Reprint Series
20 October 1978, Volume 202, pp. 315-318

SCIENCE

The Attention Operating Characteristic: Examples from Visual Search

George Sperling and Melvin J. Melchner

The Attention Operating Characteristic: Examples from Visual Search

Abstract. *Even in the absence of eye movements, we show that subjects are able, upon instruction, to selectively attend to certain kinds of targets and parts of visual arrays. The major mechanism of altering attention is the switching of attention from trial to trial, although intermediate states of shared attention do occur. Attention operating characteristics are shown to be a useful way of describing such data and of assessing the compatibility of tasks to be performed simultaneously.*

The primary mechanisms of visual attention are overt physical acts: turning the eyes, head, and body toward the object of attention. Nevertheless, within a single eye fixation, attention can determine what parts of a complex stimulus will be remembered (*1*) and, in a simple reaction-time task, which reaction-stimuli will elicit fast and which will elicit slow responses (*2*). In contrast to these results in memory and reaction-time tasks (which involve complex short-term memory and response processes), in visual detection tasks (which primarily involve perceptual mechanisms) there is, as yet, no evidence that selective attention can alter processing within a brief exposure. In fact, there are many experiments that have been interpreted to mean that attention does not play an important role in detection (*3*, *4*).

To demonstrate the crucial role of attention in visual detection, we used a variant of the classical visual search technique. In classical visual search, the subject examines an array of stimuli (background objects) for a target object by moving his eyes over the array (*5*). While the pattern of eye movements is interesting in itself (*6*), it adds a complication not under experimental control to the analysis of attention. Therefore, in our experiments eye movements are eliminated by having the subject keep his eyes fixated on the center of a display and presenting new stimuli to him every 240 msec. This method allows precise control over the flow of visual stimuli while approximating the sequence the eyes produce for themselves in spontaneous visual search.

We present a sequence of arrays of alphanumeric characters, preceded by a fixation field, on a cathode-ray tube (*7*). The subject's task is to detect two numerals (the target characters) among uppercase letters of the alphabet (background characters). The targets occur in only one array, the critical array. This is preceded by a random number (from 7 to 12) of noncritical arrays and followed by at least 12 more noncritical arrays. The subject does not know which array will contain the target characters, nor which of the ten numerals will occur, nor where in the array they will be located. His task is to report the identity and location of each of the target characters and his degree of confidence in the correctness of each report (*8*, p. 209).

In a previous study (*3*) using a similar paradigm, Sperling *et al*. observed that a subject can scan for an unknown one-of-ten numeral as effectively as for a particular known numeral. They concluded that subjects scan for ten numerals in parallel. They further noted that subjects can scan 15 to 25 locations of an array in parallel. The purpose of the present experiment was to determine whether subjects could selectively attend to certain parts and kinds of targets in the array, even in a situation in which eye movements (should they occur) would be of no benefit.

We used the experimental paradigm described above, in which the critical array contained two different target numerals, chosen independently (*9*). The subject's task was to report both numerals, both locations, and two confidence ratings. Sample arrays are shown at the top

0036/8075/78/1020-0315$00.50/0

of Fig. 1. In the first condition (*small*), each array consisted of four small inside characters surrounded by 16 larger outside characters. Since targets nearer the fixation point are easier to detect, we adjusted the sizes of the inside letters to approximately equalize the difficulty of detecting the inside and outside targets.

Two other conditions were investigated, *noise* and *reversal*. In the *noise* condition, the inside consisted of large characters (the same size as the outside), but detection of the target numeral was made more difficult by superimposing a randomly chosen squiggly line ("noise") on each inside character. In the *reversal* condition, background characters in the inside were numbers, and the target was a letter; that is, the types of targets and of background characters in the inside were reversed compared to all other conditions.

In all conditions, the outside was the same. The background characters were all the letters of the English alphabet except B, S, Z, Q, O, and I. In the reversal condition the numerals 0 and 1 were also omitted.

In some blocks of trials the subject was instructed to give most of his attention to the inside characters, in other blocks to the outside characters, and in still others he was told to pay equal attention to both. Control sessions were also run, in which the subject was told to report only inside targets or only outside targets.

Data from two subjects are shown in Fig. 1. Each point represents the mean performance for one block, consisting of 30 to 60 trials. In each graph, the ordinate indicates the probability of correctly identifying the inside target, and the abscissa indicates the probability of correctly identifying the outside target. (Both kinds of targets always occurred in each array.)

Figure 1 indicates that the subjects were able to follow the attention instructions. The data show that it is possible to "trade off" performance on one class of targets for performance on the other. The range of performances produced, as attention varies from being focused entirely on the inside targets to being focused entirely on the outside targets, defines a subject's attention operating characteristic (AOC) for this task (*10*). In this task, the AOC is approximately a straight line with slope of −1, indicating

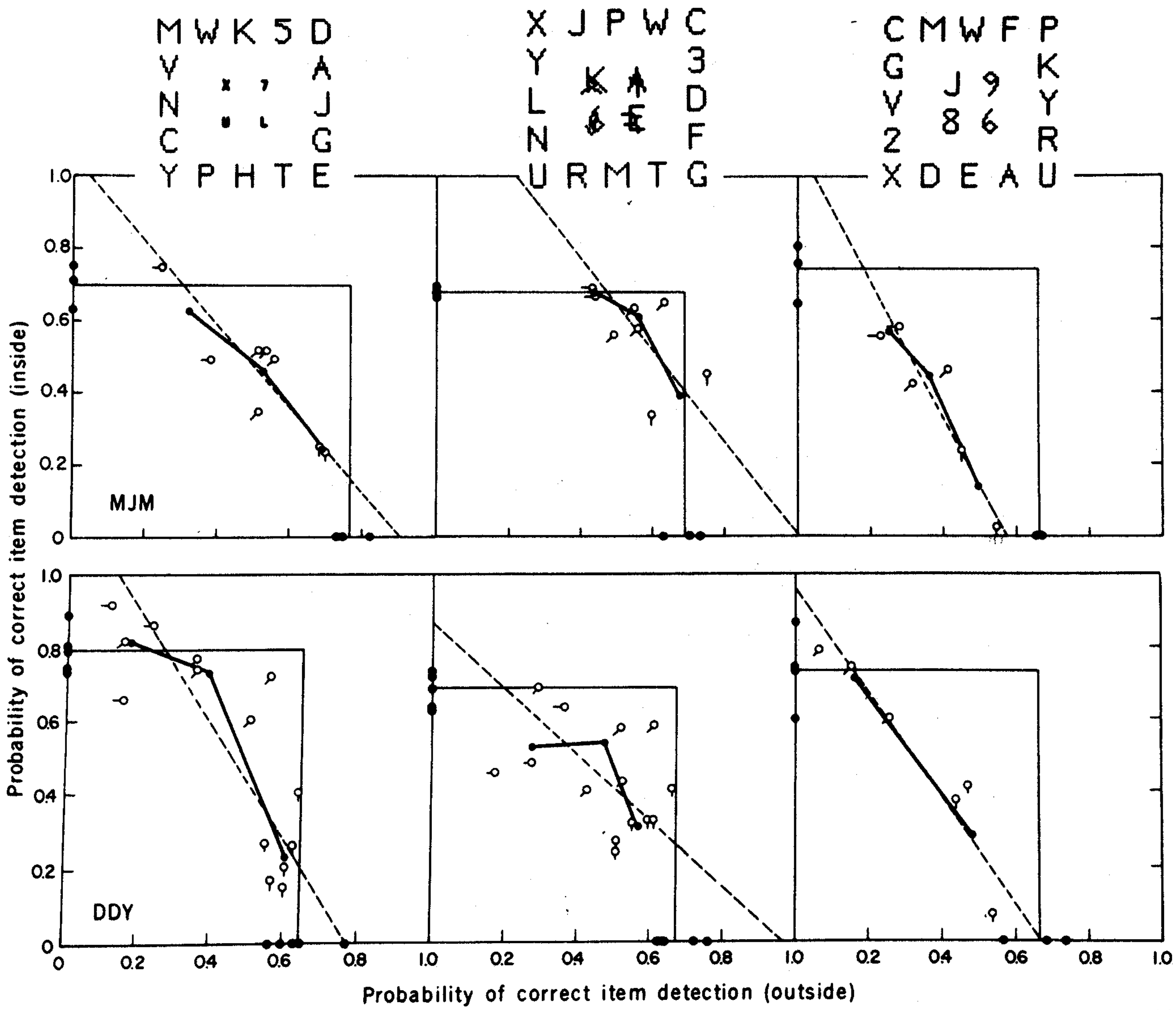

Fig. 1. The three displays at the top show typical stimuli from the *small*, *noise*, and *reversal* conditions; data from two subjects for each condition are shown beneath. Open circles represent sessions of 30 to 60 trials in which both targets were reported; the direction of the "tail" indicates the attention instructions; tail down, "give 90 percent of your attention to the outside"; tail left, "90 percent to the inside"; tail diagonal, "equal attention to both inside and outside targets." Closed circles on the axes represent control sessions in which only one previously specified type of target was to be reported; the vertical and horizontal lines represent the means of these control data. The heavy lines connect the average performance in each attention condition; they represent the empirically estimated attention operating characteristics. The light diagonal lines are the best staight-line fits to the data.

that the subject can exchange a certain amount of probability of correctness on one task for an equal amount on the other.

The data from the control sessions, in which the subject reported just one kind of target (for example, the outside target), are graphed directly on the axes of Fig. 1. A vertical line is drawn through the mean of the outside control data, and a horizontal line through the inside mean. The intersection of these two lines defines the "independence point," the point at which the subject would operate if he could perform both search tasks simultaneously without any interference—that is, independently of each other. Insofar as the AOC lies inside the independence point, it represents some degree of interference between the two tasks (*11*).

Interference between two search tasks does not occur because of any difficulty in remembering the targets long enough to report them. To prove this the display was altered so that the targets remained the same but each background character was replaced with just a single dot. In this case, subjects gave errorless reports of both targets. Thus, the subject's inability to report both targets in the experimental condition is due to the difficulty of executing the two complex search tasks simultaneously, and not merely to difficulty in reporting two targets.

When we compare performance in the *small* condition (Fig. 1, left) with that in the *noise* condition (Fig. 1, center), we note that the outside search task was the same in both conditions; the inside search task was matched to be of equal difficulty. Nonetheless, we see that for subject MJM the AOC curve is much closer to the independence point in the *noise* than in the *small* condition. This subject can carry out these two search tasks with targets of equal size with much less mutual interference than when the targets are of different sizes.

The right-hand portion of Fig. 1 illustrates performance in the *reversal* condition, where the subject searches for a letter target among numerals on the inside, and for a numeral target among letters on the outside. The data show that the mutual incompatibility of these two search tasks is nearly total.

In order to examine the mechanism by which the subject moves along the AOC curve—that is, the mechanism by which attention is shifted from one search task to the other—we examine the 2 × 2 contingency table (Table 1) which gives the joint occurrences of correct reports on the two tasks. This table has three degrees of freedom: two of these, the marginals P_1 and P_2, are used to define the AOC. The third degree of freedom (contingency, K) provides information about the mechanism of attention. We consider here two (of many) possible mechanisms: sharing and switching. The mechanisms are outlined below without formal derivations.

Table 1. Contingency table for the joint distribution of responses in tasks 1 and 2 of a divided-attention experiment. The marginal probabilities P_1 and P_2 reflect overall performance on each of the two tasks; the contingency parameter K reflects the degree of attention switching between tasks from trial to trial.

	Task 1		
Task 2	Wrong	Right	
Wrong	$(1-P_1)(1-P_2)$ $+K$	$P_1(1-P_2)$ $-K$	$1-P_2$
Right	$(1-P_1)(P_2)$ $-K$	$P_1 P_2$ $+K$	P_2
	$1-P_1$	P_1	

In attention sharing, attention is assumed to be divided between the two tasks in some fixed proportion that does not vary from trial to trial. Insofar as there is less attention devoted to each task than in a control condition, performance suffers relative to the control. In a pure sharing state (no trial-to-trial variations in attention), the 2 × 2 contingency table is assumed to show statistical independence—the probability of a correct response on one task is not influenced by whether the response on the other task was right or wrong.

In attention switching, one of two different attention states (A_1 or A_2) is assumed to occur randomly on any given trial. (A_1 and A_2 themselves may be pure states or mixtures.) To move along the AOC curve, the subject varies the proportion of times he is in A_1. Two interesting properties of attention switching are (i) mixtures of A_1 and A_2 produce a straight-line AOC curve connecting A_1 and A_2, and (ii) the contingency table for a mixed state is the mixture of the two separate contingency tables (A_1 and A_2). From property (ii) it can be shown that, under the conditions of the experiment, any contingency table produced by switching between states with purely independent tables has a negative correlation (corresponding to $K < 0$) and, given enough data, would show nonindependence by the chi-square test. In other words, on trials where the subject responds correctly on one task, he is less likely to respond correctly on the other.

When this analysis is applied to the data described above, we discover that the major mechanism of altering attention is switching, that is, altering the proportion of times the subject is in state A_1 or A_2. On the other hand, we can reject the hypothesis, at least for some of the data, that there are only two attentional states (that is, the states determined by the intersections of the AOC curves with the control-condition lines). The subject moves along an AOC by switching between different attentional states, but the particular states between which he switches are themselves states of shared attention influenced by the desired net performance.

We investigated how long it takes a subject to switch from one attention state to another. In a separate series of tests in the *reversal* condition, we placed the numeral and letter targets in different arrays of the sequence. When the letter target followed the numeral target by at least two arrays (480 msec) we observed greater independence (in the contingency analysis) and an increase in letter-detection accuracy. The results imply that after detection of an outside target, the subject switched attention from the outside to the inside in 240 and 480 msec, an estimate which is consistent with estimates from another technique (*12*) of measuring the reaction time of an attention switch.

In conclusion, we see that instructions to attend to one part of an array or another are enormously potent in determining from which part of the array signals will be detected. The instruction to give equal attention to the search for two different-sized targets caused our subjects to switch their attention from trial to trial, sometimes searching primarily for large targets, sometimes searching primarily for small. This result stands in remarkable contrast to our earlier finding (*3*) that a subject can search for ten different numerals in parallel when they are all the same size.

In a more general vein, we suggest that the AOC is a useful way of characterizing attention and particularly of describing the compatibility of two tasks. The compatibility of a pair of tasks to be performed simultaneously determines their AOC. To compare two pairs of tasks, one cannot use just one condition of attention for each pair, as this would be comparing one point from each of two curves and not comparing two curves (*13*). The mechanism by which a subject varies his performance along an AOC in the tasks we studied was primarily by switching attention between extreme states, but some sharing of attention also occurred.

GEORGE SPERLING*
Bell Laboratories,
Murray Hill, New Jersey 07974, and
New York University, New York 10003
MELVIN J. MELCHNER
Bell Laboratories,
Murray Hill, New Jersey

References and Notes

1. G. Sperling, *Psychol. Monogr.* **74**, (No. 11), (whole No. 498) (1960).
2. M. I. Posner, M. J. Nissen, W. C. Ogden, in *Modes of Perception*, H. J. Pick, Ed. (Erlbaum, Hillsdale, N.J., 1977); H. Egeth, in *The Psychology of Learning and Motivation*, G. H. Bower, Ed. (Academic Press, New York, 1977), vol. 11.
3. G. Sperling, J. Budiansky, J. G. Spivak, and M. C. Johnson [*Science* **174**, 307 (1971)] demonstrated parallel search for ten possible numeral targets. Thus, attention could not determine the sequence of mental search operations but only the relative effort devoted to each of the simultaneous search processes. According to R. M. Shiffrin and W. Schneider [*Psychol. Rev.* **84**, 127 (1977)], this kind of processing is "automatic" and not entirely—if at all—under voluntary control.
4. Several serious attempts to find evidence of an effect of selective attention on detection in a brief exposure have failed: J. J. Mertens, *J. Opt. Soc. Am.* **46**, 1069 (1956); H. Schuckman, *Am. J. Optom. Arch. Am. Acad. Optom.* **40**, 284 (1963). C. I. Howarth and G. Lowe [*Nature (London)* **212**, 324 (1966)] actually noted a small deleterious effect of signal uncertainty upon detection, although they ignored it in their conclusion.

   In instances where an effect of an attention instruction is observed, it has been attributed either to a change in effective noise level, as in tasks where stimulus signal-to-noise is the limiting factor [T. E. Cohn and D. J. Lasley, *J. Opt. Soc. Am.* **64**, 1715 (1974)], or to the way that partial information, which the subject obtains from the exposure, is weighted in his final decision [R. A. Kinchla, *Percep. Psychophys.* **22**, 19 (1977)]. In these cases, the subject is asserted to obtain the same information from the stimulus; he merely uses it differently according to the instructional demand.

   G. C. Grindley and V. Townsend [*Q. J. Exp. Psychol.* **20**, 11 (1968)] observed effects of attention instructions (informing subjects where targets would appear) on peripheral acuity and on differential luminance thresholds. In audition, similar results were obtained in studies of two or more tones being detected simultaneously against a noise background. See L. D. Pohlmann and R. D. Sorkin [*Percept. Psychophys.* **20**, 179 (1976)] for additional references. Unfortunately, the Grindley and Townsend study has serious methodological flaws: the attention instruction reduced uncertainty as to *where* targets would appear (therefore serving to "reduce noise"); the subjects' criteria for deciding whether to report or not could have varied between conditions; and finally, different, unreported exposure durations were used in single and multiple stimulus presentations, so that comparison between them is impossible.

   M. L. Shaw and P. Shaw [*J. Exp. Psychol. Hum. Percept. Perform.* **3**, 201 (1977)] demonstrated that targets are detected best when they occur in areas of display where they are presented most frequently. They interpret their data as resulting from the optimal allocation of mental processing resources, but their single-target paradigm does not rule out the alternative "uncertainty reduction" explanation. That is, when subjects know that signals occur more frequently in one area of a display, the subjects can profitably disregard partial information from other areas of the display that—without this foreknowledge—could have produced incorrect responses.
5. U. Neisser, *Cognitive Psychology* (Appleton-Century-Crofts, New York, 1967), pp. 67ff.
6. R. A. Monty and J. W. Senders, Eds., *Eye Movements and Psychological Processes* (Erlbaum, Hillsdale, N.J., 1976).
7. The cathode-ray tube was controlled by a Honeywell DDP/224 computer. It produced characters defined on 10 × 10 dot matrices; the average number of points per character was 22. Characters were painted once. The luminous energy per point per painting was 1.5 cd/μsec [G. Sperling, *Behav. Res. Methods Instrum.* **3**, 148 (1971)]. The background screen luminance was 0.3 cd/m^2. The large letters were 1.0 cm high and spaced 1.7 cm apart center to center. Small letters were 0.42 cm and spaced 1.7 cm apart. Viewing distance was 1.1 m.
8. Confidence categories were used to reduce the effect of chance guessing on the data. When responses in a confidence category were shown to be statistically unrelated to the stimulus, they were all scored as incorrect. See G. Sperling and M. J. Melchner, *J. Math. Psychol.* **13**, 192 (1976).
9. ______, "Multiple detections in a brief visual stimulus: the sharing and switching of attention," paper presented to the Psychonomic Society, Denver, 7 November 1975; in *Information Processing in the Visual System*, V. D. Glezer, Ed. (U.S.S.R Academy of Sciences, Pavlov Institute, Leningrad, 1976), pp. 224–230.
10. The term "attention operating characteristic" was first proposed by R. A. Kinchla, unpublished address at Attention and Performance III, Soesterberg, Netherlands, 4 to 8 August 1969; also in *Tech. Rept. No. 29* (Department of Psychology, McMaster University, Hamilton, 1969).
11. According to D. A. Norman and D. G. Bobrow [*Cognitive Psychol.* **7**, 44 (1975)], the AOC is a "performance-performance" operating characteristic; the fact that the sloping portion of the AOC does not pass through the points representing data from control conditions means that near the axes the dual task is "data limited" and it becomes "resource limited" only when sufficient attention is withdrawn from a component task to impair its performance.
12. G. Sperling and A. Reeves, "Reaction time of an *un*observable response," unpublished address, Psychonomic Society, St. Louis, 11 November 1976.
13. A similar problem occurs in signal detection theory with receiver operating characteristics (ROC curves). The profound analogy between mechanisms that generate AOC and ROC curves is developed by G. Sperling and M. J. Melchner, in *Attention and Performance VII*, J. Requin, Ed. (Erlbaum, Hillsdale, N.J., 1978), pp. 675–686.
14. We wish to acknowledge the assistance of Judith Harris.

* Send requests for reprints to G.S., Room 2D-518, Bell Laboratories, Murray Hill, N.J. 07974.

21 March 1978; revised 5 July 1978