [$F(1,22) = 19.33$, $MS_e = 46,220.5$, $p < .01$]. This interaction arose because response times did not differ much across distractor condition order for inside distractors (1,021 msec when inside distractors were presented in the first half of the experimental trials vs. 1,017 msec when inside distractors were presented in the second half of the experimental trials), but for outside distractors the order of the distractor conditions had a large effect (951 msec when outside distractors were presented in the first half of the experimental trials vs. 797 msec when outside distractors were presented in the second half of the experimental trials).

The three-way interaction between distractor condition order, distractor type, and distance was also significant [$F(3,66) = 4.83$, $MS_e = 7,993.0$, $p < .01$], as was the interaction between distractor condition order, distractor type, and the linear component of distance [$F(1,22) = 8.16$, $MS_e = 9,566.0$, $p < .01$]. This interaction arose because the slope of the distance function for inside distractor pairs and outside distractor pairs differed very little for the group of subjects who were presented with outside distractors first (27.6 msec/deg for inside distractors vs. 26.5 msec/deg for outside distractors), but differed substantially for the group of subjects who were presented

with inside distractors first (36.1 msec/deg for inside distractors vs. 21.0 msec/deg for outside distractors). The three-way interaction between distractor condition order, distractor type, and the quadratic component of distance was not significant ($F < 1$).

Different responses. The results for *different* responses are presented in Figure 7. These data were subjected to a repeated measures ANOVA that included the distractor condition order variable as a between-subjects factor and the variable distractor type as a within-subjects factor. Inside distractor curve pairs were responded to more slowly than outside distractor curve pairs [$F(1,22) = 42.12$, $MS_e = 327,114.1$, $p < .01$]. Distractor type interacted with presentation order [$F(1,22) = 6.65$, $MS_e = 48,348.4$, $p < .01$]. As can be seen in Figure 7, when inside distractors were presented in the second half of the experimental trials, *different* responses were slightly slower than they were when the inside distractors were presented as the first half of the experimental trials. For outside distractors, *different* responses were substantially faster when outside distractors constituted the second half of the experimental trials than when they constituted the first half of the experimental trials.

Error Rates

Same responses. The error rates are presented at the bottom of Figure 7. These data were subjected to a repeated measures ANOVA with the same model that was used in the analysis for response times. There was no effect of the order of the distractor condition, nor were there any interactions involving this variable (all $ps > .17$).

There was a significant effect of distance [$F(3,66) = 14.8$, $MS_e = 68.79$, $p < .01$], the linear component of which was significant [$F(1,22) = 17.42$, $MS_e = 136.3$, $p < .01$], as was the quadratic component [$F(1,22) = 14.15$, $MS_e = 47.31$, $p < .01$]. There was a significant interaction between distractor type and distance [$F(3,66) = 3.91$, $MS_e = 22.56$, $p < .01$]. This interaction likely comes about because of a larger jump in error rates for outside distractor curves at Distance 4 than for inside distractor curves. This tendency was also reflected in a marginal interaction between distractor type and the linear component of distance [$F(1,22) = 4.17$, $MS_e = 27.32$, $p < .06$], which suggests a tendency for a steeper slope in the distance function for outside curves (.74% errors per degree) than for the distance function for inside curves (.47% errors per degree). The interaction between distractor type and the quadratic component of distance was not significant [$F(1,22) = 2.86$, $MS_e = 28.09$, $p < .12$]. The pattern of errors generally resembles the pattern of response times. For outside distractors, performance is relatively flat over the first three distances and then jumps up at Distance 4, whereas for inside distractors, the trend is a more linear increase in response times and errors across all four distances. Furthermore, there is no hint of a possible speed-accuracy tradeoff ac-

count if one considers only the first three dot locations. Yet, for these locations, there is good support for our zoom lens model in the pattern of response times.

Different responses. The error rates for *different* responses are given at the bottom of Figure 7. A repeated measures ANOVA, following the same model as that used for response times, uncovered no significant effects, although the main effect of presentation order approached significance [$F(1,22) = 3.56$, $MS_e = 432.0$, $p < .08$], as did the interaction between presentation order and distractor type [$F(1,22) = 2.34$, $MS_e = 39.93$, $p < .12$].

Discussion

In Experiment 2, empirical control over the shape of the distance functions (i.e., linear or nonlinear) was replicated. Regressing distance on response time for inside curve pairs (collapsed across presentation order) yielded $R^2 = .97$, whereas for outside curve pairs, $R^2 = .83$ was observed. There was no evidence that repeated exposure effects occurred within a block of trials or were transferred across blocks of experimental trials. For outside curve pairs, starting with the inside distractor set appeared to make the task easier than it was when the experiment began with the outside set. This was reflected both by faster response times and by a slightly shallower distance function for that presentation order. However, in both groups of subjects, the effects of distance for inside curve pairs were clearly more linear than those for outside curve pairs (Figure 7).

It is possible, as suggested by the results of Jolicoeur and Ingleton (1991), that the increased nonlinearity is facilitated by pairing target curves with both inside and outside distractors. However, this possibility remains tentative, and these repetition effects will require further empirical investigation before their source can be identified clearly. Exploration of this phenomenon goes beyond the goals of the present research. Instead we focus on a quantitative analysis of the zoom lens curve tracing model based on the present data set, which is not confounded by repetition effects.

GENERAL DISCUSSION

Earlier, we outlined some of the functional properties of a zoom lens curve tracing operator. However, other curve tracing models have been proposed. Jolicoeur et al. (in press) have described an operator that is sensitive to distractor proximity and to the curvature of the line being traced. They contrast this operator with what would be expected from a simple pixel-by-pixel tracing scheme. We turn now to a discussion and comparison of these three models. Each model makes quantifiable predictions about *same* response times for each dot location in each stimulus pair. These predictions are coded and used in multiple regression analysis with the mean response time (from Experiment 2) for each *same* dot location in each stimulus pair as the dependent variable. The three models are

then evaluated in terms of how well they predict the results from Experiment 2.

In order to extract mean response times across stimulus conditions, the data from Experiment 2 were subjected to an item analysis of variance. The data were broken down into 64 cells (8 target curves $\times$ 2 distractor types $\times$ 4 dot locations, averaging across subjects). The response times in these cells were analyzed for outliers according to the recursive procedure used in Experiments 1 and 2. This resulted in exclusion of 7.8% of the response times. The means generated from the outlier analysis are presented in Appendix B. These mean response times were used in the regression analysis presented below and were also subjected to a repeated measures ANOVA that included target curve as the repeated variable, and distractor curve and distance as within-item factors. The results of the item analysis supported the conclusions drawn from Experiment 2. There were main effects of both distractor type (inside vs. outside) [$F(1,7) = 15.85$, $MS_e = 22,422.1$, $p < .01$] and distance [$F(3,21) = 94.74$, $MS_e = 2,428.7$, $p < .01$]. The linear component of distance was significant [$F(1,7) = 169.33$, $MS_e = 3,665.5$, $p < .01$], as was the quadratic component [$F(1,7) = 21.44$, $MS_e = 3,187.4$, $p < .01$]. The interaction between distractor curve and distance approached significance [$F(3,21) = 2.76$, $MS_e = 3,414.9$, $p < .07$]. The interaction between distractor curve and the linear component of distance was not significant [$F(1,7) = 1.90$, $MS_e = 7,632.7$, $p > .20$], suggesting that the slopes did not differ significantly across distractor conditions. However, the quadratic component of distance did interact with distractor type [$F(1,7) = 9.89$, $MS_e = 1,106.5$, $p < .02$].

Three Curve Tracing Models

Pixel-by-pixel tracing. Curve tracing may be accomplished by implementing an operator that is as small as the finest resolution of the visual system. As the name *pixel by pixel* implies, the model is described by analogy with a simple computer algorithm. A pixel is the finest resolution element of a digital computer image. A computer program could be given the image of two lines and two dots as input. The program could trace a curve by starting at the first dot and moving a pointer from one "on" pixel to the next (adjacent) "on" pixel until the second dot was found or an exhaustive search of the curve was completed.

Pixel-by-pixel tracing can be thought of as a limiting case in which effects of distance with no effect of curvature or distractor proximity are expected. It predicts a linear effect of distance on response time; hence its coding as a predictor variable would be a simple linear transformation of the units used to measure curve distance. Therefore, the dot locations on the target curves of the stimuli used in Experiment 2 were coded as 1, 2, 3, or 4 units of relative distance. The simplicity of the pixel-by-pixel model of curve tracing is reflected by the regular use of the linear component of distance to examine the interaction of independent variables with distance

Figure 8. (A) The Jolicoeur, Ullman, and MacKay (in press) bipartite receptive field operator and its two processing regions (labeled "A" and "B"; see text for details). (B) An example of how the tracing time for the bipartite operator can be quantified. The number of shifts needed to traverse a certain segment can be used to predict response time. It takes 4 shifts to trace from the center dot to the first dot location, 8 shifts to reach the second dot location, 12 shifts to reach the third location, and 16 shifts to reach the fourth location.

(e.g., Jolicoeur & Ingleton, 1991; Jolicoeur et al., 1986, in press; Experiments 1 and 2 of the present article).

The bipartite receptive field operator. Jolicoeur et al. (in press) have described a more powerful curve tracing operator that is more efficient than pixel-by-pixel tracing because it is sensitive to target curve curvature and the proximity of distractor stimuli. The operator, which is centered on the curve, is an oval divided into two regions (see Figure 8A). The two regions (labeled "A" and "B" in Figure 8A) are defined by placing two perpendicular lines through the center of the operator at a 45° rotation from the vertical axis of the oval. Curve tracing is accomplished by moving the receptive field of the operator along the curve in steps determined by the size of the receptive field. A large receptive field would take a larger step than a small receptive field. The size of the receptive field is variable and adjusted to be as large as possible, subject to three constraints that prevent the operator from erroneously trying to process two different curve segments simultaneously. Recall that if two curves fall within the processing region, the operator may shift to

the wrong curve and then continue to process that curve. These are the three constraints: (1) There can be no line segment passing through Region B. (2) The line passing through Region A cannot turn more than 45° from the vertical axis of the receptive field of the operator. (3) Region A must not contain any line terminators. Jolicoeur et al. have discussed how these constraints are sufficient to guarantee that there is only one curve passing through the receptive field.

The bipartite operator can account, in a qualitative way, for both curvature and distractor proximity effects observed in previous research. The constraint that the curve being traced cannot turn more than 45° within the receptive field of the operator means that as curvature increases, the receptive field needs to become smaller, resulting in the need for more shifts. As with the zoom lens model discussed in the introduction, the number of shifts that the bipartite operator needs to traverse a curve segment is the major factor affecting response time. Thus, as the receptive field gets smaller, more shifts are required, and response time increases. The constraint that the distractor stimuli cannot fall within the receptive field of the operator means that as distractor stimuli get closer to the target curve, the receptive field must become smaller, resulting in more shifts and consequently longer tracing times.

Figure 8B depicts an example of how predictions made by the bipartite operator can be quantified for one of the stimuli used in the present research. In the same way that relative distance was used to code dot locations for the pixel-by-pixel model, the number of shifts of the receptive field required by the bipartite operator to trace the curve between the two dots can be used to predict response time for each dot location. For example, to trace the curve segment between the first dot (the dot that occurs at the spatial location of the fixation stimulus) and the dot location at Distance 3, the operator needs to shift eight times (i.e., make eight "fixations"). Bipartite receptive fields were fit by hand to each stimulus pair used in Experiments 1 and 2 in the same way as for the stimulus in Figure 8B. This was done by one of the experimenters, who fit the receptive fields by drawing them on the stimuli with a Macintosh drawing program. For each "fixation," the size of the receptive field was maximized without violating any of the constraints outlined earlier. The codings (i.e., the number of shifts) for each dot location on each target curve are given in Appendix B.

The bipartite receptive field model predicts the same results for inside and outside curves (see Appendix B). The failure of the model to pick up these differences is due to both the centering of the receptive field on the target curve and the curvature constraint described earlier. Recall that when the present stimuli were modified, a piece of the distractor stimuli was moved from either the inside to the outside of the first lobe of the target curve or from the outside to the inside of the first lobe. There is very little difference in terms of the overall proximity of an inside or an outside distractor with a single target curve. Whether the distractor curve passes along the outside or

A

Figure 9. Two examples of how the tracing times for the zoom lens model can be quantified. For the inside curve pair in panel A, it takes three shifts to trace from the center dot to the second dot location; for the outside curve pair in panel B, it takes only one shift to reach the second dot location.

along the inside of the target curve is not an important factor for an operator whose receptive field is centered on the target curve. In addition, it can be seen in Figure 8B that for many of the shifts, the curvature of the target curve resulted in the need for the shift. In many cases, the size of the receptive field was constrained more by curvature than by the proximity of distractor curves.

The zoom lens operator. The zoom lens operator was described earlier. It differs from the bipartite receptive field operator in two ways. It is not divided into regions, and it is not necessarily centered on the curve. Without these constraints, it is still possible for the zoom lens operator to trace curves successfully. This is accomplished by including the processes involved in determining that there is only one curve within the receptive field of the operator.

Figure 9 gives an example of how predictions made by the zoom lens operator can be quantified for two of the stimuli used in the present research. Two assumptions were made in order to code the response time predictions made with the present model. First, as can be seen in Figure 9, the shape of the receptive field of the operators is circular. Although we make no strong claims concerning the shape of the operator, we suspect that it has a convex

hull. However, for the present purposes we assume that a circle is a reasonable approximation of the shape of the receptive field. Second, we assume that the number of shifts required to trace a curve segment is an adequate coding scheme for quantifying the model's prediction of response times. Although an argument could be made that a zooming component should be added to the coding scheme, we do not include one directly. Indirectly, a zooming component is contained within the number of shifts, in that with each new shift more zooming is required (see the introduction). Jolicoeur and Ingelton's (1991) finding of size invariance also suggests that response time is more dependent on the number of shifts than on the amount of zooming. Recall that Jolicoeur and Ingelton found that the relative slope of the curve distance effect did not change when the absolute size of the stimulus was varied. That is, coding distance as 1, 2, 3, or 4 units of relative distance yielded the same slope for a stimulus, regardless of the overall size of the stimulus (within the range studied). A zooming component would suggest that, in terms of relative distance, the slope for a stimulus presented so that one unit of relative distance equaled 2° of visual angle would differ from the slope from the same stimulus presented so that one unit of relative distance equaled 4° . The latter would require larger changes in receptive field size than would the former. The size invariance effect is more compatible with the notion that the number of shifts, not the amount of zooming, predicts response times. That is, stimulus of the type used by Jolicoeur and Ingelton will require the same number of shifts, regardless of its overall size. The circular receptive fields were fit by hand to each curve pair used in Experiments 1 and 2. This was done by one of the experimenters, who fit the operators by drawing them on the stimuli with a Macintosh drawing program. Again, the size of the receptive field was maximized for each "fixation," without violating any of the constraints out-

Table 1
Correlation Matrix for the Variables Response Time (RT), Zoom Lens Predictions (ZL), Pixel-by-Pixel Predictions (PXP), and the Bipartite Receptive Field Predictions (BRF)

Variable	RT	ZL	PXP	CSO
RT	1.000	0.871	0.633	0.663
ZL	0.871	1.000	0.697	0.705
PXP	0.633	0.697	1.000	0.975
BRF	0.663	0.705	0.975	1.000

Table 2
Results from Multiple Regression Analyses Involving the Variables Response Time (RT; Dependent Variable), Zoom Lens Predictions (ZL), Pixel-by-Pixel Predictions (PXP), and the Bipartite Receptive Field Predictions (BRF)

Predictor Variable	Zero-Order Correlation	Beta	Slope	Test of Unique Variance (Semipartial Correlation)
ZL	0.871	0.81	74.06	$F(1,60) = 87.14, p < .01$
PXP	0.633	-0.43	-59.90	$F(1,60) = 2.42, p > .12$
BRF	0.663	0.51	14.88	$F(1,60) = 3.33, p < .07$

Note—Intercept = 746.59. Multiple $R = 0.88$; multiple $R^2 = 0.77$.

Table 3
Standardized Regression Equations and Multiple R^2 from the Regression of Response Time on Combinations of the Variables Zoom Lens Predictions (ZL), Pixel-by-Pixel Predictions (PXP), and the Bipartite Receptive Field Predictions (BRF)

Predictor Variables	Standardized Regression Equation	Multiple R^2
ZL, PXP, BRF	$RT = (.81)ZL - (.43)PXP + (.51)BRF$	.773
PXP	$RT = (.63)PXP$	.401
PXP, ZL	$RT = (.05)PXP + (.84)ZL$	.760
BRF	$RT = (.66)BRF$	.440
PXP, BRF	$RT = (-.26)PXP + (.92)BRF$	.443
ZL	$RT = (.87)ZL$	.759
ZL, BRF	$RT = (.80)ZL + (.10)BRF$	.772

lined earlier. The codings (i.e., the number of shifts) for each dot location on each target curve are given in Appendix B.

An Evaluation of the Three Models

The data in Appendix B were subjected to a multiple regression analysis with response time as the dependent variable and the codings from each of the three models as predictor variables. The correlation matrix is given in Table 1. There are two points of interest in the zero-order correlations. First, the zoom lens model has a higher correlation with response time than either distance (i.e., pixel by pixel) or the bipartite operator. Second, the correlation between the bipartite operator and the pixel-by-pixel model is very high ($R = .975$).

The results from the full regression model are summarized in Table 2. The statistical significance of each semi-partial correlation suggests that each model is capturing unique variance in mean response times. However, the negative beta weight (the standardized regression coefficient) associated with curve distance (i.e., the pixel-by-pixel model) suggests that it is acting as a suppressor variable. Two forward stepwise analyses were performed to evaluate the three models. First, response time was regressed on relative curve distance (i.e., the coding from the pixel-by-pixel model). Adding the zoom lens operator variable to the regression model resulted in a significant improvement in the multiple R^2 [$\Delta R^2 = .359$; $F(1,61) = 91.2$, $p < .01$]. The results from this partial regression model are summarized in Table 3. Starting with only the pixel-by-pixel model and adding the bipartite operator variable to the regression model also resulted in a significant (but smaller) improvement in the multiple R^2 [$\Delta R^2 = .042$; $F(1,61) = 7.44$, $p < .01$]. However, unlike the partial regression model that included the zoom lens operator and the pixel-by-pixel coding, when the partial regression model contained the bipartite operator and the pixel-by-pixel coding, the pixel-by-pixel variable again had a negative beta weight associated with it and thus served as a suppressor variable (see Table 3). This is likely due to the high correlation between the pixel-by-pixel model and the curvature-sensitive operator (see Table 1).

A second forward stepwise analysis was performed on the data. Response time was regressed on only the zoom lens operator (see Table 2). Adding the pixel-by-pixel

coding to the regression model did not significantly improve the multiple R^2 ($\Delta R^2 = .001$; $F < 1$). Likewise, adding only the bipartite operator to the regression model did not significantly improve the multiple R^2 [$\Delta R^2 = .013$; $F(1,61) = 1.23$, $p > .10$]. The results from this partial regression model are summarized in Table 3.

Of the three models, then, the zoom lens model provides the best fit for the response time data. It accounts for a significant proportion of the variance that curve distance (i.e., the pixel-by-pixel coding) alone cannot account for. As the second stepwise analysis demonstrated, neither the pixel-by-pixel model nor the bipartite operator significantly improved the fit of the zoom lens model. In fact, the full regression model using all three predictors does not account for significantly more variance than the zoom lens model alone [$\Delta R^2 = .014$; $F(2,60) = 1.83$, $p > .10$]. The zoom lens model on its own accounts for over 75% of the variance in response time.

The obvious functional advantage that the zoom lens model has over the other two models is that it can account for the difference between inside and outside curves. The

Figure 10. A comparison of the mean response times from the item analysis and the mean number of shifts predicted by the zoom lens model. The scale for the number of shifts was calculated from the regression equation of response time on the predictions made by the zoom lens model (see text for details).

ability of the model to do this can be seen in Figure 10. The graph compares the response time data from Experiment 2, collapsed over blocks, with the scaled predictions of the zoom lens model. The scaling was achieved by using the regression equation from the regression of response time on the zoom lens predictor variable. The mean number of shifts across target curves for each distance-by-distractor-type cell was entered into the equation and the predicted response time plotted. In addition to how well the zoom lens model predicts a main effect of inside and outside curves, it also emulates the shape of the distance functions for each of the distractor conditions. It should be noted that although the model does not predict a perfect linear function for inside curves, it does predict a fairly linear pattern, as was found in the response data from Experiment 2 and Block 1 of Experiment 1.

SUMMARY AND CONCLUSIONS

In the present study, we have demonstrated that the nonlinearity observed in previous curve tracing experiments done with intertwining stimuli was due to characteristics of the target and distractor curve relationship. More specifically, when the distractor curve is drawn along the outside of the first lobe of the curve to be traced, it appears that subjects can process multiple dot locations simultaneously, possibly by using an operator whose receptive field has zoom lens properties. Enlarging the receptive field of the operator reduces the number of shifts required to trace the curve over certain sections, thereby reducing or eliminating the effects of distance over these regions. These results are empirically as well as theoretically important. Because the inside distractor curve set yielded fairly linear distance effects, these stimuli represent a good alternative to the stimuli employed by Jolicoeur et al. (1986) and Jolicoeur and Ingleton (1991) for future work on curve tracing.

The predictions made by the zoom lens analogy at the beginning of this paper were supported by the results of both experiments. The evidence is consistent with the notion that the receptive field of the curve tracing operator has a flexible size and that this zoom lens property may have been responsible for the nonlinearity observed previously. Our notion of a zoom lens curve tracing operator is quite similar to the zoom lens metaphor of visual attention. The results in the present study are consistent with the view that curve tracing and shifting visual attention may be part of a common, more general, system (McCormick & Jolicoeur, in press; Ullman, 1984).

The results also suggest that Jolicoeur et al.'s (in press) bipartite operator does not seem to reflect how humans trace the intertwining curves used in the present experiment. In addition, we have provided converging evidence that curve distance, in and of itself, is not always the best

predictor of response time. The zoom lens model, as specified in the present article, would appear to be a good starting point from which a more complete model of curve tracing could be developed. However, a number of issues still require empirical investigation: the time course of focusing, the spatial distribution (i.e., the shape) of the receptive field of operator, and the effects of repeated exposure observed in Experiment 1. In addition, whereas the bipartite operator predicts effects of curvature, such as those studied by Jolicoeur et al., it is not clear how these curvature effects might be accommodated by the zoom lens model. Despite this limitation, if the zoom lens operator is analogous to visual attention as it is studied in the literature on orienting of attention, questions that are answered concerning the curve tracing operator may have a direct bearing on our knowledge of the role of orienting visual attention in tasks requiring visual information processing.

REFERENCES

- ERIKSEN, C. W., & HOFFMAN, J. E. (1972). Temporal and spatial characteristics of selective encoding from visual displays. *Perception & Psychophysics*, *12*, 201-204.
- ERIKSEN, C. W., & ROHRBAUGH, J. W. (1970). Some factors determining efficiency of selective attention. *American Journal of Psychology*, *83*, 330-342.
- ERIKSEN, C. W., & ST. JAMES, J. D. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception & Psychophysics*, *40*, 225-240.
- JOLICOEUR, P. (1988). Curve tracing operations and the perception of spatial relations. In Z. Pylyshyn (Ed.), *Computational processes in human vision: An interdisciplinary perspective* (pp. 133-168). Norwood, NJ: Ablex.
- JOLICOEUR, P., & INGLETON, M. A. (1991). Size invariance in curve tracing. *Memory & Cognition*, *19*, 21-36.
- JOLICOEUR, P., ULLMAN, S., & MACKEY, M. (1986). Curve tracing: A possible basic operation in the perception of spatial relations. *Memory & Cognition*, *14*, 129-140.
- JOLICOEUR, P., ULLMAN, S., & MACKEY, M. (in press). Visual curve tracing properties. *Journal of Experimental Psychology: Human Perception & Performance*.
- MCCORMICK, P. A., & JOLICOEUR, P. (in press). Capturing visual attention and the curve tracing operation. *Journal of Experimental Psychology: Human Perception & Performance*.
- MCCORMICK, P. A., & KLEIN, R. M. (1991). The spatial distribution of attention during covert visual orienting. *Acta Psychologica*, *75*, 225-242.
- POSNER, M. I., SNYDER, C. R. R., & DAVIDSON, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General*, *109*, 160-174.
- PRINGLE, R., & EGETH, H. E. (1988). Mental curve tracing with elementary stimuli. *Journal of Experimental Psychology: Human Perception & Performance*, *14*, 716-728.
- SHEPHERD, M., & MÜLLER, H. J. (1989). Movement versus focusing of visual attention. *Perception & Psychophysics*, *46*, 146-154.
- STERNBERG, S. (1969). Memory scanning: Mental processes revealed by reaction time experiments. *American Scientist*, *57*, 421-457.
- STERNBERG, S. (1975). Memory scanning: New findings and current controversies. *Quarterly Journal of Experimental Psychology*, *27*, 1-32.
- ULLMAN, S. (1984). Visual routines. *Cognition*, *18*, 97-159.

APPENDIX A
Experimental and Practice Stimuli Used in Experiments 1 and 2

APPENDIX B
Mean Response Times (in Milliseconds) and Codings for the Predictions of the Zoom Lens Operator, Pixel-by-Pixel Tracing, and the Bipartite Receptive Field Operator, for Each Same Curve Distance and Each Stimulus Pair

Stimulus	Curve Distance	Response Time	Zoom Lens	Pixel by Pixel	Bipartite Receptive Field
Inside 1	1	819	1	1	4
	2	836	3	2	8
	3	869	3	3	12
	4	1,026	5	4	16
Outside 1	1	832	1	1	4
	2	749	1	2	8
	3	897	2	3	12
	4	1,089	4	4	16
Inside 2	1	971	2	1	5
	2	1,032	3	2	11
	3	1,082	4	3	16
	4	1,418	5	4	20

APPENDIX B (Continued)

Stimulus	Curve Distance	Response Time	Zoom Lens	Pixel by Pixel	Bipartite Receptive Field
Outside 2	1	813	0	1	5
	2	786	1	2	11
	3	891	2	3	16
	4	1,035	3	4	20
Inside 3	1	818	1	1	4
	2	899	3	2	8
	3	943	4	3	14
	4	1,085	6	4	19
Outside 3	1	767	0	1	4
	2	768	0	2	8
	3	764	1	3	14
	4	935	2	4	19
Inside 4	1	948	2	1	4
	2	1,037	4	4	8
	3	1,205	5	3	14
	4	1,427	7	4	19
Outside 4	1	851	1	1	3
	2	788	1	2	7
	3	803	2	3	13
	4	997	3	4	18
Inside 5	1	902	1	1	4
	2	875	3	2	8
	3	930	4	3	13
	4	1,037	5	4	17
Outside 5	1	830	1	1	4
	2	809	1	2	8
	3	877	2	3	13
	4	1,069	3	4	17
Inside 6	1	895	2	1	4
	2	1,094	4	2	9
	3	1,179	5	3	14
	4	1,388	6	4	17
Outside 6	1	836	0	1	4
	2	800	1	2	9
	3	945	2	3	14
	4	1,035	3	4	17
Inside 7	1	815	1	1	3
	2	934	3	2	8
	3	1,016	3	3	13
	4	1,061	5	4	17
Outside 7	1	780	0	1	3
	2	817	0	2	8
	3	858	1	3	13
	4	1,043	3	4	17
Inside 8	1	934	2	1	4
	2	1,054	3	2	10
	3	1,109	5	3	15
	4	1,177	5	4	20
Outside 8	1	780	1	1	4
	2	807	2	2	10
	3	933	2	3	15
	4	1,063	3	4	20

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