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Further toward a model of the mind's eye's movement

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An experiment that tests two models to account for shifts of attention in the visual field is described. One model posits that a shift of attention corresponds to a shift in processing resources among several simultaneously analyzed locations. The other model assumes that a shift of attention involves adding a prior stage of analysis that concentrates on the attended location to an otherwise simultaneous processing of several locations. Examination of reaction time distribution characteristics provided support for the latter model.

When one wishes to concentrate on a particular spot in the visual field, one should shift fixation so that the spot's image falls on the most sensitive area of the retina, the fovea. The reason for this is quite clear: nonfoveal portions of the retina are not nearly as sensitive in processing visual images as is the fovea itself. Consequently, when careful analysis of a visual stimulus is warranted, foveal input is engaged. In a sense, one could claim that the visual resolving power of the retina is limited, and foveation is the mechanism that permits one to overcome this limitation on a local basis.

Apparently, a mechanism like foveation exists at a different level of the visual system as well. A number of experiments have established that subjects can shift their internal allocation of processing resources from one location in the visual field to another without shifting gaze (Eriksen & Hoffman, 1972, 1973, 1974; Jonides, 1980, 1981; Posner, Nissen, & Ogden, 1978). The function of movements of the mind's eye seems as clear as that for movements of the body's eye: The processing capacity of the visual system is limited, and concentrating resources on a particular spatial locus is just another way of overcoming this limit on a local basis. It is not clear, of course, why two mechanisms have developed to overcome this limitation, a central and a peripheral one. Some researchers have speculated that the two may be more or less related (Klein, 1980; Nissen, Posner, & Snyder, Note 1). In any case, it is important to understand the mechanism that mediates central shifts of attention, much as we are beginning to understand the oculomotor mechanism that mediates peripheral shifts of attention.

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Toward this end, Jonides (1980) tested a class of models to account for attention shifts. The tests were conducted in the context of an experimental paradigm introduced by Sperling (1960) and later modified by Eriksen and by Posner (e.g., Eriksen & Hoffman, 1974; Posner et al., 1978). The task was visual search through eight-letter arrays for the target letters "L" or "R." Before each array was presented, a marker that signaled the location of the target with a high probability appeared. These trials were compared with ones on which the marker was locationally uninformative. The typical result obtained in this task is that response times for target identification are faster when the marker is locationally informative and valid (i.e., correctly indicates the target's location) than when it is not informative. In addition, response times are slower when the marker is informative but invalid (i.e., signals a nontarget location) than when it is not informative. By quantitatively examining details of these benefits and costs in response times, Jonides (1980) rejected models whose major assumption is that processing resources can be allocated to only one spatial location at a time.

The major alternative assumption that seems most plausible is that there is some simultaneous processing of several spatial locations. Jonides (1980) tested one model incorporating this assumption—that all resources are always allocated to the cued location first, and then, if the target is not found there, resources are distributed among the remaining loci. This model also proved unattractive.

Yet the assumption that resources are allocated simultaneously is still plausible. There are two models that retain this assumption and that can account for previous results. In the first of these (hereafter called the one-process model), one must suppose that resources are distributed among all array locations simultaneously. The effect of a cue is to cause a disproportionate share of these resources to be allocated to the cued location. This, in turn, causes faster processing of the cued location and slower processing of uncued locations than does a condition in which the cue is locationally uninformative. The exact magnitudes of benefits and costs depend on the function that relates resource allocation to processing time. Without specifying this function, one cannot make exact predictions about the quantitative magnitudes of benefits and costs. Nevertheless, the one-process model does predict that increased resource allocation to the cued location leads to decreased processing time.

A second model (the two-process model) also retains the assumption of some parallel processing of array items but adds a prior stage of analysis during which the cue has its impact. The model supposes that there is some probability that the cued item is processed first. This probability is related to the overall effectiveness of the cue at drawing attention. If the cued item is not the target, the remaining display items will then be examined simultaneously until a target is identified. On trials on which the cue does not attract attention, all items are processed simultaneously with equal weight. The extent of resource allocation to the cued location is always fixed, by hypothesis. Consequently, an item may either receive the benefit of having all the available processing resources applied to it if it is cued and attended, or share in the resources equally. Thus, a difference in the effectiveness of the cue, according to the two-process model, causes a change only in the proportion of trials on which the cued location receives preferential treatment. It cannot cause a gradation in the increment of resources applied.

One procedure that permits a test of these two alternatives is to vary the efficiency of the cue in drawing attention to its indicated location. According to the one-process model, increased efficiency of the cue should result in more resources being applied to this location, and hence faster processing of the target if it is present at this location. The two-process model also predicts faster target processing with a more efficient cue, but it attributes this to a greater proportion of trials on which the cue attracts attention.

METHOD

Design

There were two conditions in the experiment, in both of which the primary task was identification of an "L" or an "R" that appeared among seven other letters. In the peripheral-cue condition, each search display was preceded by an arrowhead that was placed near one of the letter positions. In the central-cue condition, an arrowhead was also used as a locational cue, but it was placed in the center of the display, which subjects were told to fixate (Jonides, 1981, has shown that a peripheral cue is more efficient at capturing attention). The subjects participated in two sessions, in each of which they received trials with both types of cues. The cues were presented in blocked fashion. In one session, half the subjects saw peripheral cues first and the other half saw central cues first. In the second session, the order was reversed for all subjects. The design of the experiment was thus completely within subjects in nature.

A modified version of the cost-benefit technique of Posner et al. (1978) was used to assess shifts of attention. On 50% of the trials with peripheral and central cues (valid trials), the arrowhead correctly indicated the position of the impending target. On the remaining 50% of the trials (invalid trials), the arrowhead pointed to a nontarget location. We diagnosed shifts of attention by examining differences in performance between valid and invalid trials.

Subjects

Twenty undergraduates were paid for participation in two sessions of 40-min duration each.

Apparatus

A computer controlled the presentation of the stimuli, which were displayed on a Hewlett-Packard graphic display device equipped with a P-4 phosphor. The subjects were seated such that the viewing distance to the screen was approximately 60 cm. The testing room was kept dimly illuminated throughout the experiment.

Stimuli

The stimulus arrays consisted of letters evenly spaced around the circumference of an imaginary circle 7.5 deg in diameter. Each letter was 1.2 deg in height and 0.8 deg in width. Each stimulus array was constructed by first locating an uppercase "L" or an uppercase "R" at one of the eight array positions, and then randomly selecting uppercase letters from the remainder of the alphabet, without replacement, to fill the seven remaining display positions. On peripheral-cue trials, the stimulus arrays were preceded by an outline arrowhead (0.8 deg in length) that pointed to one of the eight array locations. The arrowhead was positioned in the display such that its tip was 0.7 deg from the closest position of the letter to which it pointed and such that the arrowhead was within the imaginary circle that contained the letters. On the central-cue trials, an arrowhead also preceded the letter displays, but it was always positioned in the center of the imaginary circle that contained the letters.

Each experimental session consisted of four blocks of 80 trials each, two for each cue condition. The first block of each cue condition was preceded by 30 practice trials appropriate for that condition. In each of the two conditions, there were 40 valid and 40 invalid trials, with targets appearing equally often at each display position for each of these types of trials. The practice trials were constructed using the same principles as those used for the test trials that they preceded. Data from these practice trials are not included in the analyses presented below.

Procedure

The subjects were told about the design of the experiment and about the two conditions in which they would participate. This included instructions about cue validities. Then they were told the order of events on each trial: First, a dot would appear in the center of the screen and remain in view for 2 sec. Then, the dot would be replaced by the cue, which was displayed for 25 msec. Following this, the screen would be blank for 50 msec, and then an eight-letter display would be presented for 25 msec. The subjects were told to press a left response key if the display contained an "L" and a right key if it contained an "R." They were instructed to respond as quickly, yet as accurately, as possible.

We exercised two precautions to insure that subjects maintained fixation throughout the trials. First, we vigorously instructed and reminded subjects about the importance of maintaining fixation throughout the experiment. Second, we used a level of delay (50 msec) such that the total duration of cue plus delay plus display was only 100 msec. This value was much less than the average saccade latency reported in experiments similar to the present one (Colegate, Hoffman, & Eriksen, 1973).

RESULTS AND DISCUSSION

Table 1 presents mean reaction times and error proportions for valid and invalid trials in the two cue conditions. These data were analyzed using two separate analyses of variance, one for each dependent variable. Each analysis included the factors of type of cue (peripheral vs. central), validity (valid vs. invalid), and subjects. The value of $p < .05$ is used to report significance levels.

For the reaction time data, the main effect of validity was highly significant [$F(1,19) = 43.24$], whereas the effect of cue was not ($F < 1$). The interaction between these two factors was also reliable [$F(1,19) = 6.48$]. Contrasts using the Bonferroni method revealed that peripheral valid responses were faster than central valid, and peripheral invalid responses were slower than central invalid.

Analysis of the error data revealed the same pattern of significance. The validity factor proved reliable [$F(1,19) = 44.14$], whereas the cue factor did not [$F(1,19) = 2.75$]. The interaction was also significant [$F(1,19) = 5.45$]. The interaction is apparently attributable largely to the greater error rate for peripheral than for central invalid trials, as shown by Bonferroni tests. The contrast between valid trials showed no reliable difference.

These data are consistent with the pattern of results reported previously for tasks involving these cues (Jonides, 1981). The results are most easily understood if one presumes that peripheral cues produce more automatic shifts of attention than do central cues. This would account for the greater speed in responding to a target that is correctly indicated by a peripheral cue. And it would account for the results on invalid-cue trials as well: If one's attention is better captured by a peripheral cue and if the cue does not indicate the target's location, then it will be more difficult to reorient attention to the noncued locations to complete the search task.

As outlined above, there are competing one-process and two-process models that can account for the obtained reaction time and error results. These two models can be distinguished because they make differential predictions about extreme reaction times. Consider the two-process model. The cause of the differences between the types of cues for valid and invalid trials is the hypothesized difference in the proportions of trials on which the cue directs attention to its indicated location. According to this model, if we could examine only those trials on which attention has been shifted, then we should find identical performance for the two cues. Likewise, performance on trials in which attention has not been shifted to the cue should be identical. In contrast, the one-process model predicts that valid and invalid peripheral trials are different from valid and invalid central trials because of differences in the proportion of resources applied to the cued location.

To test these predictions, we examined minimum and maximum reaction times for valid and invalid trials with both types of cues. Comparing valid against valid trials and invalid against invalid, these times should be indistinguishable according to the two-process model, but different according to the one-process model.

Table 2 presents the minimum and maximum reaction times averaged over subjects for both conditions and both cue validities.

There are four critical reaction time differences that are of interest: For minimum reaction times, the valid peripheral minus valid central difference = 2 msec (confidence interval halfwidth = 41 msec), and the invalid peripheral minus invalid central difference = 32 msec (confidence interval halfwidth = 72 msec). For maximum reaction times, the valid peripheral minus valid central difference = –5 msec (confidence interval halfwidth = 100 msec), and the invalid peripheral minus invalid central difference = 30 msec (confidence interval halfwidth = 111 msec).

Let us examine these differences. The first point to make is that the data, not surprisingly, are somewhat noisy. This is so because each subject contributes but one reaction time (i.e., the datum from one trial) to each cell of Table 2. The noise is especially apparent for the maximum reaction times. This is so even though the data reported in Table 2 were calculated after unusually extreme response times had been deleted (greater than 3.5 standard deviations of the mean; there were six such trials for maximum response times, and none for minimum times). We suspect that the lack of difference between maximum reaction times, although consistent with the analysis of minimum times, should be viewed cautiously.

The noise in the data notwithstanding, however, there is a consistent pattern that appears for both minimum and maximum response times: All the average differences between central and peripheral trials are quite small, and all the confidence intervals include 0.

How do we interpret these small, perhaps nonexistent, differences? One possibility is that the slowest and fastest responses in an experiment of this sort are a result of slow and fast guesses. If this were the case, then

Table 1
Means and Standard Deviations for Reaction Times (in Milliseconds) and Error Proportions

	Peripheral Cue				Central Cue			
	Valid		Invalid		Valid		Invalid	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Reaction Times	529	104	683	171	569	122	644	166
Error Proportions	.024	.021	.098	.048	.026	.017	.076	.048

Table 2
Minimum and Maximum Reaction Times (in Milliseconds) and Standard Deviations for Valid and Invalid Trials in the Peripheral and Central-Cue Conditions

	Peripheral Cue				Central Cue			
	Valid		Invalid		Valid		Invalid	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Minima	342	80	466	141	340	94	434	165
Maxima	1063	200	1287	220	1068	248	1258	243

one would naturally not expect any differences between central- and peripheral-cue conditions. In addition, however, one would not expect a difference between valid and invalid trials for each cue. After all, before any trial, a subject does not know whether the cue will be valid or not. So if his fastest and slowest responses represent lucky guesses, then the speed of these responses should be equivalent for valid and invalid trials. But they are not. The four relevant differences are: 124 msec for peripheral invalid minus peripheral valid minima (confidence interval halfwidth = 47 msec); 94 msec for central invalid minus central valid minima (confidence interval halfwidth = 50 msec); 224 msec for peripheral invalid minus peripheral valid maxima (confidence interval halfwidth = 95 msec); 190 msec for central invalid minus central valid maxima (confidence interval halfwidth = 131 msec). For none of these differences do the confidence intervals include 0.

We conclude that the lack of difference between central and peripheral trials for extreme response times coupled with the differences for mean response times that are displayed in Table 1 lends support to the two-process model of attention shifts. According to this model, on any trial, attention may be shifted to a cued location with some probability that is a function of the attractiveness of the cue (and, as Jonides, 1980, showed, is also a function of the validity of the cue). If attention has been drawn to the cued location, the item there is identified first. If this item is identified as the target, a response is initiated. If it is not the target, then search proceeds over the remaining items in parallel until a target is identified (see Jonides, 1980, to rule out a sequential analysis of the remaining items). If, on a given trial, attention is not drawn to the cued item, then all array items are analyzed simultaneously until the target is identified.

In a sense, then, we have supplied some evidence in favor of a general theory of attention that makes use of an all-or-none principle in the allocation of processing resources. This principle is, of course, quite similar to one proposed originally by Broadbent (1958). The all-or-none principle by itself will not suffice to account for processing in the visual domain, however. In fact, the model advocated in the present paper adds a stage of simultaneous processing, when needed, to the focused processing induced by the cue. More generally, however, in order for an all-or-none mechanism to be effective in the analysis of spatially arrayed stimuli, it must be coupled with the ability to reallocate resources quickly and frequently. This may be accomplished by shifts of gaze or by the fast concentration of processing activity on a new locus in the visual field (Remington, 1980). In this sense, we may view the mind's eye as analogous to the body's eye: It has a field of concentrated processing like the fovea, and it is free to traverse a wide range of available spatial locations.

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