COGNITIVE PSYCHOLOGY 3, 674 698 (1972)

Parallel Processing of Multielement Displays[1]

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The spatiotemporal characteristics of mechanisms that extract information from complex alphanumeric displays were investigated in a series of experiments using search and same–different detection tasks. Under several (but not all) experimental conditions the functions relating reaction time to the number of elements in the display were flat. Such data are consistent with a model in which individual elements are examined by independent parallel channels. Interestingly, this model was appropriate even in a search task in which the target was specified as any digit and the nontargets were a random assortment of letters.

In recent years considerable effort has been devoted to the analysis of tasks in which Ss must respond on the basis of information contained in a briefly presented display such as an array of alphanumeric characters. There have been two main thrusts to this research. One has been to develop measures of the "span of apprehension" in the absence of response or memory limitations (e.g., Sperling, 1960), while the other has been to determine the mode of processing of such displays (e.g., Estes & Taylor, 1966). This latter topic forms the focus of the present study. More specifically, this research is designed to explore the parallel/serial processing issue that has received so much attention in recent years (see, e.g., Corcoran, 1971, Ch. 2).

Gardner (1970) has provided an excellent summary of previous work on the spatiotemporal characteristics of visual information processing. In that review he divided the research into four categories on the basis of experimental methodology: whole report, partial report, masking, and detection. In the whole report paradigm S is required to identify as many of the elements in the display as possible after stimulus offset; this procedure was widely used in early work on the span of apprehension (Woodworth & Schlosberg, 1954, Ch. 4). Unfortunately for an investigator interested in studying characteristics of the perceptual system, the whole report method is compromised because performance is limited by the capacity of the short-term memory system. Indeed, Ss forced to use the whole report method frequently complain that they can "see" more than they report; by the time they have identified a few elements, the others have faded away. Sperling (1960) reduced the influence of memory on the measurement of the span by using a partial report paradigm. Shortly after termination of the stimulus array (a three-row matrix) an auditory signal indicated which row of elements to report. However, even when the poststimulus cue indicates that only a single stimulus is to be identified (Averbach & Coriell, 1961), this technique still implicates memory, as the display must be retained until the cue is presented and deciphered. This same criticism may be made of the backward masking paradigm in which inferences are made about the mode of processing from performance when display processing is terminated by a field of visual noise presented some time after the termination of the stimulus array (Sperling, 1963).

Perhaps the best method for studying perceptual aspects of visual information processing is the detection paradigm, which is a generic name for a variety of experimental tasks. What these tasks have in common is that the S is asked to make a simple response such as a key press as soon as he detects some predefined aspect of the display. In contrast to the previously described paradigms, the response is very simple and there is little need for S to load the *display* into short-term memory because he knows what to look for and can start processing immediately upon presentation of the stimulus array. Of course memory *is* implicated to the extent that the criterion for response is difficult to remember.

The two major varieties of detection tasks are search and same–different discrimination. In a search task an S may be asked to indicate whether or not a particular element, called the target, is present in the array; this may be referred to as a yes–no (or a presence–absence) response. Alternatively, S may be asked to indicate which one of two (or more) specified target elements is contained in an array; this is a forced-choice response. In the same–different task Ss are asked to indicate whether the elements of the array are all identical to one another or whether (at least) one element differs from the others.

There are several ways in which detection experiments have been used to help to elucidate how the information in a brief visual display is processed. To cite just a few examples, response accuracy has been studied

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[1] This research was supported in part by a contract between The Johns Hopkins University and the Engineering Psychology Programs Office of Naval Research, and in part by a grant from the United States Office of Education, Grant OEG-3-3002840037-(010). The authors thank W. Bevan and H. Hock for their helpful suggestions during the running of the experiments, and to S. Collyer, G. Gardner, E. Smith, S. Sternberg, and J. Townsend for many useful comments on earlier drafts of this paper.

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as a function of the total number of elements in a display (Estes & Taylor, 1964), and as a function of the rate of presentation of display elements (Eriksen & Spencer, 1969), while reaction time has been studied as a function of the number of target elements (Bjork & Estes, 1971) and the number of total elements (Atkinson, Holmgren, & Juola, 1969). In the present paper the variables of major interest were mean reaction time (RT) and the total number of display elements (*N*). This choice of variables was based on the analytic power that has been demonstrated for latency measures, especially when used in conjunction with number of stimulus elements (e.g., Sternberg, 1966). In the following sections several information processing models are described and their predictions concerning the relation between mean RT and *N* are presented. Relevant findings from previous experiments are also discussed.

Serial Processing

Consider a model in which a decision is reached by examining the elements of a display one after another. On such a model the relation between RT and *N* should be linear (Egeth, 1966; Sternberg, 1966). Note that this is merely the simplest prediction from the model; it is based on certain implicit assumptions which, if violated, may require a modification in the prediction. For example, suppose a display were to be presented so briefly that the quality of its "image" decayed substantially before all of its elements were processed. As *N* increased more elements would have to be processed in a decayed state, and RT would not necessarily be a linear function of *N*. Another potential complication worth mentioning concerns the concept of examination. Without specifying further details, we assume that each display element is associated with an operation called examination. However, it is possible that elements are not examined in precisely the same way when a target is specified before stimulus presentation (search) as when no target is presented (same–different).

In yes–no search tasks and same–different tasks the two responses are not logically equivalent because "No" and "Same" responses must be based on examination of all of the stimulus elements, i.e., testing must be exhaustive. In contrast, "Yes" and "Different" responses may, logically, be made as soon as a critical element (a target or a "Different" element) is detected, i.e., testing may be self-terminating. Of course testing need not be self-terminating just because the logical possibility exists (cf. Sternberg, 1967). It is possible to distinguish between the exhaustive and self-terminating varieties of processing by comparing RT as a function of *N* for the two kinds of response. If processing is exhaustive the functions should have the same slope, while if it is self-terminating and a single critical element is contained in the display the "Yes" (or "Different") function will have a slope half as large as the "No" (or "Same") function. The reasoning here is that if a single target or a different element is present it will be examined and thus detected, on the average, after $(N + 1)/2$ of the elements in the display have been examined.

There are other aspects of a serial model that may be tested empirically such as whether the order of examination of elements is fixed or random (Egeth, 1966), but the preceding will suffice for the present analysis.

Some of the strongest support for a model of serial examination of stimulus elements comes from yes–no search tasks. Sternberg (1967) studied visual search in the context of an experiment in which search through memory was also being investigated. On each trial Ss were given a short list of digits to memorize; they were then presented with a visual display consisting of 1, 2, or 3 digits. The task was to indicate whether or not any of the digits in memory matched any of the digits in the visual display. The RT data led Sternberg to conclude that the two kinds of searches (visual and memory) progress at about the same rate (37 msec/element) but that memory search is exhaustive while visual search is self-terminating. These conclusions are consistent with data obtained by Nickerson (1966) in a very similar experiment.

Atkinson, Holmgren, and Juola (1969) also used a yes–no response in a search task. On each trial a single consonant was specified as the target element and S had to search through a horizontal array of from one to five consonants to determine if it was present or absent. The functions relating mean RT to *N* were linear, but the slopes for the "No" and "Yes" responses were both about 25 msec/element.[4] Thus although these data are consistent with a serial model, they are inconsistent with Sternberg's conclusion that visual search is self-terminating.

Estes and Wessel (1966) determined mean RT and accuracy as functions of *N* is a forced-choice version of the detection paradigm. As *N* assumed the values 1, 4, and 8 (Expt II) mean RT increased from 587 msec to 775. We might translate this into a slope of approximately 27 msec/element, however, this calculation is somewhat suspect because the function was not quite linear, and because the error rates varied from 3% to more than 20% across conditions. It is possible that the departure from linearity was due to the brevity of the stimulus exposure (1 msec) which may have resulted in rapid decay of the visual image as discussed earlier.

Holmgren (1970, Expt 1) also used a forced-choice search task but with an exposure duration of 400 msec. In this study as *N* assumed the values one through five the function relating mean RT to *N* was linear with a slope of about 54 msec/element.

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[4] The slope estimate of 25 msec/element is taken from "Terminal Response" data, Table 3, of Atkinson, Holmgren, and Juola (1969).

Using the same–different discrimination paradigm, results partially in accord with the notion of serial processing were obtained by Beller (1970, Expt 1). Stimuli were 2, 4, or 8 letters presented in a horizontal row. The Ss were instructed to respond "Same" if all of the letters had the same *name*, and "Different" otherwise. Note that the criterion for decision was not physical identity but conceptual identity (i.e., G and g were regarded as the same). Although mean "Same" RTs did not increase with N, the mean "Different" RTs did. Indeed, for the conditions in which only a single element differed from the others the function relating mean RT to N was linear with a slope of about 20 msec/element.[5] If it is assumed that these "Different" responses were the result of a self-terminating process, then the slope implies that elements were processed at a rate of about 40 msec each.

Parallel Processing

Parallel models are characterized by the assumption that stimulus elements can be examined simultaneously. For the sake of simplicity we shall further assume the processing of all elements begins simultaneously although the examinations do not necessarily end simultaneously.

With all stimulus elements being examined simultaneously, it might appear that mean RT should not increase with N. Actually, however, only a subset of parallel models leads to such a prediction. There are two important issues that bear on this point. One concerns processing "capacity." (Alternatively, this argument might be phrased in terms of processing "energy.") If processing capacity is limited in amount, then as N is increased the capacity available per element must decrease, and such a decrease might lengthen stimulus examination time. Atkinson, Holmgren, and Juola (1969), Corcoran (1971), and Townsend (1971) have all discussed this issue and have pointed out that linearly increasing mean RT functions need not be inconsistent with a limited-capacity model. Thus, it is possible that some of the studies that have been taken as evidence for a serial model may turn out upon closer inspection to be consistent with a parallel model. In contrast to a model in which processing capacity per element varies inversely with N, it is possible to describe a model in which processing capacity per element is independent of N. The basic assumption underlying this conception is that there are a number of independent information processing channels available, and that each element is allotted to a separate channel. Thus the processing capacity utilized on any trial is simply proportional to the number of elements, as long as N does not exceed the number of channels.

The second important issue concerns the variability of examination times for individual stimulus elements. If these times are not fixed then even on an independent parallel channels model mean RT need not be unrelated to N. Imagine a process in which the amount of processing capacity available for any given element is independent of N. For an exhaustive process ("No" or "Same"), if the component tests have nonzero variances, and have stochastically independent durations, then mean RT ought to increase with N (cf. Gumbel, 1954; Rapoport, 1959). Briefly, the reason for the increase is that for an exhaustive process a correct decision must wait upon the outcome of the slowest examination, and the larger the number of such tests the greater is the expected value of the last test to be completed. It is not possible to describe exactly the function relating mean RT to N for this model without specifying the distribution of examination times for a single component.

The preceding arguments suggest that mean RT would be unrelated to N for an exhaustive parallel process only if: (1) processing capacity per element did not decrease as N increased, and (2) examination times were fixed rather than randomly distributed, and were equal from one element to another. For a self-terminating process when the stimulus array contains a single target or different element the requirements are relaxed somewhat; all that seems necessary for the prediction of a flat mean RT function is the assumption of independent parallel channels.

It is worth noting that the only way a serial model could account for mean RT being unrelated to N (without recourse to a speed–accuracy tradeoff) would be to assume that examination times decrease as the number of elements is increased. As this seems psychologically implausible we shall consider a flat function relating mean RT to N as evidence of parallel processing. Some studies in which such functions were obtained are discussed below.

Donderi and Zelnicker (1969) used a same–different task in which Ss had to indicate whether all of the elements in the visual field were identical to one another or whether there was a discrepant element present. The elements were geometric forms such as circles and squares, which varied randomly in number from 2 to 13. The finding of chief interest was that mean RT was unrelated to N for both "Same" and "Different" responses, averaging about 1200 msec. This work was repeated under conditions designed to decrease the average RT (Donderi & Case, 1970), and in this experiment mean RT was again unrelated to N, but now averaged about 800 msec.

Connor (1971) used a task like Donderi and Zelnicker's in which the

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[5] This slope was estimated by plotting "Different" RT as a function of N from data given by Beller (1970) in his Table 2 (the values used for $N = 2$, 4, and 8 were, respectively, 528, 565, and 650 msec).

elements were letters and N assumed the values of 3, 6, and 12. Mean RT, which averaged about 550 msec, was again unrelated to N.

In the previously cited study by Beller (1970) Ss were asked to judge whether elements all had the same name or not. Unlike the times for "Different" responses, mean "Same" RTs were not significantly affected by N. In particular when the elements were all physically identical (e.g., AAAA) mean RTs averaged about 465 msec.

This brief review indicates that in several experiments mean RT increased 25–55 msec for each element added to a display, while in several other studies mean RT was uninfluenced by N. Even apart from the possible significance of these results in examining the issue of parallel and serial processing, the difference in outcomes is striking and deserves further investigation.

As might be expected, the studies cited above differ from one another in many ways such as display duration, overall visual angle, stimulus materials, arrangement of elements, degree of practice, etc. In the present experiments no effort was made to investigate these factors parametrically. Instead a single set of conditions similar to those used by Donderi and Zelnicker (1969) was selected for all of the present experiments. Overall visual angle of the displays was held constant and elements were located randomly within the displays. If visual angle were allowed to increase with N as it has in most of the cited studies, then mean RT might be expected to increase somewhat with N due simply to the fall off in sensitivity with increasing distance from the fovea. And if elements were arranged in an orderly fashion such as along a horizontal line, reading habits might induce a strategy of serial scanning. In short, the conditions selected were considered to be fair to all competing models.

GENERAL METHOD

Tasks

Search and same–different tasks were employed in this research. In the search tasks, on half of the trials the array contained one target element along with nontargets, while on the other half of the trials only nontargets were present. Two sets of Ss were employed. One set (presence responders) was instructed to respond by pressing a telegraph key as soon as they detected a target item, and to refrain from responding when no target item was present. The other set of Ss (absence responders) was instructed to press the key as soon as they had ascertained that no target was present, and to refrain from responding otherwise.

Similarly, in the same–different task, on half of the trials all of the stimulus elements were identical to one another while on the other half there was a single different element present. The two sets of Ss used here shall be referred to as sameness responders and difference responders.

Stimuli

The stimulus elements were Prestype 24 pt black Futura Demi numerals and uppercase letters. They were mounted on cards within a 76 by 76 mm white area.

The number of stimulus elements on a card varied from 1 to 6 in the search experiments and from to 2 to 6 in the same–different experiment. It was deemed more desirable to keep overall visual angle controlled from trial to trial and thus let display "density" increase with N, than to keep density controlled and let overall visual angle increase. To accomplish this and to provide a systematic method of constructing stimulus cards, the configuration shown in Fig. 1 was used. Stimuli appeared equally often at the 12 locations. In a search task when only one element was present (be it a target or a nontarget), it was located at one of the loci. When two elements were present, they were located at diametrically opposed loci. When three elements were present, two (including the target when a target was present) were at diametrically opposed loci, while the third location was randomly selected from the remaining positions. Similar procedures were used for 4, 5, and 6 element trials. The important point is that on every trial with two or more stimuli, there were at least a pair of stimuli separated by the diameter of the stimulus array. To avoid crowding, the use of more than three adjacent loci was not permitted. When such a sequence occurred, one of the elements was randomly relocated.

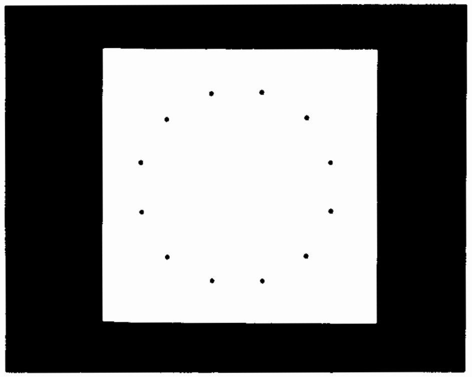

FIG. 1. Loci used for placement of stimulus elements. No dots were present on actual stimulus cards.

The construction of cards for the same–different conditions was essentially the same as in the search conditions, except that where special precautions had been taken to place the target elements now these precautions were taken in the placement of "Different" elements.

As errors tend to be disruptive in a reaction time task, some additional cards were prepared, and whenever an error was made, one of these extra cards was used on the next trial. Data were not collected on a trial following an error.

Procedure

Stimulus cards were displayed for 150 msec in a Scientific Prototype two-channel tachistoscope at a viewing distance of 84 cm. The center-to-center distance between diametrically opposed stimulus elements subtended a visual angle of 3.4°, and between the closest adjacent elements 0.9°. The elements themselves were approximately 0.3° in height with a stroke width of 0.06°.

Between trials a small black fixation point on a white background indicated the center of the visual field. One second before stimulus presentation Ss were alerted with a verbal ready signal. The intertrial interval was approximately 5 sec.

Response latency was measured from the onset of the stimulus to the depression of the telegraph key with the thumb of the preferred hand. Errors were also noted and reported to S after each trial, although no feedback was provided about response speed.

The Ss were instructed to ". . . work accurately, and within that limitation as quickly as possible." All Ss received $1.50 for participating in a session. The sessions ranged from 15–30 min depending on the experiment. Only experiment four required more than a single session; no S served in more than one experiment.

EXPERIMENT I

Method

A same–different task was used in which the elements to be discriminated consisted of 4s and Cs. On each "Same" card all of the elements were identical to one another (all Cs or all 4s) while on each "Different" card one discrepant element was present (e.g., one C and three 4s; one 4 and five Cs).

The number of elements varied from 2 to 6 and there were 24 cards prepared for each level of *N*, for a total of 120. Half were "Same" and half "Different" at each level of *N*. These stimulus cards were presented in a different random order to each S. In addition to the 120 test cards there were 10 practice cards and some extra cards to follow error trials.

In the construction of stimulus cards every effort was made to eliminate biases that might be noticed by Ss. Thus, overall, 4s and Cs were used equally often, and each was used equally often as the discrepant element of "Different" cards. Moreover, the 12 possible loci were used equally often for discrepant elements, and very nearly equally often overall.

The Ss were male students at the Johns Hopkins University. Six served as sameness responders, six as difference responders.

Results and Discussion

Mean RT is plotted as a function of *N* in Fig. 2, error rates are given in Table 1, and summary statistics appear in Table 2. It is obvious that mean RT is unrelated to *N*. It is equally clear that error rates are also not systematically related to *N*. It should be noted that virtually all these errors were errors of commission (false positive response) rather than omission (missed responses). As a result of pilot testing, it became clear that errors of omission were rare (less than 5% of all errors), and as a result we have not tabulated them separately from errors of commission.

The results of this first experiment suggest that processing of elements is carried out in parallel. The results confirm the findings of Donderi and Zelnicker (1969), Donderi and Case (1970), and Connor (1971). The mean RTs in the present study are substantially faster than any obtained

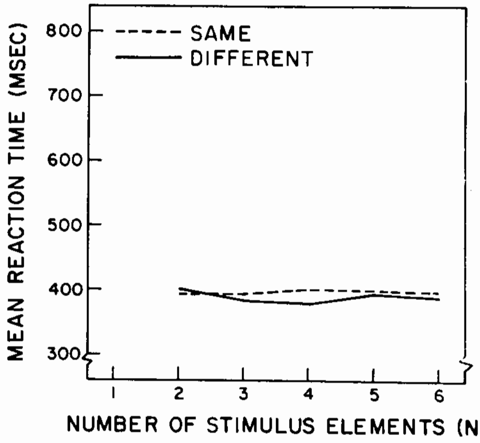

FIG. 2. Mean reaction time as a function of the number of stimulus elements. Expt I.

TABLE 1

Proportion of Errors at each level of N in each Experiment[a]

Expt Day	Condition	No. of Stimulus elements 1	2	3	4	5	6
I	Same	—	0	.014	.007	.021	.007
	Different	—	.021	.056	.035	.014	.014
II	Absent	0	.014	.056	.056	.042	.035
	Present	.014	.021	.014	.049	.035	.035
III	Absent	.021	.042	.021	.031	.052	.058
	Present	.016	.016	.021	.037	.042	.058
IV	Absent						
1		.062	.021	.042	.083	.062	.125
2		.104	.021	.021	.062	.042	.062
3		.062	.000	.000	.062	.021	.021
4		.042	.042	.021	.021	.000	.042
	Present						
1		.062	.083	.083	.062	.042	.042
2		.062	.062	.083	.042	.062	.042
3		.062	.062	.083	.042	.062	.083
4		.062	.042	.146	.146	.021	.062

[a] Entries are proportions of total errors, including omissions as well as commissions in Expts I, II, and III.

in the previous same–different studies, which is important to the extent that long RTs suggest the importation of additional factors (such as double-checking or unnecessary exhaustiveness) into what is meant to be a simple situation.

In the next experiment essentially the same materials were used in the context of a search task to provide a basis for comparing the two varieties of detection paradigm.

EXPERIMENT II

Method

In this study a search task was used in which the target element was a 4 and the nontargets were Cs. On each "Absent" card all of the elements were Cs, while on a "Present" card a single 4 was present (e.g., one 4 and three Cs).

The number of elements varied from 1 to 6, and at each level of N there were 12 "Present" and 12 "Absent" cards, for a total of 144 cards. These cards were shown in a different random order to each S. The same kinds of precaution taken with the construction of stimuli in Expt I were

TABLE 2

Summary Statistics for Expts I, II, III, and IV

Expt	Response (day)	Anova significance of effect of N p	Intercept ±SE[a]	Slope ± SE (msec/element)[a]	Significance of linear component[b] p	Percentage linear[c]
I	Same	NS	396 ± 9.0	0.9 ± 1.3	NS	—
	Different	NS	395 ± 19.2	−1.5 ± 2.0	NS	—
II	Absent	NS	416 ± 19.0	−0.2 ± 2.1	NS	—
	Present	<.01	294 ± 7.2	6.3 ± 0.9	<.001	87.7
III	Absent	<.001	458 ± 24.9	26.0 ± 4.1	<.001	91.4
	Present	NS	369 ± 14.0	3.9 ± 2.1	<.05	74.2
IV	Absent					
	1	<.001	472 ± 22.4	28.1 ± 5.8	<.001	98.5
	2	<.01	449 ± 24.2	13.1 ± 2.7	<.001	91.4
	3	<.05	453 ± 31.2	7.2 ± 1.2	<.01	69.6
	4	NS	436 ± 23.4	4.1 ± 2.1	NS	—
	Present					
	1	NS	448 ± 24.3	7.0 ± 3.0	NS	—
	2	NS	428 ± 14.6	2.9 ± 2.9	NS	—
	3	NS	415 ± 14.8	3.2 ± 1.6	NS	—
	4	NS	408 ± 17.7	0.7 ± 1.0	NS	—

[a] Intercepts, slopes, and their corresponding standard errors are based on individual regression analyses by subject.

[b] Significance of linear components were calculated by overall trend analysis using orthogonal polynomials.

[c] All functions were tested for departure from linearity; none were significant.

also taken with the placement of stimuli in the present experiment. There were 12 practice trials before the test sequence was shown.

Six *Ss* were instructed to respond to the presence of a 4, while six were instructed to respond to the absence of a 4.

Results and Discussion

Mean RT is plotted as a function of *N* in Fig. 3, error rates are given in Table 1, and summary statistics appear in Table 2.

Mean "Absence" RT was unrelated to *N*, however, mean "Presence" RT was significantly affected, with the linear component accounting for 87.7% of the variance. Error rates increased somewhat with *N*, but not monotonically.

As a preliminary statement we may point out that the "Absence" data are consistent with an independent parallel-channels model with fixed examination times, if one assumes that the associated error data are well approximated by a function that does not increase with *N*. The slight slope for mean "Presence" RT renders those data more difficult to interpret.

In the preceding two studies stimulus elements were easily distinguishable. Indeed, it is likely that any of several distinctive features could serve as the basis for decision. In the following experiment an attempt was made to investigate search processes in circumstances where a conceptual rather than a physical classification was called for.

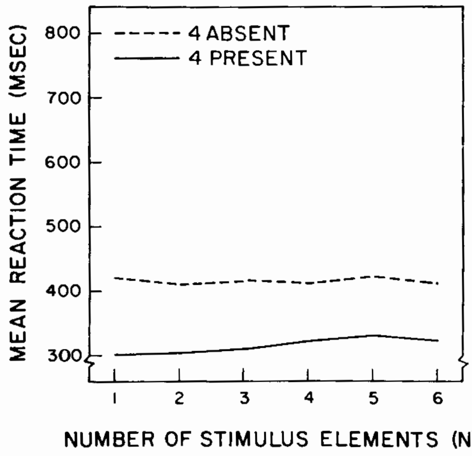

FIG. 3. Mean reaction time as a function of the number of stimulus elements. Expt II.

EXPERIMENT III

Method

A search task was used in which the target was defined as *any digit,* while the nontargets were letters. (Actually, to avoid confusion, the numerals 1 and 0, and the letters I, O, Q, S were excluded.) On each "Absent" card all of the elements were letters (e.g., G, P, X, Y), while each "Present" card contained one number (e.g., 6; as another example, N 7 R P A).

There were 24 cards prepared for each level of *N* (1–6), 12 "Presence" and 12 "Absence," for a total of 144 cards. These cards were shown in a different random order to each *S*. The choice of digit for each "Present" card was random without replacement as was the choice of letters on both "Present" and "Absent" cards. In all other respects the stimuli and procedures were the same as Expts I and II.

Sixteen *Ss* served, half as presence responders, half as absence responders.

Results and Discussion

Mean RT for each level of *N* is shown in Fig. 4, error rates are given in Table 1, and summary statistics appear in Table 2.

The relation between mean "Absent" RT and *N* was strong with a slope of 26.0 msec/element. However, for "Present" responses the 3.9 msec/element rate of increase of mean RT with *N* was so small, relative to

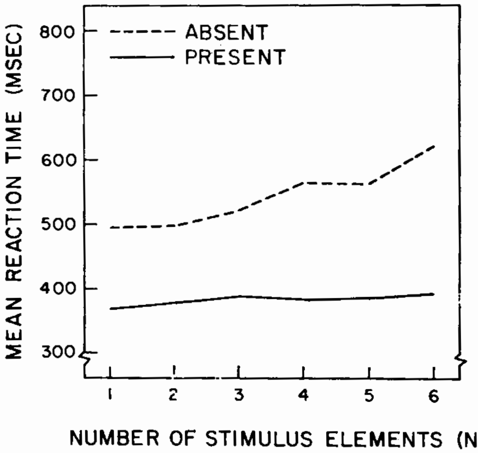

FIG. 4. Mean reaction time as a function of the number of stimulus elements. Expt III.

both the rate for "Absent" and to the rate for "Present" in other studies, that we feel that a suitable description of the data is that mean RT is invariant with N.

One possible interpretation of these results is that in the search for a digit, information is first processed from all elements simultaneously. If no number is actually present, the elements are then examined serially at a rate of 26 msec/element before S is willing to actually conclude that no number is present. In other words, the responses of "Present" and "Absent" may be triggered as the result of two separate test mechanisms, the former being fast and parallel, the other being relatively slow and serial. A similar idea has been offered to account for data obtained in same–different tasks (e.g., Bamber, 1969; Egeth & Blecker, 1971), and the suggestion may also be appropriate here.

EXPERIMENT IV

Method

As an extension of the preceding work this experiment was undertaken to determine if "Presence" and "Absence" information is handled differently when each S must make both kinds of response. Because pilot data showed that the two-response task is more difficult than the one-response tasks, Ss were observed during four experimental sessions.

Stimulus materials were identical to the ones used in the previous experiment. Four Ss were run for 4 days each. On each day they received 12 practice trials and 144 test trials (plus any extra trials needed to follow errors). The cards were shuffled thoroughly before each session. Two of the Ss responded "Present" with their preferred hand while two responded "Absent" with their preferred hand.

Results and Discussion

Mean RTs as a function of N for each day of practice are presented in Figs. 5 and 6, corresponding error rates are given in Table 1, and summary statistics appear in Table 2.

For "Presence," mean RT was not significantly related to N in any of the four sessions. The slope of the "Absence" function decreased monotonically with practice. It started at a highly significant 28.2 msec/element and decreased by the fourth session to an insignificant 2.9 msec/element. Errors were not systematically related to N at any level of practice.

EXPERIMENT V

It is tempting to consider the several flat functions we have obtained as evidence for a parallel model, especially where error rates were also unrelated to N. However, it is possible to account for flat or nearly flat mean RT functions without recourse to the concept of parallel processing. One such alternative explanation is that in any given experiment Ss may have responded consistently at the speed appropriate to the most difficult condition (i.e., $N = 6$). This strategy would have "artificially" raised the mean RTs for all other conditions to the RT appropriate for $N = 6$, thus yielding a flat function. To test this alternative hypothesis all of the

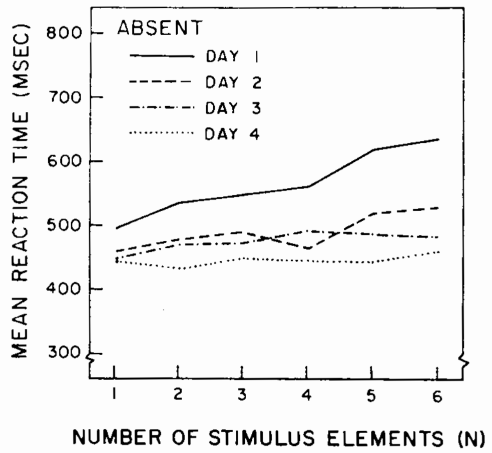

FIG. 5. Mean "Absence" reaction time as a function of the number of stimulus elements. Expt IV.

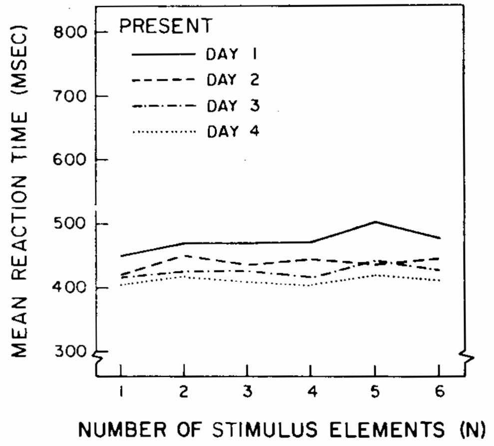

FIG. 6. Mean "Presence" reaction time as a function of the number of stimulus elements. Expt IV.

cards from the deck used in Expt III were selected on which there were one or six elements; there were 24 of each. Sixteen Ss, all presence responders, were divided into two equal groups. One group was presented only with the stimuli with one element; they received 4 practice trials and then the 24 test trials. The other group was treated in the same way except that they were shown only the six-element stimuli. For the Ss in the one-element group mean RT was 367 msec (5.2% errors), while for the Ss in the six-element group mean RT was 433 msec (4.7% errors). Comparing these results to the lower function in Fig. 4, it is clear that the mean RT for the one-element Ss in this study was *not* any slower than the corresponding mean RT in Expt III (369 msec). However, the six-element Ss of the present study were substantially slower than their counterparts.

It should be pointed out that the Ss serving in Expt V received fewer trials overall than those who had served in Expt III (about one-sixth as many since they only were shown the stimuli appropriate to a single level of N). Thus, although Ss in the two experiments were equated in terms of specific practice at the relevant levels of N they were not equated in terms of general practice at the task. While this presents a potentially troublesome problem, inspection of practice effects within Expt III indicated that they were quite small—and for $N = 1$ actually nonexistent. (Note: the substantial practice effects in Expt IV were in all likelihood due to the initial difficulty of the two-response task. With the single-response task used in the other experiments there was little, if any, improvement beyond the first few trials.) In all, it does not seem likely that Ss serving in the mixed-list design of Expt III were responding artificially slowly when N was less than six.

The comparison of the data from Expts III and V is provocative. It is not yet clear why a within-S manipulation of N should yield a virtually flat mean RT function while a between-Ss manipulation of the same variable results in a substantial effect (367 vs 433). One possibility is that Ss may trade speed for accuracy differently under the two kinds of manipulations. More specifically, perhaps the virtual invariance of mean RT with N in the mixed-list design results from Ss attempting to keep response speed fairly constant and permitting errors to increase with N. This possibility must be kept in mind as an alternative to a parallel model.

GENERAL DISCUSSION

In the Introduction several of the difficulties involved in distinguishing parallel from serial processing were discussed. At this point these difficulties come back to haunt us with a vengeance. In particular, the interpretation of functions in which mean RT increases with N is difficult, as both parallel and serial models are consistent with such data. Let us turn first, therefore, to data that may be interpreted with less ambiguity.

In the same–different task of Expt I the functions relating mean RT to N were virtually flat. Moreover, errors did not increase with N, and thus we need not be concerned with the possibility that the flatness of the functions is due to a tradeoff between speed and accuracy of response. These data are consistent with a model in which all stimulus elements are examined simultaneously and independently. Furthermore, since the response "Same" is the result of an exhaustive process we may follow the reasoning presented in the Introduction and conclude that examination times are fixed, not randomly distributed.

The relation between "Same" and "Different" RTs deserves some comment. In the present study they were essentially identical. However, in pilot work we consistently found "sames" to be slower, by at least 25 msec and often considerably more. The lack of difference in overall level between the two functions in Fig. 2 may possibly be due to sampling variability, since the standard error of the difference between intercepts was 21 msec.

The other set of clear data comes from Day 4 of Expt IV. Mean "Present" RTs, mean "Absent" RTs, and error rates were all unaffected by N. These data indicate that after several days of practice the classification of stimulus elements as numbers or letters can be carried out simultaneously and independently on up to six characters. Again, the flatness of the function for the exhaustive process ("Absent") suggests that examination times were fixed rather than distributed. The results of this experiment must be considered the most striking of the present series of studies because they suggest that fairly complex classifications of stimuli can be carried out in parallel. This is quite different from the situation in Expt I where Ss might have based their decision on a single distinctive feature, and thus exhibited a capacity for parallel processing at a fairly low level.

In a recent paper Brand (1971) has suggested that there may be some conceptual categorization processes that are quite "immediate." Specifically, her experiments compared conditions of visual search in which Ss looked for any digit in a background of letters with conditions in which they looked for a specific digit. The results indicated that these two searches were accomplished at about the same speed, and that both were faster than a condition in which Ss looked for a specific letter in a background of other letters. It might have been expected that search for a specific character would be faster than search for "any digit" because in the former case Ss could set themselves to look for a distinctive feature or combination of features. However, her results belie this expectation; they are consistent with the notion that the categorization of a stimulus element as being a number or a letter may *precede* analysis of distinctive physical features. To put the matter differently, the overlearned categorization is the "easy" task, while discrimination based on physical configuration is the "difficult" task. Obviously the present series of studies was not designed to investigate this same point. However, the finding that supposedly complex number/letter categorizations can be carried out in parallel is nicely consistent with Brand's results.

The remaining data are somewhat more difficult to interpret. For example, in the search task of Expt II mean "Absent" RT was unrelated to N, whereas mean "Present" RT did increase, by about 6 msec with each additional element. The data for "Absent" responses are thus consistent with the same strong conclusions drawn above for exhaustive processes in Expt I and on Day 4 of Expt IV. However, if processing were parallel with unlimited capacity, then mean RT for "Present" responses should not have increased with N. One possible resolution of this apparent paradox is that the flatness of the "Absent" function may have been due to a tradeoff between speed and accuracy. In Table 1 it is evident that errors tended to increase with N in Expt II. If Ss had maintained the same error rate throughout then mean "Absent" RT would likely have increased somewhat with N as did mean "Present" RT, thus indicating either fast serial processing or limited-capacity parallel processing. Should this explanation be tentatively accepted, a new problem would appear; viz, why a same–different task (Expt I) and a search task (Expt II) using essentially the same stimuli should give somewhat discrepant results.

The data of Expt III present an interesting picture; mean "Presence" RTs were not strongly related to N but mean "Absence" RTs increased by 24.7 msec for each additional stimulus element. Error rates increased somewhat with N for both kinds of responses. Apart from the possibility of a speed–accuracy tradeoff contaminating the results, the "Presence" data are consistent with an independent parallel channels model. However, it is not clear how to interpret the steeply increasing "Absence" function. Obviously, it could be the result of a serial process. But, as mentioned earlier, it could also be the result of a limited-capacity parallel process or of an independent channels parallel process. In Expt IV the same interpretive difficulty arises on Days 1, 2, and 3, as mean "Absence" RTs were related to N at those levels of practice (however, errors did not vary systematically with N in this experiment). There are no really clear grounds within the present experiments to choose among the alternative models for "Absent" responses. Perhaps the most parsimonious explanation of the results of the digit–letter experiments may be stated in the following way. Under the conditions of these experiments there is the capacity for examining individual elements with independent parallel channels, with fixed examination times. When a target is detected by one of the input channels a response is initiated. However, if after some interval, a "Present" decision has not been reached, *S* then examines elements one at a time to verify that no target is present. This verification may reflect an habitual reluctance to accept "null hypotheses." However, with practice the *S* learns that if no target is detected in his initial parallel examination then there really is no target present. Thus, with practice, *S* gradually comes to make an "Absent" response as if it were simply the opposite of a "Present" response—something he could *logically* have done at the outset of practice.

Some Remaining Problems

Comparison of search and same–different tasks. There is a puzzling discrepancy between the results of a comparable same–different task (Expt I) and search task (Expt II). In both cases the trials requiring exhaustive processing ("Same" and "Absent") resulted in flat functions with similar intercepts. However the "Different" and "Present" functions differed significantly ($p < .01$) in both slope and intercept. Given this difference it is very likely that processing is different in the two tasks. In this paper we have considered the basic unit of perceptual analysis to involve an undefined operation called "examination." It is easy to understand what this operation might mean in the context of a search task: a target is specified, the *S* then "examines" elements in the array to determine whether or not they match the target. However, it is more difficult to understand what the concept of examination might refer to in a same–different task. One possibility might be that on a particular trial the *S* selects, at random, a single one of the displayed elements and then uses it as a target item in a search task. Since the "target" must be selected and a mental representation of it formed subsequent to the display onset, this could explain why "Different" responses are slower than "Present" responses. However, such an explanation would not account for the discrepancy in slopes, and would not account for the "Absent" responses being somewhat slower than "Same" responses. Indeed, no simple explanation for the overall pattern of results in Expts I and II has occurred to the writers. Perhaps a more thorough analysis of the concept of examination will help resolve the puzzle.

Fixed vs distributed examination times. Another problem concerns the data for exhaustive processes; it should be explicitly noted that the idea of "fixed" rather than distributed examination times does not rest easily with the writers. Since all known psychological processes are subject to random variation it would be worthwhile to explore other explanations for the flatness of the functions that have led us to conclude that examination time is not variable. One way to approach this problem may be to examine the effects of redundant critical elements on reaction time. The existing research on this topic is inconclusive; Donderi and Case (1970) found "Different" RT to be faster the greater the number of discrepant elements in a same–different task, while Bjork and Estes (1971) found RT to be invariant with the number of redundant target elements in a forced-choice search task. The latter results are consistent with an independent parallel-channels model with fixed examination times. However, the former results conflict with such a model; if examination time is fixed, there should be no advantage in increasing the number of discrepant elements. Clearly further research on this issue is necessary.

Errors. The effect of errors on the interpretation of reaction time data has not yet received a widely accepted treatment. In this paper a fairly conventional approach has been implicity accepted in that we have accepted as "clearcut" only those data from conditions in which error rate did not increase with N. However, it is worth pointing out that there are some rather different ways of considering errors that may be appropriate in the present circumstances. In particular, if we take seriously the idea that our flat and nearly flat functions are consistent with a model positing independent parallel channels, then the error analysis applied by Eriksen & Spencer (1969) in the context of a tachistoscopic detection experiment may be especially appropriate.

Consider false positive rates for a presence responder. To give a specific example, with $N = 1$ assume the probability of a false positive to be .01. If input channels are independent, then with $N = 6$ and mean RT the same as for $N = 1$, the probability of a false positive should be $1 - (.99)^6$ or about .06. In general, if mean RT is constant false positive rate should increase with N. However, if S manages to keep his false positive rate constant, it is clear that mean RT will increase with N, assuming a speed–accuracy tradeoff.

The point of this discussion is simply to indicate the existence of some possibly useful ways of treating errors. It is not our purpose to elaborate on the Eriksen and Spencer model at this time, as there are some unresolved problems that stand in the way of its straightforward application. For example, the argument is meant to apply only to perceptual errors not response confusions. Thus, to determine the expected increase in false positives with N it is necessary to exclude response errors from consideration. It is not yet obvious how to accomplish this.

Comparison with previous work. Finally, there remains the problem of accounting for the differences in the results of the various studies that have used the detection paradigm. To keep the focus of this inquiry relatively narrow, it may be useful to consider only "Present" latencies, as they provide the clearest contrast with previous work. The question then, is: Why should mean "Present" RT increase substantially (about 30 msec/element) with N in some experiments but not others? Clearly, the present studies did not include enough systematic manipulation of experimental variables to permit a definitive answer to this question. Nevertheless, it is tempting to offer several speculative (but testable) explanations.

One factor that might be of considerable importance in determining the outcome of a search experiment is the spatial arrangement of elements within displays. In the previously cited research in which RT increased substantially with N, elements were arranged in a horizontal line. The use of this kind of display creates several problems. First, overall visual angle increased with N, and thus the elements of large displays fell on retinal locations that were less sensitive, on the average, than the locations stimulated by small displays. While it is not obvious that the retinal sensitivity gradient should result in a 30 msec/element increase in RT, it is possible that some fraction of the increase in the mean RT with N was due to this factor. Another possible consequence of using horizontal displays is that they may have elicited a left to right serial scanning strategy because of their similarity to printed words. There is not yet any strong evidence either for or against this conjecture in the context of these search tasks. Finally, to the extent that elements are close to one another (whether in a horizontal display or not) we may expect some increase in lateral masking as N increases. Again, there is no obvious reason for thinking that this effect will produce a linear change in mean RT, but it should produce some change (cf. Shaw, 1969; Estes & Wolford, 1971; Townsend, Taylor, & Brown, 1971). By contrast to the horizontal display format, the circular displays used in the present experiments should have been relatively free of the problems produced by differential retinal sensitivity, reading habits, and spacing. The flat and nearly flat functions obtained in several of our experiments suggests that this was the case.

Another possible source of the differences among experiments may have to do with the conceptual properties of the target and nontarget field elements. It may be the case that a flat or nearly flat "Present" RT function obtains only when target and nontarget elements belong to mutually exclusive, easily remembered sets. This was the case in all of the present experiments (4 vs C, digits vs letters). However, in previous experiments that yielded steeply increasing functions for "Present" RT, targets and nontargets were often not members of well-learned different sets. Furthermore, Sternberg (1967), Atkinson, Holmgren and Juola

(1969), and Holmgren (1970) varied the target (or set of targets) randomly from trial to trial. Such a procedure could have two deleterious consequences. First, it might increase the difficulty of remembering the target set, especially where it contains more than a single character, and lead to serial subvocal rehearsal. Second, it might result in some degree of confusion or response conflict since a given stimulus could appear as a target on one trial and a nontarget on another trial. These circumstances may induce Ss to adopt a strategy of examining display elements serially. Briggs and Blaha (1969) performed a search study similar in design to Sternberg's (1967) in which the number of targets in memory and the number of elements in the visual display were varied orthogonally. The elements that could appear as targets and nontargets throughout the experiment were drawn from disjoint sets, and the elements composing any given size of target set were fixed throughout the experiment. According to the argument advanced above, these conditions should have resulted in a virtually flat function for "Presence," but instead N had a pronounced effect on RT. While this finding is not in accord with our argument, it should be noted that the stimuli were random eight-sided polygons. It is unlikely that such stimuli would be easily remembered without very extensive practice.

Burrows and Murdock (1969) also varied the number of targets in memory and the number of elements in a visual display orthogonally. Their stimuli were digits, and they compared a fixed target group with a varied target group. For both groups the slope of RT versus N was about 30 msec/element early in practice. This provides evidence against our hypothesis, but again there is some ambiguity because a digit that appeared as a "Yes" stimulus in one condition might appear as a "No" stimulus in a later condition (Burrows, personal communication).

Implicit in the preceding discussion is the hypothesis that the slope of the function relating mean "Present" RT to N can be manipulated over a wide range (from near zero to more than 30 msec/element) by varying factors such as the spatial arrangement of elements and the constitution of the target and nontarget sets. Tests of this hypothesis are now being conducted by the authors.

REFERENCES

Atkinson, R. C., Holmgren, J. E., & Juola, J. F. Processing time as influenced by the number of elements in a visual display. *Perception & Psychophysics,* 1969, **6**, 321–326.

Averbach, E., & Coriell, A. S. Short-term memory in vision. *Bell System Technical Journal,* 1961, **40**, 309–328.

Bamber, D. Reaction times and error rates for "same"-"different" judgments of multidimensional stimuli. *Perception & Psychophysics,* 1969, **6**, 169–174.

Beller, H. K. Parallel and serial stages in matching. *Journal of Experimental Psychology,* 1970, **84**, 213–219.

Bjork, E. L., & Estes, W. K. Detection and placement of redundant signal elements in tachistoscopic displays of letters. *Perception & Psychophysics,* 1971, **9**, 439–442.

Brand, J. Classification without identification in visual search. *Quarterly Journal of Experimental Psychology,* 1971, **23**, 178–186.

Briggs, G. E., & Blaha, J. Memory retrieval and central comparison times in information processing. *Journal of Experimental Psychology,* 1969, **79**, 395–402.

Burrows, D., & Murdock, B. B., Jr. Effects of extended practice on high-speed scanning. *Journal of Experimental Psychology,* 1969, **82**, 231–237.

Connor, J. M. Factors affecting parallel processing of visual displays. Unpublished doctoral dissertation, University of Wisconsin, 1971.

Corcoran, D. W. J. *Pattern recognition.* Baltimore: Penguin, 1971.

Donderi, D., & Case, B. Parallel visual processing: constant same-different decision latency with two to fourteen shapes. *Perception & Psychophysics,* 1970, **8**, 373–375.

Donderi, D. C., & Zelnicker, D. Parallel processing in visual same-different decisions. *Perception & Psychophysics,* 1969, **5**, 197–200.

Egeth, H. E. Parallel versus serial processes in multidimensional stimulus discrimination. *Perception & Psychophysics,* 1966, **1**, 245–252.

Egeth, H. E., & Blecker, D. L. Differential effects of familiarity on judgments of sameness and difference. *Perception & Psychophysics,* 1971, **9**, 321–326.

Eriksen, C. W., & Spencer, T. Rate of information processing in visual perception: Some results and methodological considerations. *Journal of Experimental Psychology Monograph,* 1969, **79**, No. **2**.

Estes, W. K., & Taylor, H. A. A detection method and probabilistic models for assessing information processing from brief visual displays. *Proceedings of the National Academy of Sciences,* 1964, **52**, 446–454.

Estes, W. K., & Taylor, H. A. Visual detection in relation to display size and redundancy of critical elements. *Perception & Psychophysics,* 1966, **1**, 9–16.

Estes, W. K., & Wessel, D. L. Reaction time in relation to display size and correctness of response in forced-choice visual signal detection. *Perception & Psychophysics,* 1966, **1**, 369–373.

Estes, W. K., & Wolford, G. L. Effects of spaces on report from tachistoscopically presented letter strings. *Psychonomic Science,* 1971, **25**, 77–80.

Gardner, G. T. Spatial processing characteristics in the perception of brief visual arrays. Doctoral dissertation, University of Michigan, 1970. Appears as Technical Report No. 23 from the University of Michigan, Human Performance Center.

Gumbel, E. J. The maxima of the mean largest value and of the range. *Annals of Mathematical Statistics,* 1954, **25**, 76–84.

Holmgren, J. E. Response latency as an indicant of information processing in visual search tasks. Technical Report No. 153, Institute for Mathematical Studies in the Social Sciences, Stanford University, 1970.

Nickerson, R. S. Response times with a memory-dependent decision task. *Journal of Experimental Psychology,* 1966, **72**, 761–769.

Rapoport, A. A study of disjunctive reaction times. *Behavioral Science,* 1959, **4**, 299–315.

Shaw, P. Processing of tachistoscopic displays with controlled order of characters and spaces. *Perception & Psychophysics,* 1969, **6**, 257–266.

Sperling, G. The information available in brief visual presentations. *Psychological Monographs,* 1960, **74,** (11, Whole No. 498).

Sperling, G. A model for visual memory tasks. *Human Factors,* 1963, **5,** 19–31.

Sternberg, S. High-speed scanning in human memory. *Science,* 1966 **153,** 652–654.

Sternberg, S. Scanning a persisting visual image versus a memorized list. Paper presented at the annual meeting of the Eastern Psychological Association, 1967.

Townsend, J. T. A note on the identifiability of parallel and serial processes. *Perception & Psychophysics,* 1971, **10,** 161–163.

Townsend, J. T., Taylor, S. G., & Brown, D. R. Lateral masking for letters with unlimited viewing time. *Perception & Psychophysics,* 1971, **10,** 375–378.

Woodworth, R. S., & Schlosberg, H. *Experimental Psychology.* (2nd ed.) New York: Holt, 1954.

(Accepted May 3, 1972)