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Control of Attention Around the Fovea

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Three experiments tested young adults' abilities to use size and location cues to find and identify a target letter in a visual field containing 8 to 12 letters. Location cues (relatively near to or far from the fovea) and size cues (relatively large or small) were given before the display. Compared with response times on neutral, no-cue trials, location and size cues produced independent cost and benefit effects. The best fitting quantitative models allow attentional resources to be distributed in ringlike areas varying in distance from the fixation point, within which further selection of items by their relative size is possible.

Visual selective attention is usually manifested by a tendency to fixate that which captures attention. However, attention and fixation are not perfectly correlated, because attention is drawn to salient environmental features, such as abrupt change, motion, and contrast visible in parafoveal and peripheral vision. By this argument, the point of fixation might well represent the result of attentional processes rather than the current locus of attention.

The distinction between line of sight and orientation of attention has been made since the beginnings of experimental psychology (see Helmholtz, 1911; James, 1890; and Wundt, 1903; and discussions from historical points of view by Grindley & Townsend, 1968; Posner, 1980; and Shiffrin, 1988). In the laboratory, attention can be directed by a cue to prepare subjects for a stimulus that might occur in a specific part of the visual field. Cues that reduce or eliminate positional uncertainty have been shown to improve stimulus detection (Bashinski & Bacharach, 1980; Engel, 1971; see also Smith & Blaha, as cited in Posner, Snyder, & Davidson, 1980), stimulus identification (Egly & Homa, 1984; van der Heijden, Schreuder, & Wolters, 1985), simple and choice reaction times (Eriksen & Yeh, 1985; Posner, Nissen, & Ogden, 1978; Posner et al., 1980), naming latencies (Eriksen & Hoffman, 1972), and stimulus localization (Egly & Homa, 1984). It has been hypothesized that a spatial cue energizes an "attentional spotlight" or "zoom lens" that can be moved about the retinal image independently of the point of fixation to select regions for enhanced processing (Eriksen & St. James, 1986; Posner et al., 1980; Tsal, 1983).

One question to be addressed is whether attention can be allocated to multiple or broadly defined regions around the fixation point, or whether it necessarily is focused on relatively narrow regions of the visual field. Several researchers have examined the effects of multiple or general spatial cues provided before stimulus onset to determine whether such cues can result in benefits in signal processing compared with a no-cue control. For example, Shaw and Shaw (1977) found that letter identification was enhanced when the number of possible letter positions was reduced from eight to two along a circular array. This enhancement could have been due either to parallel allocation of attention to the disparate locations or to alternate allocation over trials to one or the other of the expected positions. Posner et al. (1980) and Eriksen and Yeh (1985) rejected the notion of multiple foci of attention because they found benefits only for a primary spatial cue and failed to find any advantage for stimuli occurring in the second most likely stimulus location. Thus, the evidence does not favor an ability to split or divide attention over several positions in space; rather, like a spotlight beam, it appears that attention is usually directed to some focal point or region of interest. Stimuli presented at or near this point are processed more efficiently, resulting in benefits in speed or accuracy as opposed to a no-cue control condition. Stimuli presented away from the cued position generally incur costs, such that performance is inferior to that obtained without cues. It is as though attention is a limited-capacity resource: Its concentration in any one area produces local benefits along with costs

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elsewhere across the field of view, whereas in a no-cue condition attention is presumably dispersed more uniformly (e.g., Jonides, 1980, 1983).

If multiple foci of attention are unlikely modes of distribution over the field, then it remains to be determined whether attention must be concentrated around a single focus, as in the spotlight metaphor, or whether it can be spread over a more general area at will. Posner et al. (1980) demonstrated that attention could be extended over several degrees of visual angle along a horizontal array to facilitate responses to stimuli at either of two adjacent locations. Similarly, LaBerge (1983) induced subjects to attend either to a central letter or to all items in a five-letter array. Responses to an occasional probe digit indicated that attention behaved like a zoom lens that could be adjusted to encompass either a single letter or the entire five-letter string. Even larger fields of attentional distribution have been reported by Hughes and Zimba (1985) in a simple reaction time task. They found a general, but weak, facilitation extending over the cued hemifield and an inhibition of responses for stimuli presented in the noncued hemifield.

Egly and Homa (1984) also demonstrated that attention can be directed to general areas in the visual field. They used concentric rings of either 1°, 2°, or 3° in radius around the fixation point, along each of which a single letter could occur. With only relative distance cued (close, medium, or distant), a letter was identified more accurately when the ring containing it was cued in advance than when no cue was given. In a subsequent experiment, in which subjects had to indicate which position in the ring was occupied by a single letter, both costs for invalid cues and benefits for valid cues of distance from fixation were found. Similar results were reported by Sperling and Melchner (1978), who had subjects detect numeral targets embedded in letter arrays. The arrays consisted of 4 inner characters and 16 outer characters arranged into boxes centered on the fixation point. Instructions to attend to the inner or outer box increased subjects' detection accuracy for the attended box and decreased accuracy for the nonattended box in relation to a neutral, equal-attention condition.

Whereas results such as LaBerge's (1983) suggest that attention can be expanded or contracted like the field of a zoom lens, Egly and Homa (1984) argued that even more control than mere expansion and contraction can be exhibited. Specifically, their data suggested that subjects could attend to ringlike regions of probable stimulus location, and the diameter of the ring could be adjusted according to the cue. Some difficulties exist in interpreting Egly and Homa's data, because their measure of localization produced error rates of about 50% overall. Furthermore, if subjects used the cues to guide their guesses when they failed to detect the target, they would have increased their probability of being correct on valid cue trials and decreased this probability after invalid cues, thus exaggerating the costs–benefits effect. To correct some of these problems, Juola, Crouch, and Cocklin (1987) used distance cues in a choice reaction time task. They cued target distance by indicating that a letter could occur either inside or outside a circle of 1° radius. Although the costs–benefits analysis indicated that subjects could use the cues to attend selectively to internal or external regions around the circle, the results were not compelling in discriminating between the zoom lens and ring models.

The preceding review has emphasized various spatial analogies that have been used to represent the concept of visual attention. Most of these have viewed attention as moving through space, either expanding or contracting like the field of view of a zoom lens or moving from one relatively narrow focus to another, much as a spotlight is panned across a background scene (e.g., see Eriksen & St. James, 1986; Eriksen & Yeh, 1985; Tsal, 1983; for alternative views see also Eriksen & Murphy, 1987; Murphy & Eriksen, 1987; Yantis, 1988). The ring model of attention is an example of a class of models that allows for flexible allocation of processing resources to broad regions of somewhat arbitrary size and shape. These models are not specific, however, about whether the attended area is energized equally (i.e., resources are distributed uniformly) or whether, in fact, a narrow spotlight examines items successively while following a more or less continuous path within the attended region. The latter alternative even calls into question the uniquely spatial nature of visual attention, because, if attention can be modeled as the sequential selection of items from a display, there is no a priori reason for location to be the sole basis for this selection. Although location might in some sense be special as an attentional cue (e.g., Nissen, 1985; Tsal & Lavie, 1988), there is no reason that other discriminative cues, such as color, size, orientation, or form, could not also be used to select items for enhanced processing (as in the idea that focal attention follows an initial, preattentive search for items to be processed; Broadbent, 1958; Neisser, 1967). Perhaps the spatial metaphors of zoom lenses and spotlights are generally inappropriate for capturing the full capabilities of attention, as Duncan (1981, 1984) has suggested. Indeed, if there is some feature such as location, color, or size that distinguishes potential targets from other items in the field, it is possible that this feature can be used to eliminate distractors from consideration in an early, perhaps parallel stage of processing, and focal attention can then be confined to a relevant set of items (Duncan & Humphreys, 1989; Egeth, Virzi, & Garbart, 1984; Wolfe, Cave, & Franzel, 1989). We return to discussing these issues after analyzing the results of the present studies, which were designed to determine how attention is allocated in response to spatial and other discriminative cues.

The present series of experiments was developed to provide a clearer test of whether subjects can direct their attention to relatively large regions of the parafoveal field, and, if so, whether the spotlight, zoom lens, or some other more flexible resource allocation model provides the best analogy for attentional distribution. In the first experiment, displays included 12 letters distributed over three rings of varying distance from a central fixation point. We presented distance cues rather than specific location cues to determine what kind of control subjects could exercise over the distribution of their attentional resources. Experiments 2 and 3 were designed to test the influence of other stimulus properties, particularly relative letter size, as alternative explanations for the results of the first experiment. Together, the results support the notion that subjects can allocate attention to regions of various sizes and shapes, such as ringlike areas around the fixation point, in anticipation of stimuli occurring in these areas. Although location appears to be a particularly salient dimension to use in preparation for processing a display, other stimulus dimensions, such as relative element size, can also affect selective aspects of attention.

Experiment 1

As in Egly and Homa's (1984) study, we used three concentric rings for stimulus locations in order to provide more opportunities to test the models than were available in the Juola et al. (1987) study. The same task was used as in Juola et al.'s study, but we made the displays more complex by adding a number of noise characters to the display to strengthen the attention manipulation. As Posner (1980) had argued and Grindley and Townsend (1968) had demonstrated, a single stimulus in an otherwise empty field can rapidly and automatically attract the focus of attention, thus minimizing the effects of prior cues. Because only a single letter was used in each display in Juola et al.'s study, it is somewhat remarkable that costs and benefits were demonstrated at all. The goal of Experiment 1 is to replicate and extend our earlier findings, as well as those of Egly and Homa, and to provide more sensitive tests of how attention is directed out from the fovea.

Method

Subjects. The subjects were 8 male and 3 female volunteers who ranged in age from 20 to 43 years. They included students at the Eindhoven University of Technology, research staff at the Institute for Perception Research, and other members of the university community. All had normal or corrected-to-normal vision.

Apparatus and materials. The stimuli were presented in a two-field tachistoscope interfaced with a microcomputer and millisecond timer. The first field was used only for presentation of a fixation dot, and two circles centered on this point. The field was white, with a luminance of 130 cd/m^2, and the circles were drawn with a compass and pencil to appear as thin, gray lines. The inner circle had a radius of 0.9 cm, and the outer circle had a radius of 1.9 cm. From the subject's viewing distance of about 59 cm, each centimeter of lateral extent in the visual field corresponded almost exactly to 1° of visual angle.

We used a second field of equal luminance to present 24 different stimuli. Each of these consisted of 12 letters, which were arranged into an X pattern in such a way that 4 letters fell near the foveal fixation dot and within the inner circle, 4 letters fell between the two circles, and 4 letters fell outside the outer circle. The letters were all uppercase Xs, except for a single upper case R or L that could occupy any of the 12 positions.

As shown in Figure 1, letter size was increased with distance from the fixation dot in an attempt to trade off increases in size with decreases in parafoveal acuity (e.g., due to the cortical magnification factor). The distance from the fixation point to the center of any letter in the three respective circles was about 0.35 cm, 1.25 cm, and 2.85 cm, and the heights of the letters in the three respective rings were 0.4 cm, 0.6 cm, and 0.8 cm. We based these sizes on pilot data indicating that letter size needs to be increased linearly with distance from fixation (over the range used here) in order for perceptibility to be held fairly constant. In one pilot study, 9 subjects participated in about 300 trials each, in which the task was simply to name the unique letter (R or L) that appeared in each display. Errors were very infrequent (about 0.3%), and mean naming latencies did not differ significantly among small, inner letters (477 ms), intermediate, middle letters (470 ms), and large, outer letters (466 ms). Thus the letters were all of equivalent visibility over the range of size and eccentricity used here.

The letters were dry transfer applications onto white paper rolls, which were used for subsequent presentation in the tachistoscope. One role of 24 different configurations was made for practice trials, and three rolls of 48 displays each were made for the experimental sessions. Each experimental roll included two different random sequences of the 24 possible stimulus configurations. Each roll was then paired with two different lists of cues, which indicated that the critical letter (R or L) could occur inside the inner circle, in the middle of the two circles, or outside the outer circle. Alternatively, the neutral cue *ready* was used to indicate that all locations were equally likely. For each roll, the cues were randomly assigned to the stimuli with the constraints that 8 of the trials were no-cue (ready) trials, 32 trials had valid cues of the critical letter's distance from fixation, and 8 trials had invalid distance cues. We introduced a further constraint to balance the assignment of cues to stimuli to use all 24 display types approximately equally often in all cue conditions. Finally, the two types of invalid cues for each display were balanced in occurrence frequency (e.g., if the critical letter occurred in the inner ring, either of the invalid middle or outside cues could be given on different trials).

Procedure. The subjects were run individually in two or three sessions on separate days for a total time of about 2.5 hr. They were instructed that on each trial a single critical letter, an R or an L, would be included in the display, and they were to press a response key with the left hand if an L appeared and a different key with the right hand if an R appeared. We told subjects that on most trials a verbal cue would indicate whether the critical letter was likely to appear within the inner circle, between the two circles, or outside the outer circle, and we informed them that the location cues would be valid 80% of the time and that ready cues would precede trials on which the critical letter could occur in any of the 12 positions. The session then began with 24 practice trials and four runs through each of the three 48-trial experimental rolls, half with each instruction set. There was a short break every 48 trials while the rolls were changed, and, whenever the session was continued on a subsequent day, the 24-trial practice roll was used first. Each subject contributed a total of 576 observations, of which 96 were from neutral cue ready trials, 384 from valid distance cue trials, and 96 from invalid cue trials.

The subjects were instructed to begin each trial by looking into the tachistoscope and fixating the central dot within the two concentric circles. The experimenter than said "inside," "middle," "outside," or "ready" to cue the probable location of the critical letter or to prepare the subject for the onset of the display in the absence of a distance cue. Immediately after giving the cue, the experimenter initiated the trial sequence, which included a 2-s presentation of the fixation dot and circles, followed by a 150-ms exposure of the display containing 11 Xs and one critical letter. The first field then reappeared for about 10 s while the roll was advanced in preparation for the next trial. We instructed subjects to maintain fixation on the central dot throughout the trial but to attempt to focus attention inside, between, or outside of the two circles in the respective cue conditions, or to attend uniformly over the field in the no-cue condition. We pointed out that eye movements were likely to be harmful, because regardless of which cue was given, the directional uncertainty of the critical letter remained the same and an eye movement in the wrong direction was likely to result in failure to see the critical letter. The subjects were instructed to depress the appropriate right- or left-hand key as rapidly as possible in response to the corresponding critical letter while being

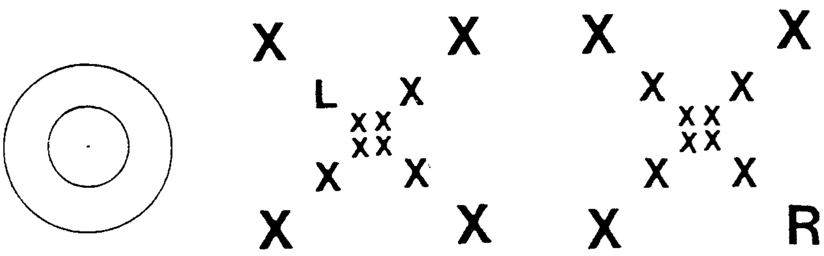

Figure 1. Relative sizes of the preexposure field, consisting of a central fixation dot with two surrounding circles, and two example displays from Experiment 1.

careful to avoid errors. Mean response times were measured from the onset of the 12-letter display until one of the response keys was depressed.

Results

Response time data. Mean response times were found for each cell of a 3 × 4 within-subject design. The variables were stimulus location (inside the inner circle, between the two circles, or outside the outer circle) and prestimulus cue (ready, inside, middle, or outside). Individual subjects' observations were discarded as outliers if they fell below 200 ms or were more than twice the mean of their cell when they were excluded; fewer than 0.3% of the data were so discarded. The means of the mean response times across subjects are shown in Figure 2, and they were subjected to an analysis of variance (ANOVA). The analysis found significant main effects of stimulus location, $F(2, 20) = 17.8$, $p < .001$, and cue condition, $F(3, 30) = 10.9$, $p < .001$, as well as a significant interaction of these two factors, $F(6, 60) = 30.5$, $p < .001$.

In all cases, responses were faster for trials with valid distance cues than for trials with invalid cues, and the response times for uncued (ready) trials fell between those for valid and invalid cues. These results are shown in a costs–benefits analysis (see Table 1). In general, if a cue has no effect, the difference between mean response times on cued and noncued trials will be about zero. However, if the cues are effective in influencing attention-based responses, valid cues should produce a positive difference when the mean for cued trials is subtracted from that for uncued trials, whereas invalid cues should produce a negative difference. The obtained values are shown in Table 1. All benefits for valid cues were significant in the response time data at $p < .01$, except for the marginally significant benefit for valid middle cues: benefit = 17 ms, $F(1, 10) = 3.8$, $p < .08$. Similarly, all costs, except for the −28-ms cost for invalid middle cues for inside letters, were significant beyond the .01 level.

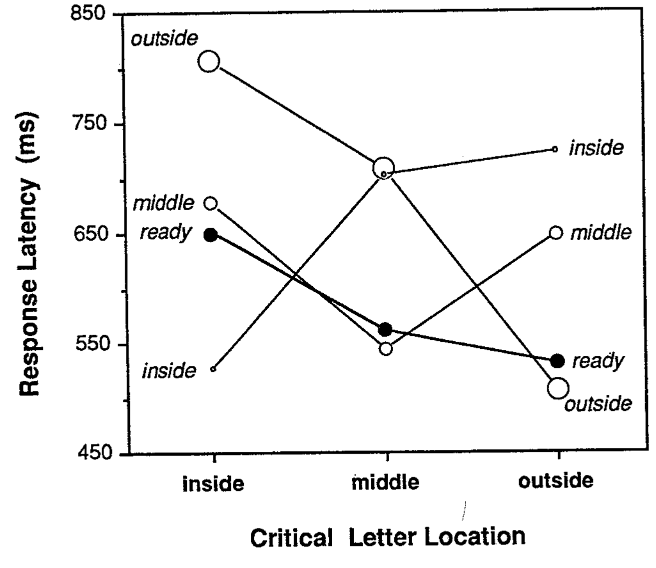

Figure 2. Mean response times plotted against critical letter location for the four different cue conditions. (The labels within the figure refer to the location cues given, whereas the labels along the abscissa refer to the actual location of the critical letter [Experiment 1].)

It is perhaps surprising that the response times in the neutral, ready cue condition showed a decrease from the inner letters (651 ms) to the middle (561 ms) and outer (532 ms) letters, $F(2, 20) = 13.6$, $p < .001$. This effect could be due to differential lateral masking or acuity effects favoring the larger, outer letters that have fewer close contours with which to interact. However, it is more likely that this effect is also attentional, as Posner (1980, p. 8) has suggested: When subjects "... are not told if the stimulus will be a peripheral or a central one, they uniformly prepare for the peripheral stimulus.... Their strategy assumes that the fovea will take care of itself." This attentional explanation for the disadvantage for inner stimuli in the neutral cue condition is supported by the result that when attention was directed to the relevant distance from fixation by valid cues, mean response times were 528, 544, and 507 ms for the inner, middle, and outer letters, respectively.

Error data. The overall error rate was 7.9%, and the mean proportions of errors per cell of the design were submitted to the same analysis as that used for the response time data. The analysis found significant main effects for stimulus location, $F(2, 20) = 11.0$, $p < .001$, prestimulus cue, $F(3, 30) = 9.0$, $p < .001$, and their interaction, $F(6, 60) = 9.7$, $p < .001$. The data are presented in Figure 3, and the costs–benefits analyses of the error data are included in Table 1.

In general, parallel trends are observed in the error and response time data, although the effects are perhaps not as strong overall in the error rates. As shown in Table 1, significant benefits were found in the error data only for valid inside cues, and significant costs were found only for invalid

Table 1

Benefits for Valid Cues and Costs for Invalid Cues in the Response Time (in ms) and Error Data (in Percentage of Incorrect Responses) From Experiment 1

	Stimulus location		
Cue	Inside	Middle	Outside
Inside			
Response time	123*	−142*	−192*
% errors	5.9*	−3.2	−2.0
Middle			
Response time	−28	17	−116*
% errors	(0.6)	(−1.3)	(0.3)
Outside			
Response time	−155*	−148*	25*
% errors	−14.3*	−10.1*	2.3

Note. Benefits fall along the main diagonal and should have positive values; costs fall off the diagonal and should be negative. Values in parentheses are positive costs or negative benefits.
$^{*}p < .01$.

outside cues. The parallel trends for both the response time and error data limit the viability of most competing explanations of the results based on differential speed–accuracy trade-offs across conditions.

Discussion

Can attention be directed to a general area rather than to a relatively narrow focus? The present results (along with those of, e.g., Egly & Homa, 1984; Hughes & Zimba, 1985; Juola et al., 1987; LaBerge, 1983; Sperling & Melchner, 1978) provide an affirmative answer. Attention can be distributed over a general area of the visual field in such a way that stimuli occurring within the cued region are responded to more rapidly and accurately than those occurring in noncued regions. In Experiment 1, both significant benefits of valid cues and significant costs of invalid cues were found in relation to the uncued condition. Given that attention can be directed toward regions that are defined in relation to a pair of circles concentric around the fixation point, the question remains as to whether the best model of attentional distribution follows the assumption that (a) attention spreads out from the foveal region, as the field of a "zoom lens" is expanded; (b) attention is distributed over regions of specific sizes and shapes, such as in rings around the fovea; or (c) attention is focused in a narrow "spotlight" that essentially examines items one at a time while following a path influenced by location cues. Implicit in this distinction among models is the assumption that when attentional resources are concentrated in specific regions in advance of the display, as in the ring model, items within the attended region are processed simultaneously, whereas the spotlight model is a serial scanning model. We will first compare the zoom lens and ring models, and then we discuss the alternative spotlight, or serial scanning models.

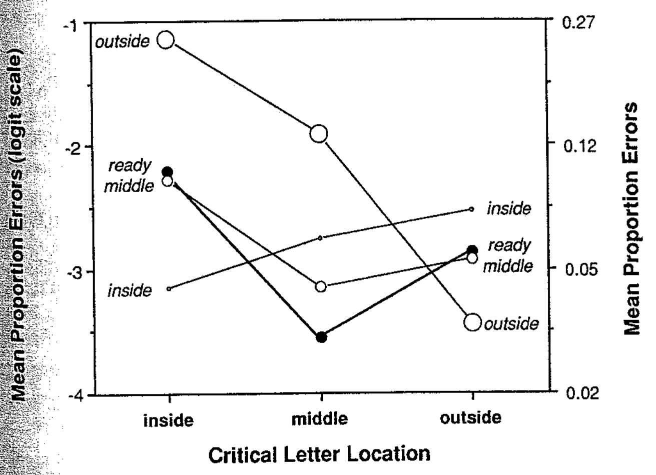

Figure 3. Mean proportions of errors plotted against critical letter location for the four different cue conditions. (The labels are used in the same way as in Figure 2 [Experiment 1].)

In the simplest version of the *zoom lens model*, attention is distributed more or less uniformly over the field in the uncued (ready) condition. In response to the outside cue, attention would be expanded to include the outer regions of the display, but inner regions would necessarily be included within the field of the lens. Thus, the model makes the same predictions for the ready and outside cue conditions. If the stimuli are all equally perceptible, then a single parameter, τ, (ϵ, for the error rate) should apply for all stimulus locations, and neither costs nor benefits should be observed for outside cues. For valid inside cues, benefits would accrue because of the concentration of attentional resources within the inner circle, and costs would occur for stimuli falling outside the attentional field. Similarly, middle cues would result in an attentional field of intermediate size, marshaling some benefits for stimuli appearing in the middle and also in the inner rings, whereas stimuli falling in the outer ring would incur costs. We can let κ represent the amount of benefit for stimuli falling within a field of intermediate size and let κ' represent the possibly greater benefit for stimuli falling within the concentrated field of attention within the smaller inner circle (e.g., see Eriksen & St. James, 1986). Costs can be represented by the parameter θ and can result from having to readjust the size of the resolved field when stimuli fall outside of its range. The predictions of the zoom lens model for the response time data are shown in Table 2, and the error data and model predictions are presented in Table 3.

An alternative to the zoom lens model is one in which attention need not be centered around the fovea but can instead be allocated to areas of various sizes and shapes in response to external cues or internal expectations of where the stimulus is likely to occur. The *ring model* is a special case of this class of resource allocation models: Attentional allocation follows cues indicating that a critical letter should occur within a ring at some distance from the fixation point. Even in the ready cue condition, there is evidence that, rather than spreading attention uniformly over the field of view, subjects prefer to let the "fovea take care of itself" and concentrate their attention along the middle and outer rings (see Posner, 1980). If we let τ be the time for responding to a stimulus in the middle or outer rings in the ready cue condition (and let ϵ represent the error rate), then some cost, θ, should occur for

Table 2
Response Time Data (in ms) and Predictions of the Zoom Lens, Ring, and Spotlight Models of Attention (Experiment 1)

Cue	Stimulus location		
	Inside	Middle	Outside
Response time data			
Ready	651	561	532
Inside	528	703	724
Middle	679	544	648
Outside	806	709	507
Predicted response times: Zoom lens model[a]			
Ready	$\tau = 628$	$\tau = 628$	$\tau = 628$
Inside	$\tau - \kappa' = 528$	$\tau + \theta = 692$	$\tau + \theta = 692$
Middle	$\tau - \kappa = 612$	$\tau - \kappa = 612$	$\tau + \theta = 692$
Outside	$\tau = 628$	$\tau = 628$	$\tau = 628$
Predicted response times: Ring model[b]			
Ready	$\tau + \theta = 678$	$\tau = 546$	$\tau = 546$
Inside	$\tau - \kappa = 526$	$\tau + \theta = 678$	$\tau + \theta' = 765$
Middle	$\tau + \theta = 678$	$\tau - \kappa = 526$	$\tau + \theta = 678$
Outside	$\tau + \theta' = 765$	$\tau + \theta = 678$	$\tau - \kappa = 526$
Predicted response times: Spotlight model[c]			
Ready	$\tau + 10.5c = 735$	$\tau + 4.5c = 581$	$\tau + 4.5c = 581$
Inside	$\tau + 2.5c = 530$	$\tau + 6.5c = 633$	$\tau + 10.5c = 735$
Middle	$\tau + 8.5c = 684$	$\tau + 2.5c = 530$	$\tau + 8.5c = 684$
Outside	$\tau + 10.5c = 735$	$\tau + 6.5c = 633$	$\tau + 2.5c = 530$

[a] Parameter values: $\tau = 628$, $\theta = 64$, $\kappa = 16$, $\kappa' = 100$. Percent variance accounted for = 22.1%.
[b] Parameter values: $\tau = 546$, $\theta = 132$, $\theta' = 219$, $\kappa = 20$. Percent variance accounted for = 92.5%.
[c] Parameter values: $\tau = 466$, $c = 26$. Percent variance accounted for = 72.6%.

stimuli appearing in the inner ring, to the inside of the attended area. Similarly, an inside cue should result in attention being concentrated in the inner ring, and costs should occur for stimuli presented in outer areas. Because an extra benefit parameter was created to reflect possible variations in concentration of attention in the zoom lens model, we can allow variations in degree of costs in the ring model and have the same number of free parameters overall. As for the zoom lens model, this decision is not arbitrary, for there is evidence that if the focus of attention is to be changed, then it moves in an analog manner, reaching areas closer to the initial focus of attention sooner than more distant regions (e.g., Shulman, Remington, & McLean, 1979; Tsal, 1983). Thus, θ is equated with the cost of detecting and identifying a critical letter in the ring next to the attended ring, and θ' is the cost for a stimulus that falls two rings away. The predictions of the ring model are shown in Tables 2 and 3.

Both models have four parameters that were estimated from the data separately by using a least-squares procedure. (A logit transformation was first applied to the error proportions as the parameters to be estimated were combined additively.) Their goodness of fit can therefore be compared directly, for example, by comparing the percentage of variance in the 12 data points in Tables 2 and 3 accounted for by the ring and zoom lens models. In the ring model, the variance accounted for was about 92.4% for the response time data and 62.9% for the error data. The zoom lens model does an inferior job of fitting the data, accounting for 22.1% and 7.3% of the variance for the response time and error data, respectively. The main difficulties for the zoom lens model are in the differences observed in the ready and outside cue conditions, when the lens should be adjusted in similar ways. Also, there are large and significant costs associated with invalid outside cues, so that when stimuli occur closer to the point of fixation than expected, much slower responses and higher error rates result than in the ready and valid cue condition.

We are left with the conclusion that of the two resource allocation models considered, the ring model—in which attention can be directed to specific ringlike areas—leads to a better fit to the data than does a model in which attention must be centered on the fovea while it expands or contracts like the field of view of a zoom lens. We have yet to consider a second class of models, represented by a *spotlight model,* in which attention remains in a relatively narrow focus but is free to scan the display in a way that is consistent with external cues or individual strategies.

Let us assume that the spotlight scans the display items one at a time and terminates when the single critical letter is found. The initial position of the spotlight is determined by

Table 3
Error Data (Proportions of Incorrect Responses) and Predictions of the Zoom Lens, Ring, and Spotlight Models of Attention (Experiment 1)

Cue	Stimulus location		
	Inside	Middle	Outside
Error data			
Ready	.100	.028	.054
Inside	.041	.060	.074
Middle	.094	.041	.051
Outside	.243	.129	.031
Predicted error proportions: Zoom lens model[a]			
Ready	$p(\epsilon) = .075$	$p(\epsilon) = .075$	$p(\epsilon) = .075$
Inside	$p(\epsilon - \kappa') = .041$	$p(\epsilon + \theta) = .061$	$p(\epsilon + \theta) = .061$
Middle	$p(\epsilon - \kappa) = .063$	$p(\epsilon - \kappa) = .063$	$p(\epsilon + \theta) = .061$
Outside	$p(\epsilon) = .075$	$p(\epsilon) = .075$	$p(\epsilon) = .075$
Predicted error proportions: Ring model[b]			
Ready	$p(\epsilon + \theta) = .082$	$p(\epsilon) = .039$	$p(\epsilon) = .039$
Inside	$p(\epsilon - \kappa) = .037$	$p(\epsilon + \theta) = .082$	$p(\epsilon + \theta') = .138$
Middle	$p(\epsilon + \theta) = .082$	$p(\epsilon - \kappa) = .037$	$p(\epsilon + \theta) = .082$
Outside	$p(\epsilon + \theta') = .138$	$p(\epsilon + \theta) = .082$	$p(\epsilon - \kappa) = .037$
Predicted error proportions: Spotlight model[c]			
Ready	.124	.051	.051
Inside	.036	.071	.124
Middle	.095	.036	.095
Outside	.124	.071	.036

[a] Parameter values: $p(\epsilon) = .075$, $p(\theta) = -(.014)$, $p(\kappa) = .012$, $p(\kappa') = .034$. Percent variance accounted for = 7.3%.
[b] Parameter values: $p(\epsilon) = .039$, $p(\theta) = .043$, $p(\theta') = .099$, $p(\kappa) = .002$. Percent variance accounted for = 62.9%.
[c] Percent variance accounted for = 41.5%.

the subject, as is its motion across the display. It is easy to show that if this path is essentially random when no cues are given, a path beginning in the cued region will generally yield benefits for valid cues and costs for invalid cues. A variety of such scanning models, differing mainly in the order that rings and items are scanned across cue conditions, were fit to the data by estimating two parameters, a base response time and the scanning time per item. Perhaps the best such model works under the assumption that all items in any ring are scanned until the critical letter is found or until the set in the ring is exhausted, and then the scan moves to the next closest ring. If the first ring is the middle one, a random decision is made about which to search next. On ready cue trials, the scan covers the outer two rings, in either order, before it moves to the inner ring, if necessary. This model has only two parameters: a base response time of about 465 ms and a scanning time of about 26 ms per letter. For the spotlight model shown in Table 2, the expected number of items scanned in each condition is determined by combining the expected number scanned if the critical letter is in the ring being examined (2.5 letters) with that from any previous ring that was scanned without finding the target (4 letters per ring). The percentage of variance accounted for in the response time data is 72.6%.

To provide a more direct comparison between the ring and spotlight models, we constructed a two-parameter ring model, with the parameters being a base response time, $\tau = 591$ ms, and a single cost–benefit parameter, $\theta = \kappa = 83$ ms (i.e., the magnitude of costs equals that of benefits), with cost incurred each time the focus of attention is forced to move to a new ring because of failure to find the critical letter. That is, the cost is 2θ for invalid outside and inside cues when the critical letter falls two rings away. As in the four-parameter ring model, the middle and outer rings are energized on ready trials, before processing the inner one if they do not contain the critical letter. This two-parameter ring model accounts for 87.4% of the variance in the response time data, which is somewhat worse than the four-parameter version but still better than the spotlight model (see Table 2). If the benefit is constrained to be less than the cost, which the data suggest, then the proportion of variance accounted for by the ring model is even higher.

The apparent difficulty of the spotlight model is its necessity to predict response times from the expected number of items processed in a serial, self-terminating scan. The superiority of models in which processing resources are distributed along a ring of anticipated stimulus location and processing times in all cue conditions are not rigidly locked to the number of items to be scanned argues against the version of the spotlight model considered here. Letter processing could perhaps be better thought of as the simultaneous search through all letters in the currently energized area, with some time required to move the locus of attentional energy if the critical letter is not within its current field (e.g., Duncan & Humphreys, 1989).

Another difficulty for scanning models is that they cannot be used directly to predict the error rates, whereas such predictions fall out in the same way as the response time estimates from the resource allocation models. According to the spotlight model, one way to estimate errors would be to assume that subjects internalize some response time criterion so that if the scan has not found the critical letter by the time the criterion is reached, a random guess is made. For purposes of estimation, we could determine differential error rates across cue conditions by simply assuming a common normal distribution for the completion times in each condition, but with a different mean, depending on the validity of the cue. The means of the distributions were taken from the estimates generated for response times in the various cue conditions by the spotlight model, as shown in Table 2. We then used a least-squares procedure to find a common standard deviation for all response time distributions (267 ms) and a location for the criterion (920 ms), which minimized the discrepancy between predicted and obtained error rates. The predicted error rates correspond to one-half of the area under the normal probability density function in the tail extending beyond the criterion. These estimates are shown in Table 3, and again, the fit is somewhat worse for the spotlight model than for the ring model. In this case, the number of parameters estimated from the data is the same for both models (i.e., 4), as the mean of the distribution in each cue condition for the spotlight model depends on a linear combination of the parameters τ and c, and the percentages of errors predicted are then determined by estimates of the common standard deviation and criterion point.

The data indicate an impressive degree of flexibility in attentional allocation over the visual field. Not only can specific areas be selected for enhanced processing, but regions of fairly specific size and shape can be attended to as well. The limits of flexibility in attentional allocation have not yet been systematically explored, but they appear to exceed limitations imposed by a serial scanning mechanism. People can apparently prepare for events in a variety of specific areas so that when these expectations are confirmed, detection and recognition processes are enhanced. Expectations can also lead to apparent inhibition of parts of the visual field, for even if stimuli are presented to the foveal region, responses will show costs in processing times and error rates if the stimuli were expected to occur parafoveally. These facts support the idea that attention can add to and sometimes even counteract effects otherwise caused by simple gradients of visual acuity.

Experiment 2

The covariation of size and eccentricity of the letters used in Experiment 1 successfully avoids some problems of interpretation but, in itself, contributes to another problem: Although subjects were instructed to use the location cues to attend to inner, middle, or outer rings in Experiment 1, it is possible that the perfect correlation between distance from fixation and letter size might have led them to convert a location cue into a size cue and selectively process the letters of the appropriate size, rather than location, for the presence of the critical letter. We view this strategy as being unlikely because the location instructions were subjectively easy to follow, and subjects reported the active attempt to preview or prepare for stimuli in the cued rings of the display. In addition, von Wright (1968) has shown that location is a superior cue to size in selecting among letters to be processed in the partial report task designed by Sperling (1960). Although there are differences between the letter recognition task used in the present research and the partial report procedure used by von Wright, one might expect an even greater advantage for location cues in the present paradigm, because the cues are given before rather than after the display, as in partial report tasks. Preparation for expected location has been demonstrably effective in many studies of attention, whereas a size cue cannot lead to the same degree of preparation. Rather, selection by size must wait until after the display has been presented and some analysis made of its contents before letters of a specific size can be examined selectively for the presence of a target. These ideas lend themselves to a stage model analysis, at least as a starting point for discussion. Let us assume that location cues affect an early, preparation stage of attention, whereas cues based on specific features or categorical relations can affect only later selection and identification stages of processing. If the effects of location and size cues are limited to these separate processing stages, then their independent contributions to observed costs and benefits should be additive. On the other hand, if both location and size information can be used to select items for further processing, with letters of the wrong size or in the uncued location rejected in parallel, then response time should depend only on the number of items selected for further processing (e.g., Duncan & Humphreys, 1989; Wolfe et al., 1989).

Regardless of the persuasiveness of the preceding arguments, it is necessary to eliminate the confounding of size and location present in the first experiment for a clear interpretation of the results. We need to determine whether, in fact, it could have been possible to use size cues alone to produce the observed results. If so, the conclusion that attention can be allocated to ringlike regions in space would be opened to serious question.

In Experiment 2, we used location and size cues both independently and in combination to determine their relative effectiveness in facilitating recognition of a critical letter in a multiletter display. Location and size were uncorrelated so that knowledge of one dimension of the critical letter gave no information about the other. We simplified the displays from those used in the first experiment to avoid potential problems of visibility for small letters in parafoveal vision. In this experiment, eight letters of two sizes were distributed over two rings. Thus either location or size could be cued in advance, with an equivalent reduction of uncertainty about the critical letter in each case.

Method

Subjects. The subjects were 5 men and 1 woman, ranging in age from 19 to 40 years. They included four students at the University of Kansas and two nonstudents from the university community, all of whom volunteered for participation and had normal or corrected-to-normal vision. One subject had participated in Experiment 1.

Apparatus and materials. The stimuli were uppercase letters printed by a plotter in jet-black ink on semigloss white paper. Each display had eight letters arranged into a X pattern, containing seven Xs and either one L or one R. The distance from the center of each display was about 1.8 cm to the centers of the nearer letters and about 4.9 cm for the outer letters. From a line-of-sight distance in the tachistoscope used, these dimensions correspond to about 0.9° and 2.5° of visual angle, respectively. The height of the small letters was about 0.8 cm (0.4°), and the height of the large letters was about 1.5 cm (0.8°). For a preexposure field, a single dark circle of 3.2 cm radius (1.6°) was drawn with a small fixation dot at its center. When superimposed over a display field, the circle enclosed the four inner letters and fell about midway between them and the four outer letters.

In combining two letter sizes with two distances from fixation, we get five different types of displays: Type 1—four large outer letters and four small inner letters; Type 2—three large and one small outer letters and one large and three small inner letters; Type 3—two large and two small letters in each ring; Type 4—one large and three small outer letters and three large and one small inner letters; and Type 5—four small outer letters and four large inner letters. For each type of display, a single large or small critical letter could appear at any possible position, and the rest of the letters were Xs. These combinations result in 16 different possible permutations of the letters for display Types 1 and 5, 256 permutations for Types 2 and 4, and 576 permutations for Type 3. We decided to sample randomly from these permutations with the constraint that exactly one small and one large version of each critical letter occur at each permissible position. This yielded 32 different displays for Types 2, 3, and 4, and, to balance the set of stimuli, two copies of each of the 16 different displays were made for Types 1 and 5, for a total of 160 displays.

All of the displays were cut to fit and glued onto 12.7 × 22.9-cm white cards for presentation in an Iconix three-field tachistoscope. A balanced set of 20 cards was made from photocopies of the original stimuli to be used for practice trials.

Procedure. The subjects were run individually in six 45-min sessions over a period of 3 to 5 days. Each session consisted of 20 practice trials, followed by the 160 experimental displays presented in a random order. If two sessions followed one another in close succession for any subject, the practice trials were not used to start the second session. The sessions were combined into three pairs, for which the instructions were the same; that is, for two sessions stimulus location was cued, for two sessions letter size was cued, and for two sessions both location and size were cued. The two sessions with the same type of cue were always run consecutively for a given subject, but the order of instruction cue type was counterbalanced across subjects. For the two sessions with the same types of cues, two different pseudorandom combinations of cue types and displays were made.

In all sessions, the neutral ready cue was given on 24 trials, and the location and/or size cue was valid on 112 trials and invalid on 24 trials. In the combined cue condition, location and size cues were either both valid or both invalid. Thus, whenever a location and/or size cue was given, it was valid with respect to the critical letter 83% of the time. The subjects were informed of the percentage of valid cues in advance.

The instructions were similar to those of Experiment 1. Subjects were told to begin each trial by looking into the tachistoscope and listening for the cue on that trial. In location cue sessions, the cues were ready, inside, or outside. In size cue sessions, the cues were ready, small, or large, and in combined sessions, the cues were ready, inside small, inside large, outside small, or outside large. The experimenter initiated the trial sequence as soon as he gave the cue. This included a 2-s exposure of the fixation point and surrounding circle, followed by a 150-ms exposure of the display field, and then an equal-luminance blank field until the beginning of the next trial. We instructed the subjects to maintain their fixation on the center of the field throughout the trial but to attempt to focus their attention according to the given cue. They were told to depress a right-hand button if an R appeared in the display and a left-hand button if an L appeared. They were asked to respond as rapidly as possible while avoiding errors, but were given feedback following errors only during

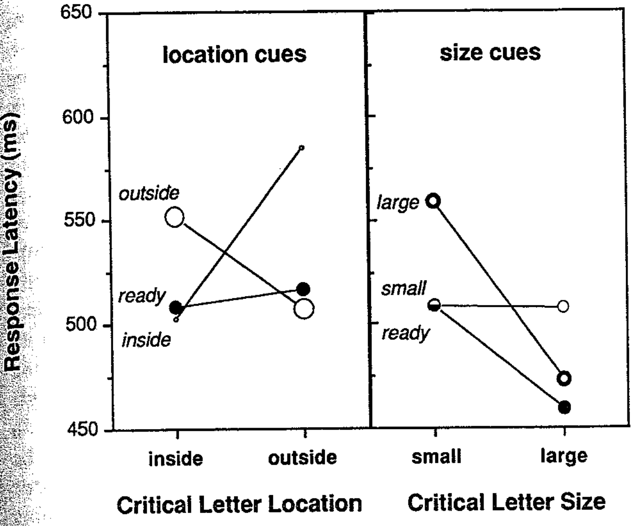

Figure 4. Mean response times plotted against critical letter location (left panel) and critical letter size (right panel) for the corresponding types of cues used in the single-cue conditions of Experiment 2. (The labels within the figure refer to the location or size cues given, whereas the labels along the abscissa refer to the actual location or size of the critical letter.)

practice trials. Mean response times were measured in milliseconds from the onset of the display until one of the response buttons was pressed.

Results

Response time data. Mean response times were found for each subject in each cell of a 2 × 2 × 3 × 3 within-subject design. The variables were critical letter location (inside or outside the preexposure circle), critical letter size (small or large), cue condition (location, size, or both), and type of cue (neutral, valid, or invalid). As in Experiment 1, fewer than 0.2% of the data were discarded as short or long response time outliers. The mean response times for each cell are plotted in Figures 4 and 5. An ANOVA found no overall differences among response times for the three instruction cue conditions, $F < 1$, but the validity of the cue given on each trial had a significant effect, $F(2, 10) = 4.19$, $p < .05$. Two other significant main effects were due to response time advantages for inside letters over outside ones, $F(1, 5) = 11.9$, $p < .05$, and for large letters over small ones, $F(1, 5) = 15.9$, $p < .05$. A final marginally significant interaction between cue type and cue condition indicated a trend for the cue validity effect to be strongest in the combined cue condition and weakest in the size-alone cue condition, $F(4, 20) = 2.47$, $p < .08$.

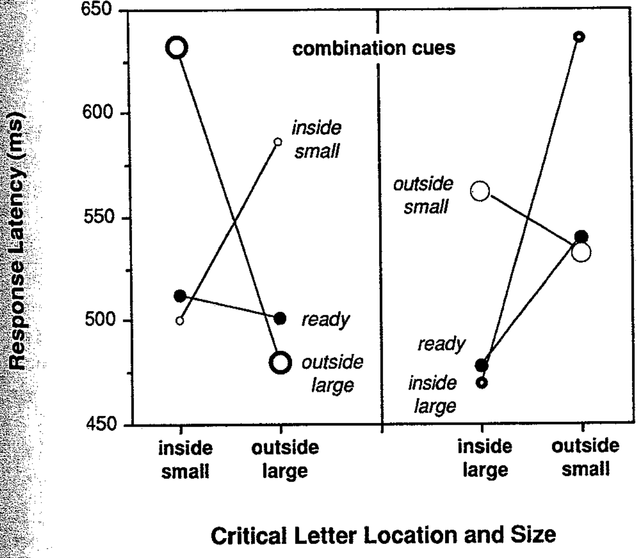

Figure 5. Mean response times plotted against critical letter size and location for the corresponding types of cues used in the combined cue condition of Experiment 2. (The labels are used in a similar way as in Figure 4.)

Error data. The overall error rate was 2.2%, and there were no significant trends across conditions. The error rate in the location, size, and combined cue conditions, respectively, was 1.7%, 2.4%, and 2.4%. It was 2.1% on valid trials, 2.1% on neutral trials, and 2.5% on invalid trials.

Discussion

The results of the second experiment demonstrated that both size and location cues could be used independently and in combination to influence subjects' identification times for which of two critical letters was present in a display. Response times were shorter in all three cue conditions when the cue was valid as opposed to when it was invalid. Although the magnitudes of the cost and benefit effects observed in the present experiment are generally less than those for Experiment 1 (perhaps because of the use of fewer rings over which attention could be spread in Experiment 2; see Juola et al., 1987), they nonetheless demonstrate that cues to attend to various ringlike regions around the point of fixation can be used to focus attention in these regions, resulting in significant improvement in letter recognition times compared with those for invalid location cues.

Location cue condition. The main point of the second experiment was to demonstrate that the effects of location cues found in Experiment 1 could not have been due solely to the confounding of location and size information offered in the cues and displays used in that study. This confounding could have led subjects to adopt a size selection strategy if, in fact, it had been easier to select potential critical letters on the basis of size rather than location. When location and size were unconfounded in Experiment 2, the results indicated that location cues were useful in themselves to produce costs and benefits consistent with the results of earlier studies (Experiment 1; see also Egly & Homa, 1984; Juola et al., 1987). The actual cost of an invalid inside cue was −68 ms (as determined by the difference between mean response times for outside critical letters that had received neutral vs. invalid cues). This value was close to the cost of invalid outside cues (−44 ms), a result clearly more supportive of the ring model than the zoom lens model, which predicts no costs for invalid outside

Table 4
Response Time Data (in ms) and Predictions of the Zoom Lens, Ring, and Spotlight Models of Attention for Location Cue Conditions in Experiment 2

Cue	Stimulus location: Inside	Stimulus location: Outside
	Response time data	
Ready	508.5	517
Inside	503	584.5
Outside	552	508
	Predicted response times: Zoom lens model[a]	
Ready	$\tau = 521$	$\tau = 521$
Inside	$\tau - \kappa = 503$	$\tau + \theta = 584$
Outside	$\tau = 521$	$\tau = 521$
	Predicted response times: Ring model[b]	
Ready	$\tau = 513$	$\tau = 513$
Inside	$\tau - \kappa = 506$	$\tau + \theta = 569$
Outside	$\tau + \theta = 569$	$\tau - \kappa = 506$
	Predicted response times: Spotlight model[c]	
Ready	$\tau + 4.5c = 529$	$\tau + 4.5c = 529$
Inside	$\tau + 2.5c = 497$	$\tau + 6.5c = 560$
Outside	$\tau + 6.5c = 560$	$\tau + 2.5c = 497$

[a] Parameter values: $\tau = 521$, $\theta = 63$, $\kappa = 18$. Percent variance accounted for = 75.4%.
[b] Parameter values: $\tau = 513$, $\theta = 56$, $\kappa = 7$. Percent variance accounted for = 89.1%.
[c] Parameter values: $\tau = 458$, $c = 15.7$. Percent variance accounted for = 74.4%.

cues. A more detailed analysis of costs and benefits and the predictions of the zoom lens, ring, and spotlight models are presented in Table 4. As in Experiment 1, the overall fit is best for the ring model. It should be noted that a two-parameter ring model is indistinguishable from the spotlight model using the location cue data from Experiment 2. This is because if costs and benefits in the ring model are set equal to each other, they will be exactly proportional to the numbers of items expected to be scanned before the critical letter is found according to the serial self-terminating spotlight model (i.e., 2.5 for valid cues, 4.5 for neutral cues, and 6.5 for invalid cues).

Size cue condition. In considering the data for size cues, we quantified both a resource allocation analogy of the ring model and a serial scanning or spotlight model. As in the ring model for the location cue data, the resource allocation model has three separate parameters for the base response time, benefits, and costs. Rather than allocating attention to specific ringlike areas in advance of the display, however, the assumption now is that attentional resources can be allocated to letters of either large or small sizes, according to the cue. Although such allocation could be represented by "priming" certain spatial-frequency channels in the visual system, it is more likely that little preparation is involved and allocation must be made after some processing of the display has identified the positions of items of different relative sizes. The fit to the data for size cue conditions is shown in Table 5. The percentage variance accounted for by the resource allocation model indicates that the fit is worse than that of either the ring or zoom lens models to the data for location cues (see Table 4). This result could have been anticipated on the basis of other data, suggesting that attentional resources can be allocated in advance to contiguous regions of the display but probably cannot be allocated simultaneously to separate locations as required to concentrate on the separate large or small letters (e.g., Eriksen & Yeh, 1985; Posner et al., 1980).

When attention is modeled as a spotlight that serially examines letters of a given size for the presence of the critical letter, there are only two parameters that need to be estimated from the data, namely, a baseline response time and the scanning time per item. This scanning model, with the single additional assumption that large letters are searched first in the ready cue condition, provides a slightly better fit to the data for size cues than does the three-parameter resource allocation model (see Table 5). The fit is also considerably better than a two-parameter (cost = benefit) resource model, which can account for only 29.6% of the variance in the response time data. Yet, the scanning model's fit to the data is also not very impressive, and the value of the scanning parameter (c in Table 5) is about half that expected if it were to represent the comparison time between two characters (e.g., Atkinson, Holmgren, & Juola, 1969; Sternberg, 1966).

Because of the unsatisfactory fits to the data for size cues offered by the resource allocation and scanning models, we

Table 5
Response Time Data (in ms) and Predictions of Resource Allocation and Spotlight Models of Attention for Size Cue Conditions in Experiment 2

Cue	Stimulus size: Small	Stimulus size: Large
	Response time data	
Ready	508.5	459.5
Small	509.0	507.5
Large	559.5	473.5
	Predicted response times: Resource allocation model[a]	
Ready	$\tau = 484$	$\tau = 484$
Small	$\tau - \kappa = 491.25$	$\tau + \theta = 533.5$
Large	$\tau + \theta = 533.5$	$\tau - \kappa = 491.25$
	Predicted response times: Spotlight model[b]	
Ready	$\tau + 6.5c = 525$	$\tau + 2.5c = 481$
Small	$\tau + 2.5c = 481$	$\tau + 6.5c = 525$
Large	$\tau + 6.5c = 525$	$\tau + 2.5c = 481$
	Predicted response times: Modified resource model[c]	
Ready	$\tau' = 510$	$\tau = 465$
Small	$\tau' = 510$	$\tau + \theta = 511$
Large	$\tau' + \theta = 556$	$\tau = 465$

[a] Parameter values: $\tau = 484$, $\theta = 49.5$, $\kappa = -7.25$. Percent variance accounted for = 47.3%.
[b] Parameter values: $\tau = 453$, $c = 11$. Percent variance accounted for = 49.2%.
[c] Parameter values: $\tau = 465$, $\tau' = 510$, $\theta = 46$. Percent variance accounted for = 97.8%.

tried a third alternative that was a modification of the earlier resource allocation model. First, it was noted that the estimate of the benefit parameter, κ, was -7.25, meaning that a valid size cue actually increased mean response time when compared with the no-cue condition. Although this effect is small, it indicates the general lack of ability to concentrate attention in a beneficial way on items of the cued size, at least to compensate for any additional processing load engendered by maintaining and using the size cue itself. Therefore, a modified resource allocation model was fit to the data for size cues in which there is no benefit parameter, but in which a base response time difference is allowed for large (τ) versus small (τ') critical letters, reflecting the general trend in the data. The third parameter is a cost, θ, associated with an invalid size cue; that is, even if a valid size cue is ineffective in demonstrating benefits, costs could still be incurred by the relatively ineffective attempt to focus attention on items of the cued size, followed by a relaxation of this attempt. As shown in the last part of Table 5, the modified resource model does a superior job of fitting the data for size cues.

Combined cue condition. Because both location and size cues have been shown to influence letter recognition times when they are used alone, any model of the data for combined cues must specify how their combination influences the detection and recognition of the critical letter. Shown in Table 6 are the response time data for the combined cues condition in Experiment 2. It had been expected that size cues would be less effective overall than location cues (e.g., Nissen, 1985; von Wright, 1968), and the effects of cue validity were, in fact, only slightly less for size cues than for location cues. Perhaps the most straightforward analysis of cue effectiveness would be to compare the differences in response times between valid and invalid cues in all conditions (i.e., costs plus benefits; see Jonides & Mack, 1984). These differences were 63 ms for the location cue condition and 43 ms for the size cue condition. In the combined condition in which both cues were either valid or invalid, the difference was 108 ms, very close to the 106-ms difference expected if additivity were absolute.

Also shown in Table 6 are the fits of several models to the response time data for the combined cues condition. The first model is a pure resource model that attributes costs and benefits to the combination of location and size cues; that is, it is analogous to a ring model. Because there are size cues effects beyond what were obtained for location cues only, some focusing of resources onto letters of the appropriate size must be possible for the model to be correct. In fact, its fit to the data using three parameters (77.6% of the variance accounted for) is slightly inferior to that of the same model to the pure location cue data (see Table 4).

The second model presented in Table 6 is a serial scanning or spotlight model, in which it is assumed that the order of scan is responsive to both location and size cues. Specifically, it is assumed that a location cue biases the search process to begin with those letters either inside or outside of the preexposure circle, and then the size cue is used to begin scanning with letters of the cued size. It follows that the number of letters searched before the process terminates with finding a critical letter differs in a regular way among the cue conditions. That is, if both location and size cues are valid, the critical letter should be one of a set of from one to four letters, depending on the specific display type presented on that trial. Averaging over the five types of displays used, the expected number of letters scanned before the critical letter is found is 1.9. On invalidly cued trials, the presumption is that attention remains in the cued ring until all letters are scanned; that is, the location cue determines where the search will begin, and then items of the cued size are the first selected. This assumption means that for invalid cues, all items in the cued ring will be examined first, attention will then shift to the other ring, items of the cued size will be examined, and finally, items of the noncued size in the noncued ring will be scanned. Across all five display types, the expected number of items scanned before the critical letter is found when both cues are invalid is 7.1. On ready trials, it is assumed that attention is more or less uniformly distributed over the field, but the data indicate a response time advantage for inside letters over outside ones and an even greater advantage for large letters over small ones. Therefore, it is presumed that items are searched in the following order: inside large, outside large, inside small, and outside small. As shown in Table 6, the fit of the two-parameter scanning model is inferior to the three-parameter resource model by about 12% of the explained variance.

The third model depicted in Table 6 represents a combination of resource allocation to location cues and subsequent selection based on size cues. That is, it is presumed there are benefits for beginning the scan in the appropriate ring and costs for beginning in the incorrect ring beyond the effects determined solely by scanning order. The fit of the combined resource-spotlight model is disappointing, in that only an additional 5% of the variance in the response time data can be accounted for by adding the scanning parameter to the resource model. Also, the least-squares estimation procedure arrives at a negative value for the benefit parameter (κ), and the scanning time per item (c) is again estimated to be rather short. To demonstrate further the inadequacy of this two-stage model, the final model shown in Table 6 is a modified resource model in which two base times are estimated—τ for large letters and τ' for small ones—to reflect possible recognition-time differences for large and small letters that overall are equidistant from the central fixation point. Processing resources are allocated in response to the combination of location and size cues, with benefits represented by the parameter κ and costs reflected in θ. Although it has the same number of parameters as the combined resource-spotlight model, the modified resource model does a much better job of fitting the data while arriving at more realistic values for the parameters. This result further undermines the viability of the spotlight or any other serial processing model in accounting for any of the data from Experiment 2.

We made an extension of this final model to all of the conditions in the second experiment, first by adding or subtracting a constant (14 ms) from the times in the combined cues condition to reflect, respectively, the overall relatively slower responses in the location-cues-alone condition and the relatively faster mean response times in the size-cues-alone condition. (Because only 6 subjects were run in all conditions

Table 6
Response Time Data (in ms) and Predictions of the Resource, Spotlight, Combined, and Modified Resource Models of Attention for the Combined Cues Condition in Experiment 2

	Stimulus location and size			
Cue	In/small	In/large	Out/small	Out/large
		Response time data		
Ready	513	478	540	501
In/small	500			586
In/large		470	636	
Out/small		562	532	
Out/large	632			480
		Predicted response times: Resource (ring) model[a]		
Ready	$\tau = 508$	$\tau = 508$	$\tau = 508$	$\tau = 508$
In/small	$\tau - \kappa = 495.5$			$\tau + \theta = 604$
In/large		$\tau - \kappa = 495.5$	$\tau + \theta = 604$	
Out/small		$\tau + \theta = 604$	$\tau - \kappa = 495.5$	
Out/large	$\tau + \theta = 604$			$\tau - \kappa = 495.5$
		Predicted response times: Spotlight model[b]		
Ready	$\tau + 5.9c = 562$	$\tau + 1.9c = 488$	$\tau + 7.1c = 583$	$\tau + 3.1c = 510$
In/small	$\tau + 1.9c = 488$			$\tau + 7.1c = 583$
In/large		$\tau + 1.9c = 488$	$\tau + 7.1c = 583$	
Out/small		$\tau + 7.1c = 583$	$\tau + 1.9c = 488$	
Out/large	$\tau + 7.1c = 583$			$\tau + 1.9c = 488$
		Predicted response times: Combination resource-spotlight model[c]		
Ready	$\tau + 5.9c = 522$	$\tau + 1.9c = 481$	$\tau + 7.1c = 535$	$\tau + 3.1c = 494$
In/small	$\tau - \kappa + 1.9c = 496$			$\tau + \theta + 7.1c = 604$
In/large		$\tau - \kappa + 1.9c = 496$	$\tau + \theta + 7.1c = 604$	
Out/small		$\tau + \theta + 7.1c = 604$	$\tau - \kappa + 1.9c = 496$	
Out/large	$\tau + \theta + 7.1c = 604$			$\tau - \kappa + 1.9c = 496$
		Predicted response times: Modified resource model[d]		
Ready	$\tau' = 531$	$\tau = 485$	$\tau' = 531$	$\tau = 485$
In/small	$\tau' - \kappa = 518$			$\tau + \theta = 581$
In/large		$\tau - \kappa = 472$	$\tau' + \theta = 627$	
Out/small		$\tau + \theta = 581$	$\tau' - \kappa = 518$	
Out/large	$\tau' + \theta = 627$			$\tau - \kappa = 472$

[a] Parameter values: $\tau = 508$, $\theta = 96$, $\kappa = 12.5$. Percent variance accounted for = 77.6%.
[b] Parameter values: $\tau = 453.5$, $c = 18.3$. Percent variance accounted for = 65.6%.
[c] Parameter values: $\tau = 462$, $\theta = 69.5$, $\kappa = -14$, $c = 10.2$. Percent variance accounted for = 82.6%.
[d] Parameter values: $\tau = 485$, $\tau' = 531$, $\theta = 96$, $\kappa = 12.5$. Percent variance accounted for = 96.0%.

in a counterbalanced order, these differences are not theoretically interesting, but reflect, most probably, differential improvement with practice for the different subjects.) The remaining four parameter estimates (in ms) were $\tau = 473$, $\tau' = 514$, $\kappa = 8.5$ (the benefit for valid location cues only), and $\theta = 50.0$ (the cost for either an invalid size or location cue; 2θ is the cost if both cues are invalid). This model accounted for 92.7% of the variance in the response time data for all three conditions in Experiment 2 combined.

Experiment 3

In Experiment 1, it was impossible to separate the individual effects of size and location because they were confounded in the cues as well as in the displays. Experiment 2 unconfounded the display variable, but location and size were either both cued validly or both cued invalidly. In the third experiment, the confounding is eliminated in the cues as well, leading to a more detailed test of how location and size cues are combined in processing a visual display.

In Experiment 3, we tested the additivity of location and size cue effects by pitting the two types of cues against each other; that is, when location and size cues were given, both could be valid, one cue could be valid and the other invalid, or both could be invalid. It was expected that if each cue were capable of producing independent costs and benefits by affecting separable components of the attentional process, their effects should combine in an additive fashion. More complex, interactive patterns of results could emerge if the cues are used conjointly in a common attentional process. If, however, one type of cue dominates the allocation of attentional resources, costs and benefits should mainly be associated with the validity of that cue only.

Method

Subjects. The subjects were 7 male and 5 female undergraduate students at the University of Kansas who volunteered or participated as part of a course requirement. All had normal or corrected-to-normal vision, and none had participated in Experiments 1 or 2.

Apparatus and materials. The apparatus and stimulus materials were the same as those used in Experiment 2.

Procedure. The subjects were run individually in two 90-min sessions completed on separate days. Each session began with 20 practice trials, followed by two runs through the 160 experimental stimuli in different random orders. In each 160-trial block, 36 trials were preceded by the neutral, ready cue, and the rest were preceded by combined size and location cues. In one session for each subject, the location cue was always spoken first, followed immediately by the size cue, whereas this order was reversed in a counterbalanced way for the other session. Of the 124 trials in any block on which joint size and location cues were given, both cues were valid on 88 trials, size-only cues were valid on 12 trials, location-only cues were valid on 12 trials, and both cues were invalid on 12 trials. Thus any particular cue was valid about 81% of the time overall. Two different pseudorandom assignments of instruction cues to displays were made to balance cue type across display type. These were used in the two blocks within each session.

All other details of the procedure were the same as in Experiment 2. Subjects were instructed to fixate the center of the preexposure circle throughout each trial. The trial began with the cue, followed 2 s later by a 150-ms flash of the display. The field then remained lighted until the start of the next trial, and subjects indicated as rapidly and accurately as possible whether the display had included an R or an L.

Results

Response time data. The data from both sessions were treated as replications and combined into a single 2 × 2 × 5 within-subject design. The variables were critical letter location (inside or outside), critical letter size (large or small), and cue type (neutral, both valid, size-only valid, location-only valid, or neither valid). Fewer than 0.5% of the data were eliminated as fast or slow outliers as in earlier studies. The mean response times are shown in Table 7 and were subjected to an ANOVA. There were significant main effects of letter size, $F(1, 11) = 97.6$, $p < .01$, and cue type, $F(4, 44) = 13.2$, $p < .01$, but the location effect was not significant, $F < 1$. In addition, the three-way interaction of location, size, and cue type was significant, $F(4, 44) = 6.63$, $p < .01$.

As can be seen in Table 7, response times were generally shortest in the neutral, ready cue condition. Nonetheless, when location and size were cued, the cues that were valid on both dimensions produced the fastest responses. Conversely, trials on which both cues were invalid generally produced the slowest responses, and intermediate times resulted for trials on which only one of the cues was valid. These results are shown in Table 8. Consistent with the additivity hypothesis, there is no significant interaction in this table, $F(1, 11) = 1.8$, $p > .20$. The effect of changing a valid size cue to an invalid one adds about 31 ms to mean response time, $F(1, 11) = 12.9$, $p < .01$, whereas changing a valid location cue to an invalid one adds about 47 ms, $F(1, 11) = 17.1$, $p < .01$. Mean response time is 78 ms shorter when both cues are valid than when both are invalid.

Error data. The overall error rate was about 2.0%, and there were no significant trends across conditions. The error rate was 2.2% on neutral trials, 1.8% when both cues were valid, 1.7% when one cue was valid and the other invalid, and 3.5% when both cues were invalid.

Discussion

The results of Experiment 3 confirm those of Experiment 2 by demonstrating independent effects of size and location cues on the speed of letter recognition responses. These results are consistent with the idea that spatial cues can energize attentional resources to the specified location in preparation for the subsequent stimulus. Similarly, size cues apparently can activate selection mechanisms for stimuli matching the cued size, but this selection process presumably operates after location cues have initiated processing in particular display regions. The successive nature of preparation and selection is based on logical grounds as well as empirical evidence. That is, preparation for a specific location has long been part of the spatial metaphor for visual attention, and neurophysiological studies of human and animal attentional systems have revealed location-specific responses of various central nervous system components in anticipation of an upcoming stimulus (e.g., Posner & Petersen, 1990). It is difficult to describe how a similar anticipatory response might occur given advance knowledge of other features of a stimulus, such as its size, shape, or color.

One apparent difference between the results of Experiments 2 and 3 is in the latency of responses in the neutral, (ready) cue condition. Although these trials resulted in relatively short response times in both experiments, there nonetheless are some benefits in Experiment 2, whereas benefits are almost entirely absent in Experiment 3; that is, responses on neutral cue trials in Experiment 3 tended to be slightly faster even than those for which both dimensions were validly cued. It is true that the subjects in Experiment 2 received more practice overall and that only one-third of the trial blocks involved two cues, whereas all trial blocks had two cues in Experiment 3. It is possible that the relative lack of practice and concentration on the use of multiple cues could have led to excessive processing demands in Experiment 3, so the neutral cue condition was not a fair control condition. That is, rather than including merely the absence of any advance cues, the neutral condition might have been easier than the cue conditions because of the absence of processing loads associated with interpreting, maintaining, and attempting to use the cues. Such a situation would tend to increase costs and minimize benefits (see Jonides & Mack, 1984).

Table 7 includes predictions of a resource model in which the processing load required for maintaining and using two cues essentially cancels the benefits that result from the effective use of these cues. That is, there is no benefit parameter, and base times are separately estimated from times for responses to large and small critical letters in neutral and valid

Table 7
Response Time Data (in ms) and Predictions of the Resource Model of Attention for the Data From Experiment 3

	Stimulus location and size			
Cue	In/small	In/large	Out/small	Out/large
		Response time data		
Ready	599	536	590	553
In/small	586	578	688	600
In/large	650	550	700	600
Out/small	666	623	602	601
Out/large	678	608	626	560
		Predicted response times: Resource model[a]		
Ready	$\tau' = 605$	$\tau = 548$	$\tau' = 605$	$\tau = 548$
In/small	$\tau' = 605$	$\tau + \theta' = 576$	$\tau' + \theta = 660$	$\tau + \theta' + \theta = 631$
In/large	$\tau' + \theta' = 633$	$\tau = 548$	$\tau' + \theta' + \theta = 688$	$\tau + \theta = 603$
Out/small	$\tau' + \theta = 660$	$\tau + \theta' + \theta = 631$	$\tau' = 605$	$\tau + \theta' = 576$
Out/large	$\tau' + \theta' + \theta = 688$	$\tau + \theta = 603$	$\tau' + \theta' = 633$	$\tau = 548$

[a] Parameter values: $\tau = 548$, $\tau' = 605$, $\theta = 55$, $\theta' = 28$. Percent variance accounted for = 90.2%.

cue combinations. The other parameters are θ for the cost of an invalid location cue and θ' for the cost of an invalid size cue. These costs are presumed to add when both cues are invalid, and this model predicts over 90% of the variance in the response time data. There is no need to distinguish among hypothetical processing stages in this model; the only conclusion supported is that both types of cues independently affect the distribution of processing resources. Location cues are apparently more effective in concentrating these resources, as the least-squares parameter estimation procedure placed the cost of an invalid location cue at about twice that for an invalid size cue. Similar models based on the serial-search notion of a spotlight model or two-stage models separating early resource allocation from later serial search failed to fit the data nearly as well with an equivalent number of parameters.

General Discussion

The term *attention* has come to have two related meanings in cognitive psychology. One emphasizes the allocation of resources to limited-capacity systems, such as sensory buffers or a central processor, engaged in handling a variety of sensory and memory codes. The other meaning emphasizes the selective nature of attentional mechanisms for channeling certain inputs into the central processor while diverting others aside. In the present study, attentional capacity in the visual mode is modeled as the voluntary allocation of resources to an area with flexible dimensions of size and location. This channeling of resources enables more efficient processing of items appearing within the attended region than those appearing outside it. If subjects are led to expect that a critical letter should occur within a particular ringlike region centered around the fovea, a model allowing for attentional rings of various diameters provides a good fit to the data. Responses were generally faster and more accurate for letters occurring along the ring of attention than for letters inside or outside of the ring. Alternative models that were considered and rejected included a zoom lens model, in which the focus of attention remains centered on the foveal region while it is expanded out from or concentrated near the fovea, and a spotlight model, in which display items are examined one at a time in a serial, self-terminating search for a target.

Table 8
Mean Response Times (in ms) for Validly and Invalidly Cued Dimensions of the Critical Letter (Experiment 3)

	Size	
Location	Valid	Invalid
Valid	575	619
Invalid	635	653

Experiments 2 and 3 emphasized the selective nature of attention, in that specification of letter properties such as relative size apparently resulted in selection of display elements with the specified property value. This conclusion rests mainly on the demonstration of costs for invalid cues, indicating that selecting items of the cued size delayed processing of other-sized items, but benefits for valid size cues were generally absent. It is as though the attempt to use size information in selecting display items in itself used up some resources, thereby masking any benefits that might have been found in comparison with no-cue conditions. Because size and location were entirely coupled in Experiment 1, there is no need to modify the interpretation of the first experiment on the basis of the latter results; that is, selection by size within the cued region would yield no further costs nor benefits, because all letters within the cued region were, by design, also of the cued size. Although selective attention can be influenced by relative item size, this selection should not have been influential in Experiment 1 beyond the effects caused by location cues alone.

In all three experiments, the effects of voluntary control of attention were measured by the benefits of valid cues and costs of invalid cues in relation to a neutral, uncued condition.

Only in attending to location was a stable benefit observed, as size cues generally resulted in no significant benefit effects. However, invalid size and location cues both incurred substantial costs. Given this situation, it might appear that the best strategy would be to ignore size cues or other cues that require greater amounts of cognitive interpretation than location cues. Even attention to the location cues should be somewhat suspect, given the larger cost than benefit effects, although it must be considered that valid trials were four times as common as invalid trials. On the whole, then, positive effects of visual selective attention seem to be relatively minor, so it remains to be explained why, at least subjectively, attention is considered to be such a powerful adjunct to perception. One explanation hinges on arguments that most automatic and voluntarily controlled attentional responses exist because they are adaptive. Rapid allocation of attentional resources to parafoveal and peripheral visual regions can have obvious value in mobilizing resources to deal with new and important events. Experiment 1 demonstrated that responses to parafoveal stimuli can be faster than responses to foveal inputs, even when they are equally visible. It seems indeed true that people can let the fovea take care of itself while attending to a wider range of visual events.

A second explanation for the positive role of attention in perception is based on the perhaps paradoxical benefit of incurring costs for wrongly directed attention. The costs show that there can be massive suppression in processing unattended material. Such suppression apparently enables limited resources to be directed in a more effective and restricted way toward the attended material, relatively unimpeded by parallel activities. Although such benefits were sometimes small for location cues and generally absent for size cues, the task of locating and identifying a unique display element involves a number of processes, only some of which might be enhanced by valid cues. The results suggest that as cue complexity increases from location to size to their combination, the effort involved in interpreting, maintaining, and applying the cues diminishes resources available for their effective use, thereby decreasing benefits and increasing costs. Subjectively, the benefits that arise from valid cues might well be caused by the suppression of competing responses to uncued items, and, when the cues are invalid, the recovery from this suppression entails substantial costs.

In the visual mode, at least, it can be argued that attentional capacity can be allocated to specific spatial regions in anticipation of some visual event, whereas selection based on stimulus features must await some preliminary analysis of the displayed items. Consistent with this view, Experiments 2 and 3 demonstrated that location and size cues have additive effects on response times for valid and invalid dimensional cues. These results argue for an impressive degree of flexibility in the voluntary control of attentional processing. Furthermore, to the extent that the model is valid, this control extends from some time before a display is presented until some time after certain features of display elements have been detected and identified. The model also suggests that separate mechanisms of attention are involved in preparation and selection processes. This conclusion is based on converging sources of evidence from (a) studies of underlying neural systems that reflect the general alerting and spatial orienting aspects of attention (e.g., Posner & Petersen, 1990), (b) the additive effects of spatial and nonspatial feature cues observed in the present experiments that are consistent with separable mechanisms, and (c) the fact that location cues produced significant benefits and costs compared with a no-cue control condition, whereas size cues resulted in smaller costs and no benefits overall.

Asymmetric costs and benefits, or the complete lack of benefits when costs are present, can be interpreted within Wolfe et al.'s (1989) guided search model. The argument begins with two (perhaps) indistinguishable ways in which potential targets are separated from probable distractors in a search task: either the positions in a location map of the display that have target features are excited, or the positions that lack target features are inhibited. Location cues have been shown to produce benefits if they are valid and costs if they are invalid, so either or both of the excitatory and inhibitory processes could be in operation. Size cues, however, produced only costs in the present study. This result suggests that only the inhibitory process is in operation for letters of the noncued size; a valid size cue might do little to excite locations corresponding to appropriate-sized letters, thus producing little or no benefits. If letters of the noncued size are inhibited, however, processing of these letters should be delayed, producing costs for invalid size cues.

A somewhat different approach follows from the work of Duncan and Humphreys (1989). In their analysis, the probability that any display item is selected for further processing depends on how many features it shares with the target template and whether or not it can be grouped with similar items as belonging to potential target or distractor sets. In the present displays, there should be some tendency to group the distractor Xs, despite variations in their size and proximity to one another. If the distractors can be grouped, they can then be rejected as a set, leaving a single unique item selected for focal attention and identification. Such a process would result in rapid selection and identification of the critical letter, leaving no benefits expected for valid cues. The fact that benefits were obtained, at least for location cues, indicates that parallel grouping and rejection of distractors is unlikely on all trials, and the initial selection process can be aided by location cues. Size cues apparently cannot be used to benefit the selection process, although both invalid size and location cues can apparently bias the selection process in favor of taking some distractor items into consideration, thus yielding costs for invalid cues.

One issue that cannot be resolved by the present data is exactly what is meant by the allocation of attentional resources to spatial locations. A common metaphor in the attention literature is that attention can be distributed or concentrated at will and that processing efficiency for any display item is directly related to its position in relation to the distribution of attention (e.g., LaBerge & Brown, 1989). Yet, is the initial attentive mechanism a parallel process such that all visible objects are segregated and prepared for focal attention at once at rates proportional to their location on the gradient of attentional concentration (e.g, by assigning selection weights to items; Duncan & Humphreys, 1989)? Or should the spotlight metaphor once again be invoked, by which the distribution of attention is captured by the serial disposition of a focal spotlight that travels from item to item along a path prescribed by cue-dependent strategies? The two-process model considered here implies an initial parallel distribution of processing resources, followed by a sequential selective mechanism. Yet this distinction is by no means straightforward (e.g., McClelland, 1979; Miller, 1988; Townsend, 1972), and it remains to be decided whether location is a special cue that is unique in its influence on early attentional mechanisms or whether attention is best viewed as a unitary process that can be influenced in similar, if not entirely equal, ways by a variety of discriminative cues.

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Butcher, Geen, Hulse, and Salthouse Appointed New Editors, 1992–1997

The Publications and Communications Board of the American Psychological Association announces the appointments of James N. Butcher, University of Minnesota; Russell G. Geen, University of Missouri; Stewart H. Hulse, John Hopkins University; and Timothy Salthouse, Georgia Institute of Technology as editors of *Psychological Assessment: A Journal of Consulting and Clinical Psychology*, the Personality Processes and Individual Differences section of the *Journal of Personality and Social Psychology*, the *Journal of Experimental Psychology: Animal Behavior Processes*, and *Psychology and Aging*, respectively. As of January 1, 1991, manuscripts should be directed as follows:

- For *Psychological Assessment* send manuscripts to James N. Butcher, Department of Psychology, Elliott Hall, University of Minnesota, 75 East River Road, Minneapolis, Minnesota 55455.
- For *JPSP: Personality* send manuscripts to Russell G. Geen, Department of Psychology, University of Missouri, Columbia, Missouri 65211.
- For *JEP: Animal* send manuscripts to Stewart H. Hulse, Johns Hopkins University, Department of Psychology, Ames Hall, Baltimore, Maryland 21218.
- For *Psychology and Aging* send manuscripts to Timothy Salthouse, Georgia Institute of Technology, School of Psychology, Atlanta, Georgia 30332.