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Attentional Demands of Processing Shape in Three-Dimensional Space: Evidence From Visual Search and Precuing Paradigms

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The hypothesis that representation of projective shape is preattentive whereas representation of objective shape in three-dimensional space requires allocation of attention was tested in 2 visual search and 2 precuing experiments. In the visual search experiments, the slope for projective shape search was expected to approach 0 and that for objective shape search was expected to be a positive monotonic function of set size. In the precuing experiments, the effects of precuing were expected to be largely limited to the task requiring representation of objective shape. The overall pattern of results conformed to expectations. The findings are interpreted in the context of a model of shape-at-a-slant processing set out by Epstein and Lovitts (1985) and Epstein and Babler (1989, 1990).

In earlier work (Epstein & Babler, 1989, 1990; Epstein & Broota, 1986; Epstein & Lovitts, 1985) we assessed the hypothesis that the process that generates a perceptual representation of two-dimensional (2D) shapes in three-dimensional (3D) space is constituted of two types of operations. The early operations, culminating in representation of projective shape and representation of orientation in 3D space, are preattentive; the later operations, integrating projective shape and orientation to generate an object-centered representation of shape at a slant, are attentional.

Support for this hypothesis was provided initially (Epstein & Lovitts, 1985) by an experiment that compared perception of shapes that were rotated in depth under two attentional conditions. Under one condition attention was withdrawn from processing shape and slant in depth; under the contrasting condition attention was directed to processing shape at a slant. On a two-alternative forced-choice test immediately following brief exposure of the target shape, under the former condition subjects chose a projective-shape equivalent as a match for the target shape, whereas under the latter condition subjects chose an objective-shape equivalent. In another study using the withdrawal-of-attention paradigm, Epstein and Babler (1989) showed that withdrawal of attention did not greatly affect discrimination of slant in depth on a same–difference task. The former finding was taken to imply that representation of projective shape is preattentive; the latter finding was taken to imply that representation of slant in depth is preattentive. Complementary evidence of preattentive detection of slant in depth was supplied by Epstein and Babler (1990) in a visual search paradigm. (See also Nakayama & Silverman, 1986, and Ramachadran & Plummer, 1989.)

In the present article we report two sets of studies designed to adduce converging evidence regarding the attentional properties of the operations that generate projective, viewer-centered representations of shape and objective, object-centered representations of shape. In the first pair of experiments we used a visual search paradigm; in the second pair, a precuing paradigm.

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Searching for Shape in 3D Space

Experiment 1

We relied on the conventional interpretation of the slopes of the reaction-time–set-size function as the basis for inferences concerning the attentional nature of the operations. Caveats (e.g., Townsend & Ashby, 1983; Ward & McClelland, 1989) notwithstanding, if the slope of the function is zero or approximately zero, the operations that support successful search are presumed to be preattentive; if the slope is a positive function of set size, the operations that support successful search are presumed to involve serial allocation of attention.

Consider two versions of a visual search task in which the targets and distractors are 2D shapes in 3D space, that is, palpable shapes in 3D space rather than graphic displays on a 2D surface. The target is either an ellipse among circles (distractors) or a trapezoid among rectangles (distractors). In one version of the task, all of the shapes are in the frontal-parallel plane aligned in an imaginary plane perpendicular to the subject's line of sight. These facts of spatial arrangement are made known to the subject. The target ellipse is the projective equivalent of the circle rotated 60° about the vertical axis. The target trapezoid is the projective equivalent of the rectangle rotated 60° about the vertical axis. Under these circumstances representation of *projective shape* is sufficient to assure detection of a target on positive trials and recognition of the absence of a target on negative trials. We call this version of the task SPS (search for projective shape). If representation of projective shape is preattentive, then search time on SPS should be independent of set size.

The alternative version of the task, SOS (search for objective shape), presents the same search sets in the same order. As in SPS, the subject is instructed to search for an ellipse or a trapezoid. The only difference between SPS and SOS is that whereas in SPS all of the shapes are frontal-parallel, in SOS all of the shapes are rotated in depth. The effect of rotating all of the shapes in depth is to cause all of the shapes in the ellipse-circle sets to project elliptical shapes and all of the shapes in the trapezoid-rectangle set to project trapezoidal shapes. Under these circumstances the output of the putative preattentive operation (a representation of projective shape) will not be sufficient to pick out the target or to detect its absence. More is needed. What is needed is the integration of projective shape and slant in depth to generate an object-centered representation of shape. By hypothesis, this computation requires allocation of attention. When more than one shape needs to be evaluated, the computations will be conducted serially and search time should be a positive function of set size.

Method

Subjects. Subjects were 7 introductory psychology students from a large midwestern university. All subjects reported normal or corrected-to-normal vision.

Apparatus and stimuli. The apparatus consisted of a two-field tachistoscope, an Apple II computer that controlled the tachistoscope fields, and a two-button response panel. The viewing window of the tachistoscope was 70 cm from the displays.

Subjects viewed four different shapes: circles, ellipses, squares, and trapezoids. The circles were 2.5 cm in diameter, and the squares were 2.5 cm. Each shape subtended a horizontal visual angle of about 2° when oriented in the frontal-parallel plane. The ellipses and trapezoids were 2.5 cm high and 1.44 cm wide. The ellipse when rotated in depth by 30° about the vertical axis and the circle when rotated in depth by 60° about the vertical axis produced the same projective shape. Likewise, the trapezoid when rotated in depth by 30° projected the same shape as the square when rotated by 60°. Rotated shapes were always oriented with the left edge forward. Multiple replicas of these shapes were constructed from thin white posterboard and mounted on flat black vertical stalks (3 mm in diameter).

The displays were horizontal spatial arrangements of 2, 3, 4, or 5 shapes. On half of the trials, the subjects searched for a single ellipse among circles. On the remaining half of the trials, the subjects searched for a single trapezoid among squares. The target shape, either an ellipse or trapezoid, was present on half of the trials. Targets appeared equally often in each of the five display locations. The angular separation between immediately adjacent shapes ranged from 0.5° to 1.3°. The largest display (i.e., Set Size 5) subtended a horizontal visual angle of about 12.0°.

During the first 80 trials (SPS) of each session, targets and distractors were all oriented in the frontal-parallel plane. During the final 80 trials (SOS) of each session, the target was always rotated in depth by 30° about its vertical axis and the distractors were rotated in depth by either 30° or 60°. With a number of exceptions involving Set Size 2, both rotations (30° and 60°) were represented in each display set. The distractors were assigned to the two orientations evenly to ensure that each distractor would be presented at 30° on half of the trials. Consequently, subjects could not pick out the target simply by degree of rotation.

Procedure. The subject's task was to search each display for a designated shape, either an ellipse or a trapezoid. Sample target shapes were presented to the subject prior to the first session. Each trial was initiated by oral designation of the target shape. The experimenter spoke the word "ellipse" or "trapezoid." A warning tone sounded 1 s prior to the presentation of the display. A positive search required a press of a button labeled "yes," whereas a negative search required a press of the "no" button. A short tone sounded following an incorrect response. Subjects were instructed to respond as quickly as possible without sacrificing accuracy. In addition, subjects were informed that the target would be present on 50% of the trials.

The experiment was initiated by a practice phase that ran for three 1-hr sessions. The aim of the practice phase was to override any tendencies toward conscious adoption of a serial search strategy that might have been prompted by the spatial arrangement of the displays. (See Epstein & Babler, 1990, for a discussion of the need for this practice phase.) The instructions during the practice phase encouraged the subjects to refrain from examining the displays one shape at a time. Instead, subjects were instructed to view the display in a single glance and to base their responses on their initial, single-glance impressions. Subjects were instructed to follow this search strategy only to the extent that it did not result in low accuracy. To further discourage adoption of a serial search, the exposure duration during the three practice sessions was fixed at 400 ms for all trials.[1] The second phase of the experiment, which ran for two 1-hr sessions, was the test phase. The instructions for the test phase rehearsed the emphasis on the single-glance search. The experimenter-controlled cap was lifted for the test sessions. For these sessions display exposure was terminated by the subject's response. In all other respects (e.g., composition of sets) SPS and SOS were identical.

There were two target shapes (ellipse and trapezoid), two response types (positive and negative), four set sizes (2, 3, 4, and 5), and five possible target locations, which created 80 different types of trials. These 80 trials were presented twice during each session for a total of 160 trials. The first set of 80 trials of each session was devoted to SPS; the second set of 80 trials of each session was devoted to SOS. Prior to the initiation of each version of the task, subjects were informed of the spatial arrangement that would prevail (e.g., "All shapes will be presented 'face on'").

Results

Two subjects were eliminated from the analyses because they failed to maintain an average error rate below 20% for both the SPS and SOS trials during the test sessions. Reaction times less than 150 ms and greater than 2,500 ms were discarded for all conditions. The upper panel of Figure 1 shows the mean correct reaction times (RTs) averaged over the two test sessions across the different conditions for the SPS and SOS trials, respectively. The reaction times were much longer for the SOS trials compared to the SPS trials, $F(1, 4) = 82.86$, $p < .01$. Averaged across conditions, an SOS trial ($M = 734$ ms, $SE = 54$) required an additional 250 ms more to complete than an SPS trial ($M = 466$ ms, $SE = 29$).

The upper panel of Figure 1 exhibits only modest effects of set size for SPS but quite obvious effects for SOS. For SPS, RT increased by only 11 ms per item; in contrast, for SOS, RT increased by 42 ms per item. The set size effect was significantly greater for SOS than for SPS, $F(3, 12) = 9.94$, $p < .01$.

Even though the slopes were relatively shallow for SPS, a separate analysis of the SPS trials did show a significant set size effect, $F(3, 12) = 18.24$, $p < .001$. Positive and negative searches yielded slopes of 7.9 and 14.6 ms per item, respectively. There were no other significant main effects or interactions for the SPS trials.

[1] The 400-ms exposure duration was selected on the basis of other search experiments reported by Epstein and Babler (1990) involving search for slant in depth.

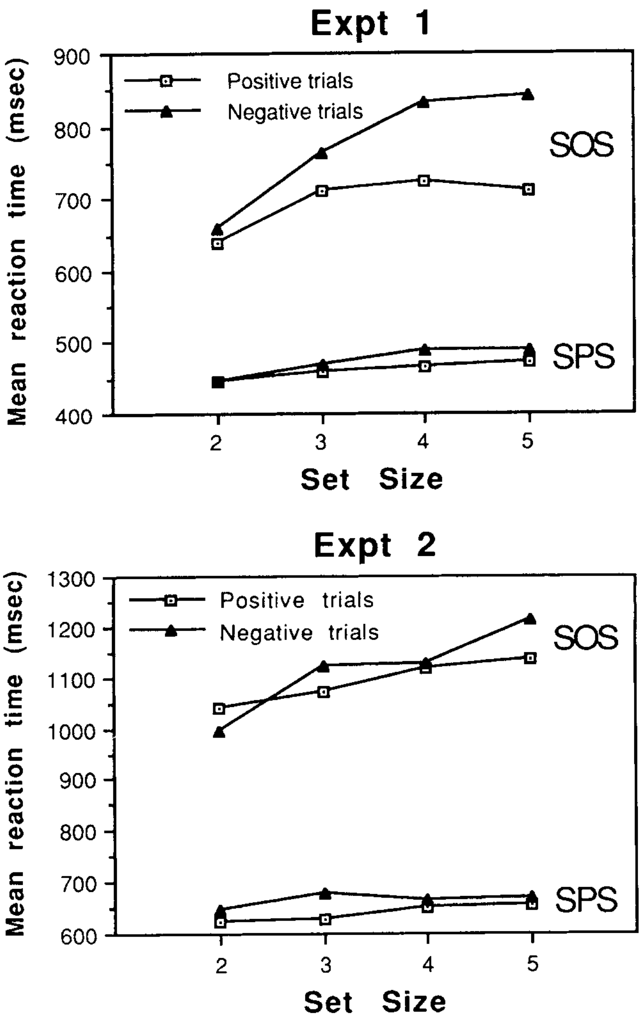

Figure 1. Mean reaction time as a function of set size for positive and negative search trials in SOS (search for objective shape) and SPS (search for projective shape) for Experiment 1 (upper panel) and Experiment 2 (lower panel).

A separate analysis of the SOS trials showed a significant effect of set size, $F(3, 12) = 15.44$, $p < .001$, and a significant Set Size × Target Absence/Presence interaction, $F(3, 12) = 8.39$, $p < .01$. Negative searches yielded a greater slope (61.6 ms per item) than did positive searches (22.2 ms per item). In addition, negative searches ($M = 772$ ms, $SE = 51$) required significantly more time than did positive searches ($M = 695$ ms, $SE = 58$), $F(1, 4) = 45.76$, $p < .01$.

The error rates averaged 11.7% during the SOS trials, but only 2.4% for the SPS trials. Error rates were not significantly affected by set size for either the SPS or SOS condition. The SOS error rates were significantly greater than the SPS error rates, $F(1, 4) = 28.49$, $p < .01$.

Conclusion

The process model that informed this experiment postulates that representation of projective shape is preattentive and that representation of objective shape demands attention. Our construal of the representations required for successful search in SPS and SOS is that for the former, representation of projective shape is sufficient but for the latter, representation of objective shape is required. On this basis we predicted that search time would be independent of set size for SPS and positively related to set size for SOS. The results did not conform perfectly with our prediction. Nevertheless, the finding that the slopes for the two versions of the task differed significantly in the expected direction is offered as an approximate confirmation of the prediction.

We mean to take the outcome of Experiment 1 as support for the process model that inspired the experiment. Are there other ways to interpret our findings? One alternative comes to mind upon considering the dependence of visual search time on the degree of similarity among distractors and between the target and distractors (e.g., Duncan & Humphreys, 1989; Neisser, 1963; Treisman & Gormican, 1988). Duncan (1989; Duncan & Humphreys, 1989) proposed a simple rule for predicting the effect that distractors will have on search: Search difficulty increases with increasing similarity between target and distractors, and search difficulty increases as similarity among distractors decreases. Although the same *objective* shapes comprised the SOS and SPS search sets, if this two-part rule is applied to the *projective* shapes of the targets and distractors constituting the search sets in the two versions of the task (SPS and SOS), the slope differences can be predicted. Under the arrangement of SPS (all shapes frontal-parallel) there was greater dissimilarity between target projective shape (e.g., ellipse) and distractor projective shapes (e.g., circles) than under the arrangement of SOS (e.g., target and distractors all yielded elliptical projective shapes). Respecting the second part of the rule, similarity among the projective shapes of the distractors was greater for SPS (all distractors projected circles) than for SOS (diverse elliptical projections). Consequently, it may be the effects of these two types of similarity that are responsible for the observed slope differences between the SPS and SOS tasks. See Duncan's (1989, Figure 1) "search surface," which summarizes the relationship between the slope of the function relating search time to the size of the search set and the two forms of similarity.

It could be argued that the similarity account is not in fact incompatible with our interpretation. If, as our model presumes, the output of the early preattentive operations is a set of representations of projective shapes, and if in fact there is higher intraset projective similarity of representations in SOS, then the lure of distractors will be greater in SOS. An additional operation will be needed to differentiate distractors from targets, and as far as we can see the only candidate operation is the application of the algorithm that takes slant in depth and projective shape into account. And this, of course, is the story line that we are promoting.

Experiment 2

Notwithstanding the foregoing counterargument, there is only one way to rule out the similarity interpretation: We need to equate both forms of similarity across the two task versions (SOS and SPS). This was our aim in Experiment 2. In Experiment 2 the search sets for the SPS and SOS task versions were identical both with respect to objective shape and slant in depth. Consequently, the shapes comprising the search sets also presented identical sets of projective shapes. Neither differences in intradistractor similarity nor differences in target–distractor similarity were present between the task versions.

Variations in the instructions administered to the subjects were used to create two versions of the task. (Evidence that manipulating instructions can lead to selective representation of projective and objective properties is summarized by Carlson, 1977.) In a within-subject design each subject was required to search each display under two instructional sets: (a) On SOS trials the question put to the subject was, "Are all of the shapes *objectively* identical or is one objectively different?" (b) On SPS trials the question put to the subject was, "Are all of the shapes *projectively* identical or is one projectively different?"

On the basis of our model and the results of Experiment 1 we expected that the slope for SPS would be affected only minimally by set size whereas the slope for SOS would be a positive monotonic function of set size. Because only instructional variation distinguished the two task versions, there can be no recourse to similarity relations of any sort in interpreting expected slope differences.

Method

Subjects. Six volunteers served as subjects. Two of these subjects were familiar with the experimental design and the aims of the experiment. All subjects reported normal or corrected-to-normal vision.

Apparatus and stimuli. The apparatus was identical to the one used in Experiment 1. Subjects viewed three different shapes: circles, ellipses with vertical major axes, and ellipses with horizontal major axes. The circles were 2 cm in diameter. The vertical ellipses were 2 cm high and about 1.15 cm wide. The dimensions of the vertical ellipses were chosen such that the vertical ellipse when rotated in depth by 30° and the circle when rotated in depth by 60° about the vertical axis would produce the same projective shape. The horizontal ellipse was 2 cm high and about 3.46 cm wide. The horizontal ellipse when rotated by 60° produced the same projective shape as the circle when rotated in depth by 30° about the vertical axis. Multiple replicas of these shapes were constructed from thin white posterboard and mounted on flat black vertical stalks.

The displays were horizontal spatial arrangements of 2, 3, 4, or 5 shapes. All shapes were rotated about their vertical axes by either 30° or 60°. The displays were divided evenly into four types: (a) displays composed of all identical objective shapes, which also produced identical projective shapes (see Panel A of Figure 2); (b) displays composed of all identical objective shapes, but with one shape that produced an "odd" projective shape (see Panel B of Figure 2); (c) displays composed of one "odd" objective shape among identical objective distractors, with all shapes in the display producing the same projective shape (see Panel C of Figure 2); and (d) displays composed of one "odd" objective shape among identical objective distractors and one "odd" projective shape among identical projective distractors (see Panel D of Figure 2). Note that the "odd" objective shape did not need to correspond to the "odd" projective shape. The locations of the distractor shapes and of the "odd" shape were randomly selected for each trial.

Procedure. The subjects' task was to determine whether the shapes in a set were all identical or whether the set included one member that differed from the others. Subjects were instructed to press a button labeled "yes" if the set included an "odd" shape (i.e., a shape that differed from the others). A "no" button was pressed if

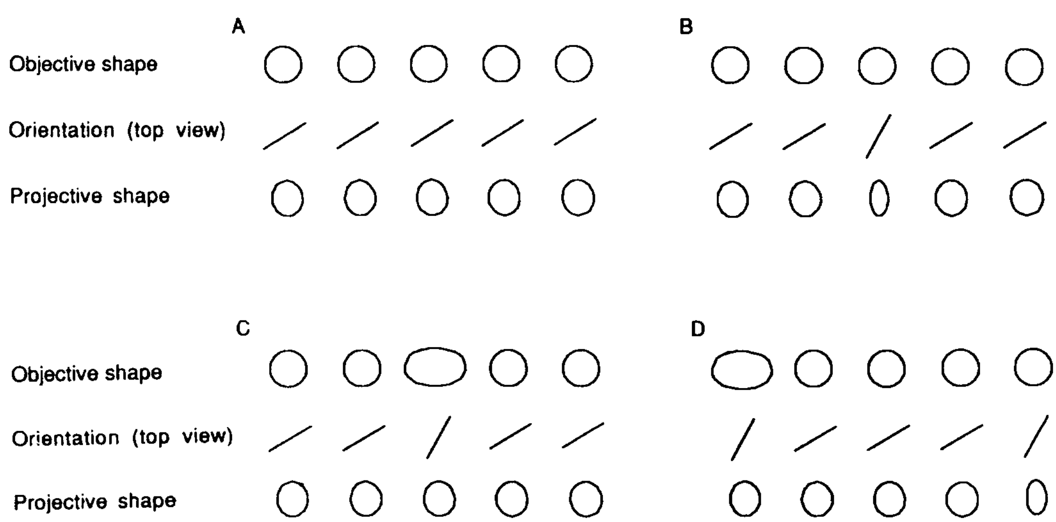

Figure 2. Examples of the four display types of Set Size 5 in Experiment 2: (A) All shapes are objectively identical and projectively identical; (B) all shapes are objectively identical, but one shape is projectively different from the others in the set; (C) one shape is objectively different from the others in the set, but all shapes are projectively identical; (D) one shape is objectively different and one shape is projectively different from the others in the set. (The top and bottom rows show the objective and projective shapes, respectively. The middle row shows a top view of each shape's orientation [rotated in depth by either 30° or 60°]. Note that examples C and D represent positive trials in search for objective shape; examples B and D represent positive trials in search for projective shape.)

all of the shapes in the set were identical. Subjects were also instructed to "respond speedily while keeping mistakes to a very low level." A warning tone sounded 1 s prior to the presentation of the display. An error tone sounded following an incorrect response. Display exposure was terminated by the subject's response.

On half of the trials (SOS), subjects were asked to consider only objective shape, disregarding projective shape. On the other half of the trials (SPS), subjects were asked to consider only projective shape, disregarding objective shape. The distinction between "objective" and "projective" shape was described fully in the instructions:

> Before I describe the procedure in detail, I need to say more about two different ways in which a shape can be described. Let's start with this shape [circle]. As you can see, the shape is a circle. Now move the shape to a different viewing angle by turning the vertical shaft. Naturally, the shape remains a circle at all viewing angles. Try the same thing with this ellipse [vertical ellipse]. And once more with this other ellipse [horizontal ellipse]. In each case, the shape remains unaffected by viewing position. I am going to call this aspect of shape: *objective shape.* If your task is to respond as speedily as possible whether all shapes in a set have the same *objective shape* or whether one differs from the rest, you would have to make sure that you have identified objective shape correctly.
>
> Next consider another aspect of the same shapes. I will call this new aspect *projective shape.* While, as we saw, objective shape is not affected by viewing angle, projective shape is affected by viewing angle. Projective shape is the shape that an objective shape projects onto your eye. Here is a simple way, invented centuries ago, to give you a direct sense of projective shape. Take the circle and hold it behind the grid painted on this sheet of glass. Notice how the objective circle projects elliptical shapes onto the grid when it is rotated from the face-on position. Next take this ellipse [horizontal]. If you rotate it slowly you will find a position where it projects a circle onto the grid. Finally, notice what happens when I place the circle and this ellipse behind the grid into predetermined positions: These two different objective shapes project identical projective shapes. Consider the grid as a substitute for your eye. The same disassociation between objective shape and projective shape occurs when the grid is removed.
>
> Now with these two types of shape descriptions in mind, I will describe two versions of the task: In one version, you will be asked to consider only objective shape, disregarding projective shape. In the other version, you will be asked to consider only projective shape, disregarding objective shape. When you are set to consider only objective shape, the question you should put to yourself is: Are all of the shapes objectively identical or is one objectively different? When you are set to consider only projective shape, the question you should put to yourself is: Are all of the shapes projectively identical or is one projectively different?

Subjects were informed of the task version (SOS or SPS) prior to each block of trials. A block of 16 trials consisted of all combinations of set size (2, 3, 4, and 5) and display type (shown in Figure 2). Trials were randomly ordered for each block. Trials with incorrect responses were repeated in a random order at the end of each block. Immediately following the initial presentation of each block of 16 trials, the task version was changed and the same 16 displays were presented again in a new random order. Consequently, identical displays were used for each task version.

Each subject participated in five 1-hr sessions. The first session consisted of 128 practice trials for each of the two task versions. Each of the four test sessions consisted of 10 blocks of 16 trials for each task version. Consequently, each subject received a total of 80 test trials at each set size for each of the two task versions.

Results

Reaction times. The lower panel of Figure 1 shows the mean RTs for each task version. The RTs were significantly longer for SOS compared to SPS, $F(1, 5) = 13.75$, $p < .05$. Averaged across positive and negative trials, searches for an odd objective shape required an additional 450 ms compared with searches for an odd projective shape. SOS trials averaged 1,102 ms ($SE = 76$), whereas SPS trials averaged 651 ms ($SE = 109$).

Also apparent in the lower panel of Figure 1 is a significant Task × Set Size interaction, $F(3, 15) = 8.36$, $p < .01$. The slopes of the functions in Figure 1 were determined by linear regression. For SOS, RTs increased by 34 and 66 ms per item for positive and negative trials, respectively. A separate analysis of the SOS trials revealed a significant set size effect, $F(3, 15) = 20.73$, $p < .001$, and a significant Set Size × Target Presence interaction, $F(3, 15) = 3.44$, $p < .05$. The slope ratio between negative and positive searches for SOS was approximately 2:1. In contrast, the slopes for SPS were quite shallow, 12.2 and 4.9 ms per item for positive and negative trials, respectively. A separate analysis of the SPS trials showed no significant effect of set size ($F < 1$).

Error rates. Error rates did not differ significantly for the two task versions. Error rates during searches for an odd objective shape averaged 11.3%. Searches for an odd projective shape yielded an average error rate of 5.9%. Errors occurred slightly more frequently during positive searches (9.9%) than during negative searches (7.3%), $F(1, 5) = 8.36$, $p < .05$. There were no other significant main effects or interactions involving the error data.

Conclusion

The results of Experiments 1 and 2 showed significant differences between the effects of set size on searching for objective and projective shape. The design of Experiment 2 rules out a similarity-based interpretation of the principal findings. Also ruled out is an interpretation that attributes the difference between SPS and SOS in Experiment 1 to the fact that the shapes in SPS were all frontal-parallel whereas the shapes in SOS were rotated in depth. It might be argued that in Experiment 1 search was for objective shape for both task versions but that objective shape was more difficult to resolve when the shapes were rotated in depth. Because in Experiment 2 the shapes were rotated in depth to the same degree for both task versions, this account of our results cannot be sustained.

Admittedly the results did not conform in all details to the expectations of the model. Thus in Experiment 1 the slope for SPS, albeit shallow, was significantly greater than zero. This discrepancy from the prediction of the model did not recur in Experiment 2. We can offer no sure reconciliation of these results.

Differential Effects of Precuing

When a target may be presented at one of several locations, advance knowledge in the form of a cue that specifies the location of the to-be-presented target often facilitates detection and identification of the target (Bashinski & Bacharach, 1980; Downing, 1988; Eriksen & Hoffman, 1973; Eriksen & Yeh, 1985; Krose & Julesz, 1989; Posner, 1980; Posner, Snyder, & Davidson, 1980; Tsal, 1983). A complementary finding is that if the precue specifies a location other than the correct location, performance will be retarded (Downing & Pinker, 1985; Posner et al., 1980; Shulman, Remington, & McLean, 1979). These effects may be assessed by comparing performance under the valid and invalid cue conditions directly or by comparing each of the two cue conditions to a no-cue condition or an uninformative (neutral) cue condition (Jonides & Mack, 1984).

The effects of precuing, costs as well as benefits, are taken to be manifestations of attentional processes. For the moment, consider only the case of the benefit conferred by precuing the location of a target that is accompanied by nontargets (distractors) in other locations. The benefit—for example, speedier identification—is widely held to result from selective attention to the cued location. In a resource allocation model of attention the benefit is due to selective allocation of processing resources to evaluation of the contents of the cued location or to the assignment of priority to the processing of the contents of the cued location.

This interpretation of the precuing effect implies that precuing effects should be observed exclusively for discriminations that require allocation of attention for their execution. If a discrimination can be carried out preattentively, then precuing should confer no advantage over a no-cue or a neutral-cue condition. The results of two experiments (Treisman, 1985, pp. 160–161, and Nakayama & Mackeben, 1989, Experiment 1) are consistent with this prediction. In both experiments cuing effects obtained in conjunction search were not observed in feature search. On the assumptions of feature integration theory (Treisman & Gelade, 1980; Treisman & Gormican, 1988) that detection of features is automatic whereas detection of conjunctions of features requires attention, precuing benefits should be confined to conjunction search.

In Experiments 3 and 4 we examined the effects of precuing on the detection of shape in 3D space. Given the results for the SPS and SOS search tasks in Experiments 1 and 2 and the general interpretation of the effect of cuing, we expected to find that cuing would affect performance on SPS and SOS tasks differently. The effect of precuing should be entirely or largely confined to search under the SOS condition. Inasmuch as under the SPS condition representation of projective shape is sufficient for detection of the target, and because, by hypothesis, representation of projective shape is preattentive, precuing should confer no advantage. In Experiment 3 we tested this prediction by comparing performance under valid-cue, invalid-cue, and neutral-cue conditions.

Experiment 3

Method

Subjects. Three volunteers served as subjects. Each subject had previous experience with the task. In addition, 2 of the subjects were familiar with the experimental design and the aims of the experiment.

Apparatus and stimuli. The apparatus was identical to the one used in Experiments 1 and 2. Subjects viewed two different shapes: circles and ellipses. The physical dimensions of these shapes were identical to those of the circle and the ellipse used in Experiment 1. The circle when rotated in depth by 60° produced the same projective shape as the ellipse when rotated by 30° about the vertical axis.

The displays were horizontal spatial arrangements of five shapes. On negative search trials, all five shapes were circles. On positive search trials, an ellipse was present among four circles. Positive and negative trials occurred equally often. In addition, the target shape, the ellipse, appeared equally often in each of the five display locations.

On half of the trials, a small equilateral triangle (1.5 cm high) was presented for 100 ms immediately prior to the appearance of the display. The triangle served as a precue for the special location of the target. The target appeared in the cued location on 75% of the positive trials (valid-cue condition). On the remaining 25% of the positive trials, the target appeared in a location other than the one precued (invalid-cue condition). The locations of the target and the invalid precue were equally distributed among the five display locations. On the other half of the trials, a neutral (uninformative) precue appeared for 100 ms immediately prior to the appearance of the display. The neutral precue consisted of five triangles occupying the five possible target locations.

Two task versions were used. For the SPS version, targets and distractors were all oriented in the frontal-parallel plane. For the SOS version, the target was always rotated in depth by 30° about its vertical axis and the distractors were rotated in depth by either 30° or 60°. The distractors were assigned evenly to the two orientations.

Procedure. The subject's task was to examine each display for the presence of an ellipse. One second after a warning tone, a visual precue appeared for 100 ms immediately prior to the appearance of the display. The display itself remained visible until the subject responded by pressing one of two buttons. Subjects were instructed to respond as quickly as possible without sacrificing accuracy. An error tone sounded following all incorrect responses. Subjects participated in four 1-hr sessions, each comprising 160 trials. Each session used one of the two task versions, SPS or SOS, with either all neutral cues or all valid and invalid cues. Subjects were informed of the task version and the cue condition prior to each session. The order of the four sessions was randomly determined for each subject.

Each session consisted of 80 negative (target not present) and 80 positive (target present) trials. For those two sessions with valid and invalid cues, the target appeared in the cued location on 75% of the positive trials and in a noncued location on the remaining positive trials. Subjects were informed about the proportion of valid and invalid cues and were instructed to attend to the precue on all trials. The 160 trials were randomly ordered for presentation prior to each session. Trials with incorrect responses or RTs outside the accepted range (100–1,500 ms) were repeated in a random order after every block of 27 trials. No trial was repeated more than once.

Results

Panels A and B in Figure 3 show the mean RTs for the SPS and SOS task versions under the three cuing conditions for positive and negative trials, respectively. Data for individual subjects were plotted separately. Each individual data plot was a close approximation of the aggregate averages shown in Figure 3, Panels A and B. Examination of Panel A reveals that both costs and benefits were observed for the positive trials. No cuing effects were observed for the negative trials (Panel B). In light of the large main effect of task version on RT, the magnitudes of the costs and benefits for the positive

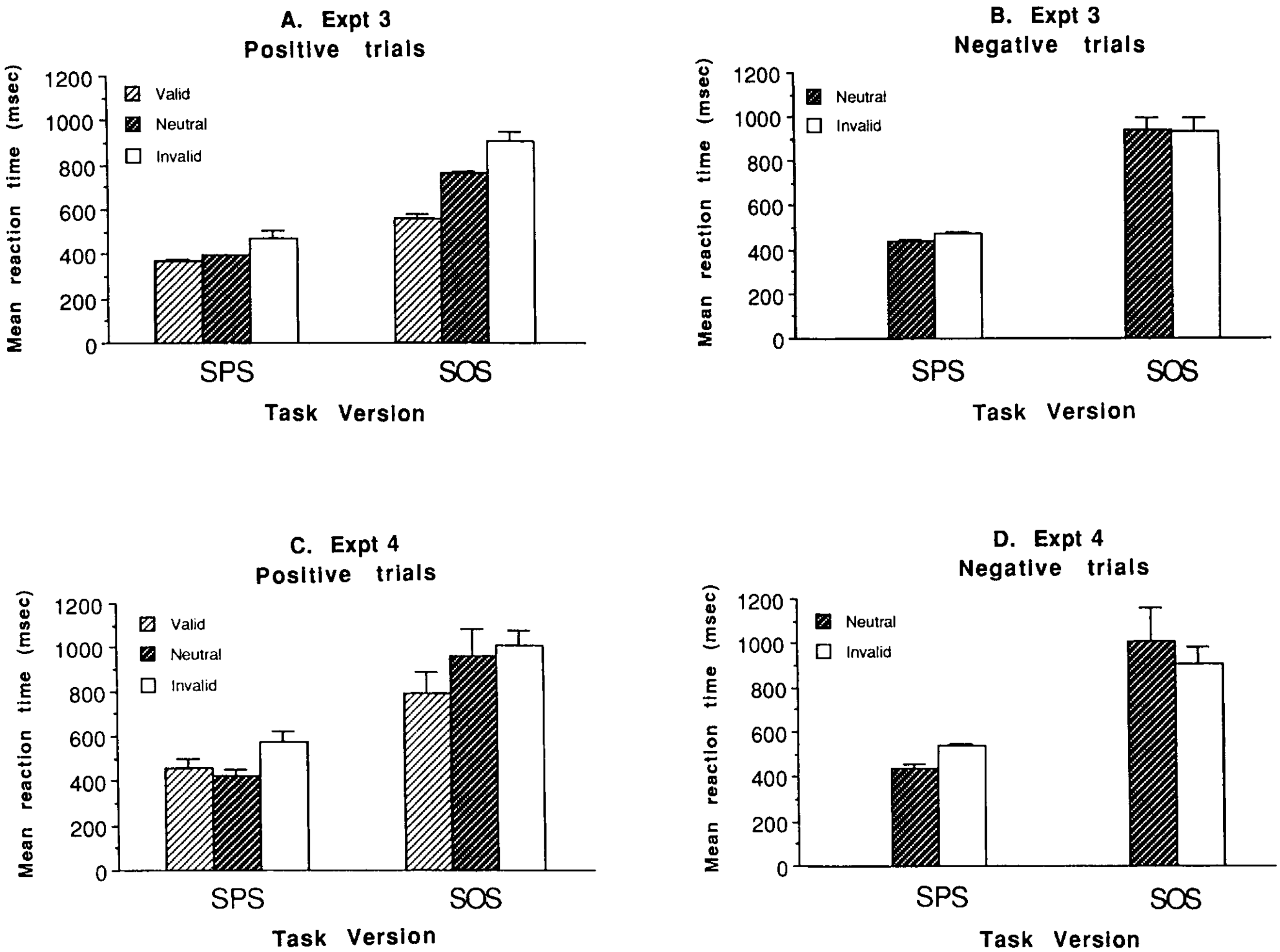

Figure 3. Mean reaction time for valid- , neutral- , and invalid-cue conditions for search for projective shape (SPS) and search for objective shape (SOS) task versions for (A) positive trials in Experiment 3, (B) negative trials in Experiment 3, (C) positive trials in Experiment 4, and (D) negative trials in Experiment 4. (On positive trials, an invalid cue designated one location and the target occupied a different location. On negative trials, an invalid cue designated a location although no target was present at any location. Error bars represent 1 mean standard error.)

trials were assessed by computing two ratios: benefit = (neutral-cue RT − valid-cue RT)/neutral-cue RT; cost = (neutral-cue RT − invalid-cue RT)/neutral-cue RT. The costs and benefits calculated in this way are presented in the upper half of Table 1. The benefit conferred by the valid precue was substantial for SOS but only negligible for SPS. The cost incurred by the invalid cue was substantial and of equal magnitude for the two task versions.

Experiment 4

In evaluating the results of Experiment 1 we considered a rival interpretation based on differential similarity among distractors and between target and distractors under the two task conditions. The same interpretation can be developed for the results of Experiment 3. We conducted Experiment 4 to assess the similarity interpretation. As was the case for Experiment 2, the SOS and SPS tasks were distinguished only by the instructions that defined the target. Inasmuch as the actual displays were identical in every respect for both tasks, differential effects of precuing of the kind observed in Experiment 3 cannot yield to an interpretation based on differential similarity.

Method

Subjects. Three volunteers served as subjects. Two of the subjects also participated in Experiments 2 and 3 and were familiar with the experimental design and the aims of the experiment. The 3rd subject was also highly practiced with the task.

Apparatus and stimuli. The apparatus was identical to the one used in the prior experiments. Subjects viewed the same three shapes used in Experiment 2: circles, vertical ellipses, and horizontal ellipses. The displays were identical to the displays of Set Size 5 used in

Table 1
Costs and Benefits in Experiments 3 and 4

Task version	Positive trials: Benefit [(N − V)/N]	Positive trials: Cost [(N − INV)/N]	Negative trials: Cost [(N − INV)/N]
		Experiment 3	
SOS	.27	−.18	.00
SPS	.07	−.19	−.07
		Experiment 4	
SOS	.18	−.05	.10
SPS	−.08	−.36	−.23

Note. SOS = search for objective shape; SPS = search for projective shape; N = neutral-cue reaction time; V = valid-cue reaction time; INV = invalid-cue reaction time.

Experiment 2. The precues were identical in all aspects to those used in Experiment 3.

Procedure. The subjects' task was identical to that in Experiment 2, with the additional instruction to attend to the precue. Subjects were informed of the task version, SOS or SPS, prior to each block of trials. A block of 16 trials consisted of four instances of each display type used in Experiment 2 (see Figure 2). Trials were randomly ordered for each block. Trials with incorrect responses were repeated in a random order at the end of each block. Immediately following the initial presentation of each block of 16 trials, the task version was changed and the same 16 displays were presented again in a new random order. Consequently, identical displays were used for each task version.

Each subject received 18 blocks of 16 trials for each task version. Nine of these blocks used valid and invalid precues. The other nine blocks used neutral precues. Practice consisted of four blocks of trials, one block for each combination of task version (SOS and SPS) and precue type (valid/invalid and neutral).

Results

Panels C and D of Figure 3 show the mean RTs for the SPS and SOS task versions under the three cuing conditions. Data for individual subjects were plotted separately. Each individual data plot was a close approximation of the aggregate averages shown in Panels C and D. Costs and benefits of the precues are shown in Panel C of Figure 3 for positive trials and in Panel D of Figure 3 for negative trials. The magnitudes of the costs and benefits of the precues were assessed by computing two ratios: benefit = (neutral-cue RT − valid-cue RT)/neutral-cue RT; cost = (neutral-cue RT − invalid-cue RT)/neutral-cue RT. The computed ratios are presented in the lower half of Table 1.

The valid precue produced no benefit during searches for an "odd" projective shape (SPS). In fact, search times were actually hindered somewhat by the presence of the valid precue during SPS trials. In contrast, searches for an "odd" objective shape (SOS) were aided substantially by the valid precue. The costs incurred by the invalid precue for the SPS task were quite substantial. Invalid precues did not produce sizable costs during SOS trials.

Conclusion

The fact that the benefit of precuing was confined largely to SOS is compatible with the model of processing shape at a slant that motivated the precuing experiments. The cost for SOS, although smaller than expected, also conformed to the model. However, the costs associated with the invalid cue for SPS were unexpected. The reasoning that led to the prediction that the valid cue would not confer benefit for SPS also led to the complementary prediction that no cost would be observed for SPS.

Why were costs observed in the absence of benefit for SPS? Paradoxically, the costs may be traced to the automaticity of the representation of projective shape. The automatic representation ("popout") of the target on SPS trials, coupled with the focusing of attention on a nontarget on the invalid-cue trials, may have generated a condition of response conflict and a consequent lengthening of RT. Although the subjects were informed that the precue would be valid on only 75% of the trials, they were encouraged to treat every cue as a valid cue rather than attempt to guess the true nature of the cue. As a result, a strong tendency to respond on the basis of the contents of the cued location was set up. On invalid-cue trials this response tendency had to be suppressed in favor of a response based on the noncued target. A "no" response had to be suppressed in favor of a "yes" response, leading to longer RT. In summary, we propose that the cost obtained for the SPS task may be attributed to the postperceptual response stage.

General Discussion

The view that achievement of an object-centered representation of shape is the product of a sequence of operations has a long history (see Epstein, 1977, chap. 1). In the current experiments, as well as in the earlier studies in this series, we set out to identify the attentional properties of the component operations. Our hypothesis proposes that the early operations that lead to representation of projective shape and representation of slant in depth are preattentive and that the operations that combine these representations are attentional. In a general sense, this hypothesis resembles other hypotheses concerning the role of attention in perception. Examples are Treisman's (1985; Treisman & Gelade, 1980; Treisman & Gormican, 1988) feature integration theory, Julesz's (1986) texton theory, and Rock's (Rock & Gutman, 1981; Rock & Nijhawan, 1989) analysis of the contribution of attention to form perception. In each case a sequential process of representational transformation is proposed, and the early representations are presumed to be the outputs of preattentive operations.

The present results, combined with the findings of our earlier studies summarized in the introduction, fit well with our hypothesis. Although individual findings may have alternative interpretations, our attentional hypothesis can accommodate all of our findings (Epstein & Babler, 1989, 1990; Epstein & Lovitts, 1985) without strain.

The model of processing shape at a slant is one instance of a general approach that characterizes the perceptual process as integrating early representations according to computational rules or algorithms designed to achieve distally correlated percepts. A summary of this general approach and an examination of many of its applications may be found in Epstein (1973, 1977). Familiar applications are the analysis of the perception of properties linked to retinal correlates that are moderated by viewing distance. Perception of size is prototypical. Perceived size is presumed to be the product of an integration of a representation of projective size and a representation of viewing distance. Using the withdrawal-of-attention paradigm, Epstein and Broota (1986) assessed the attentional demands of the putative preattentive operations, representing projective size and distance, and the putative attentive operation, combining these representations to generate an object-centered description of size. Epstein and Broota (1986) found that when attention is withdrawn from processing size at a distance, perceived size tends to covary with projective size rather than with objective size. Inasmuch as the standard account of perceiving size at a distance is analogous to the account of perceiving shape at a slant, one would expect the attentional demands of the two processes to be similarly distributed.

This expectation can be extended to any of the perceptual attainments that are taken to involve "taking-into-account" compensation, or recalibration for viewing distance. Two examples are stereoscopic depth and motion parallax depth. In both cases there is evidence (e.g., Wallach & Zuckerman, 1963, for stereoscopic depth; Ono, Rivest, & Ono, 1986, for motion parallax depth) that a combinatorial process, combining disparity and distance or combining relative optical displacement and distance, underlies perception. In fact, all four of these cases—shape, size, stereoscopic depth, and motion parallax depth—are formally alike. For this reason, an analysis that holds for one of the cases, such as shape at a slant, can reasonably be expected to hold for the others.

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