Reaction times for comparisons of successively presented visual patterns: Evidence for serial self-terminating search*

JOAN GAY SNODGRASS

New York University, University Heights, Bronx, New York 10453

Two-choice classification RTs were collected for eight conditions designed to vary the number of comparisons necessary between one or two visual patterns in perception and one or two in short-term memory (STM). Overall RT data supported both a serial self-terminating and parallel self-terminating model with distributed search times, while rejecting corresponding exhaustive models. Precise predictions for the parallel model proved difficult to derive; however, the serial model predicted the fine detail of the data surprisingly well. RTs suggested that Ss searched through all stimuli in memory first and that stimuli in both memory and perception were searched from right to left. Comparison times between identical stimuli were estimated to be longer than comparison times between different stimuli. Error rates increased with the number of hypothesized comparisons; predicted error rates, based on independence of rates within stages, also increased but failed to predict the empirical error rates very well.

A great deal of controversy has recently been generated by experiments which attempt to determine the manner in which Ss search through a set of stimuli stored in STM or present in a perceptual display. The basic paradigm used to study both search strategies is a task in which some of the stimuli to be compared are in memory and some are in perception. This task will be described by the term memory $n:m$, indicating that n stimuli in memory are to be compared with m stimuli in perception. The dependent variable is generally reaction time (RT), in which S's judgment is either "yes" or "same" if 1 . . . m stimuli in perception match 1 . . . n stimuli in memory and "no" or "different" otherwise. Typically, error rates are sufficiently low so that only RT need be considered.

Several possible strategies of search through memory or perception are logically possible. These have been reviewed by Egeth (1966) and may be classified along several binary dimensions as serial vs parallel, exhaustive vs self-terminating, and, for the parallel models, distributed vs constant times.

Sternberg (1966, 1967a, 1969), using a memory $n:1$ procedure, has found evidence that the comparison scanning process in STM is both sequential and exhaustive. His

procedure consists of presenting S with a positive set of stimuli such as digits (the target set) of variable set size s . On each trial, a single test stimulus (the probe) is presented and the S responds "yes" if it is a member of the target set and "no" otherwise. The fact that both positive and negative RTs increased linearly with s provides evidence that the search process is sequential, and the fact that the slopes of both functions were equal provides evidence that the search process is exhaustive. Further evidence for an exhaustive search is the lack of a serial position effect for positive RTs.

Sternberg finds evidence for serial self-terminating search when S must search for location, rather than merely presence/absence, information (Sternberg, 1969). Ss had to choose between digit pairs presented in correct vs reversed order; search rates were slower than in the presence/absence condition, and there was a serial position effect, suggesting a self-terminating rather than an exhaustive process.

In an extension of the original task, Sternberg (1967b) used a memory $n:m$ task in which from one to three digits were presented in a visual display; if any of these matched from one to four digits stored in STM, S was to respond "yes." Sternberg found evidence that scanning through memory remained serial and exhaustive, whereas scanning through perception was serial self-terminating. RTs suggested that S picked one item from the perceptual display and compared this item with all items in memory. Using a similar paradigm, Burrows and Murdock (1969) found that search was serial

self-terminating through both memory and perception and, furthermore, that all items in perception were scanned for each item in memory rather than the opposite, which was the strategy reported by Sternberg.

On the other hand, for a memory $1:n$ task (i.e., where only one item is in memory and n items are in a perceptual display), Atkinson, Holmgren, and Juola (1969) reported that search through items in the display was serial exhaustive, since the RT vs s function had the same slope for both positive and negative RTs and there was little evidence of a serial position curve for the positive RTs. Similarly, Briggs and Blaha (1969) reported evidence for a serial exhaustive search for both memory and perception in a $n:m$ task in which stimuli were random figures. Search through memory appeared to approach parallel processing with practice for one and two items in memory, but not for four, while perceptual search appeared to remain serial exhaustive with practice, although for negative items perception was searched sequentially and over-exhaustively—that is, Ss seemed to recheck when four items were displayed in perception and none was a member of the positive set.

Evidence for parallel instead of serial search processes in memory with practice also was obtained by Neisser and his co-workers, who used memory $1:n$ and memory $m:n$ tasks where m is much smaller than n (Neisser, 1963; Neisser, Novick, & Lazar, 1963). Neisser and his co-workers found that, after considerable practice, the number of target items in memory were scanned in parallel, whereas the serial positive curves indicated that items in perception were scanned in a serial self-terminating fashion. However, as pointed out by Atkinson et al (1969), Neisser's task involves the scanning of a long list of items, requiring eye movements, whereas many visual search tasks which obtained evidence for serial exhaustive search required only a single fixation to extract information about the entire visual display.

In summary, when only presence/absence information is required, search through the n items in memory for $n:1$ memory tasks is serial and exhaustive and search through the n items in perception for $1:n$ memory tasks is serial and exhaustive. For $n:m$ memory tasks, search through memory may be serial self-terminating or serial exhaustive, and there is evidence that it may become parallel with practice. In all of the memory $n:m$ studies reported, search through perception is serial and self-terminating.

The purpose of the present study

*This study was supported by Research Grant MH 19165-01 from the National Institute of Mental Health. The author is indebted to Robin Zelkowitz and Bruce Prussock for assistance in the collection and analysis of data. A short report of this research was presented at the meetings of the Eastern Psychological Association, Boston, Massachusetts, April 1971.

Table 1
The Eight Experimental Conditions Used in the Present Experiment

A			B		
$\begin{bmatrix} 1 \\ 1 \end{bmatrix}$	→	SAME	$\begin{bmatrix} 1 \\ 2 \end{bmatrix}$	→	RIGHT
$\begin{bmatrix} 1 \\ 2 \end{bmatrix}$	→	DIFF	$\begin{bmatrix} 1 \\ 1 \end{bmatrix}$	→	LEFT
C			D		
$\begin{bmatrix} 2 & 1 \\ 1 & 1 \end{bmatrix}$	→	RIGHT	$\begin{bmatrix} 2 & 1 \\ 3 & 1 \end{bmatrix}$	→	RIGHT
$\begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix}$	→	LEFT	$\begin{bmatrix} 2 & 1 \\ 2 & 3 \end{bmatrix}$	→	LEFT
E			F		
$\begin{bmatrix} 1 & 1 \\ 1 & 2 \end{bmatrix}$	→	SAME	$\begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix}$	→	SAME
$\begin{bmatrix} 1 & 1 \\ 2 & 1 \end{bmatrix}$	→	SAME	$\begin{bmatrix} 2 & 1 \\ 1 & 1 \end{bmatrix}$	→	SAME
$\begin{bmatrix} 1 & 1 \\ 2 & 3 \end{bmatrix}$	→	DIFF	$\begin{bmatrix} 2 & 3 \\ 1 & 1 \end{bmatrix}$	→	DIFF
G			H		
$\begin{bmatrix} 1 & 2 \\ 1 & 2 \end{bmatrix}$	→	SAME	$\begin{bmatrix} 1 & 2 \\ 1 & 3 \end{bmatrix}$	→	SAME
$\begin{bmatrix} 1 & 2 \\ 2 & 1 \end{bmatrix}$	→	SAME	$\begin{bmatrix} 1 & 2 \\ 2 & 3 \end{bmatrix}$	→	SAME
$\begin{bmatrix} 1 & 2 \\ 1 & 3 \end{bmatrix}$	→	DIFF	$\begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix}$	→	DIFF
$\begin{bmatrix} 1 & 2 \\ 2 & 3 \end{bmatrix}$	→	DIFF			

Note—The top stimulus (SP-1) is presented first and the bottom (SP-2) is presented second.

was to determine by which method Ss search through visual patterns in STM and in perception to make presence/absence judgments (i.e., do any of the patterns in perception match any of the patterns in STM?) and to make location judgments (i.e., in which location in STM does a pattern in perception occur?). The study was designed to vary the number of hypothetical comparison stages by varying the nature of the task, rather than by varying the number of items in memory or perception for a single task. All tasks were memory n:m in which $n = 1$ or 2 and $m = 1$ or 2 and in which S was required either to make presence/absence or location judgments.

The basic experimental procedure can be described as follows: During a single trial of a given experimental condition, two stimulus presentations, denoted SP-1 for the first and SP-2 for the second, are presented successively. The stimulus presentations consist of either one or two stimuli, and S is required to compare the stimuli and either make location responses (RIGHT or LEFT) or presence/absence responses (SAME or DIFFERENT). Search through stimuli in SP-1 is search through STM, and search through stimuli in SP-2 is search through perception.

The eight experimental conditions employed in the present experiment are shown in Table 1, with examples of the possible SP-2 presentations and their correct responses.

SEARCH MODELS

Four basic types of search models were compared: serial exhaustive,

serial self-terminating, parallel exhaustive, and parallel self-terminating. Predictions from them are based on the assumption that both STM and perception are searched in the same manner. Furthermore, it is assumed that spatial location of a stimulus in STM is encoded along with its identity. Hence, it takes no longer to check both the identity of a stimulus and its location than to check its identity alone. The import of this assumption may be illustrated by comparing Conditions C and F: for Condition C, the S must know both that Stimulus 1 was present in SP-1 and that it was present on the right, whereas in Condition F, he simply must know that Stimulus 1 was present in SP-1 but its location is irrelevant. We assume here that coding both location and identity takes no longer than coding identity alone; that for visual stimuli, spatial location is such a salient attribute that it is encoded automatically (e.g., O'Connor & Hermelin, 1972).

Serial exhaustive search implies that each stimulus in perception is compared in turn with each stimulus in memory; at the end of the process, the decision is made and executed. The time for serial exhaustive search is the sum of the times of all possible comparisons between stimuli in

Table 2
Predicted Additional Response Times by Condition for Each of the Four Processing Models

Condi- tion	Number Com- parisons		Serial Exhaustive	Serial Self-terminating	Parallel Exhaustive	Parallel Self- terminating
	Max	Min				
A	1	1	SAME = X DIFF = Y	SAME = X DIFF = Y	SAME = X DIFF = Y*	SAME = X DIFF = Y*
B	2	1	X + Y	$\frac{X + Y}{2}$	Y	X
C	2	1	X + Y	$\frac{X + Y}{2}$	Y	X
D	2	1	X + Y	$\frac{X + Y}{2}$	Y	X
E	2	1.5	SAME: X + Y	SAME: $\frac{2X + Y}{2}$	SAME: Y	SAME: X
	2	2	DIFF: 2Y	DIFF: 2Y	DIFF: Y	DIFF: Y
F	2	1.5	SAME: X + Y	SAME: $\frac{2X + Y}{2}$	SAME: Y	SAME: X
	2	2	DIFF: 2Y	DIFF: 2Y	DIFF: Y	DIFF: Y
G	4	2.5	SAME: 2X + 2Y	SAME: $\frac{4X + Y}{2}$	SAME: Y	SAME: X
	4	2.25	DIFF: X + 3Y	DIFF: $\frac{2X + 7Y}{4}$	DIFF: Y	DIFF: Y
H	4	2.5	SAME: X + 3Y	SAME: $\frac{2X + 3Y}{2}$	SAME: Y	SAME: X
	4	4	DIFF: 4Y	DIFF: 4Y	DIFF: Y	DIFF: Y

Note—For parallel models a single "same" comparison has been assumed faster than a single "different" comparison.

*Assume $X < Y$

perception and those in STM.

Serial self-terminating search means that each stimulus in perception is compared in series with each stimulus in STM until enough information has accumulated to make a decision. To derive predictions for this model, we assume that the comparison process begins at random for various pairs. However, because stimulus position was counterbalanced across trials for all conditions, the predictions would be identical if S had control over his order of search and always began the comparison process with a particular position.

Parallel exhaustive search implies that all possible comparisons between stimuli in perception and those in STM are initiated at once, and after the last one is terminated, the decision is made and executed. Parallel self-terminating search implies that all possible comparisons are initiated at once, but as soon as the one (or ones) that permits a decision is completed, the process is terminated and the decision is made. Predictions for the parallel search models depend strongly upon whether individual comparison times are assumed to be variable or constant. For constant times, the number of comparisons does not affect predicted decision times, as long as there is not a limited capacity effect such that increasing the number of comparisons increases the comparison time. For variable comparison times, an increase in the required number of comparisons will increase the maximum value any one of them can take, and hence will increase decision times. Initially, we consider predictions for parallel search models only for constant comparison times; some tentative predictions for distributed times will be considered subsequently.

Table 2 presents predicted decision times for each of the four models for each of the eight experimental conditions. The predicted times are the increments to the basic reaction time, consisting of perception and motor response times. The decision times are assumed to be "inserted" into the basic input and output times without interacting with these times.

Condition A produces the basic time parameters—time to make a "same" comparison, X, and time to make a "different" comparison, Y, obtained from the mean SAME and DIFFERENT RTs, respectively.¹ Since this condition involves only one comparison, all the models make identical predictions about the inserted time. The predicted times for the parallel models (constant comparison times) depend on which is longer, X or Y, since they reflect a "race" between two times, so for convenience in making predictions for

the parallel models, X has been assumed less than Y. No such assumption has been made for the serial models because those predictions are based on simple addition of comparison times.

Conditions B, C, and D, requiring location information in either memory or perception, are predicted to produce identical decision times by each of the models. B and C are symmetrical in the sense that B requires comparisons between one stimulus in memory and two in perception, whereas C requires comparisons between two stimuli in memory and one in perception. Empirical differences between RTs for Conditions B and C might reflect different search rates between items in STM and those in perception. In Condition D, one stimulus in SP-2 always matches one, and only one, stimulus in SP-1, and the matching stimuli are always in the same spatial locations. Since stimulus location is assumed to be encoded automatically, only two comparisons are necessary for the exhaustive models.

Conditions E and F are also predicted to have identical RTs by each of the four models. Conditions E

and F parallel Conditions B and C; any obtained differences between E and F, like those between B and C, might reflect different search rates through the memory and perceptual stores.

Derivations of decision times for sequential search under Conditions G and H are more complicated than those for the other conditions, and will be discussed in detail. Under Condition G, S responds SAME if and only if both stimuli in SP-2 match both stimuli in SP-1, and responds DIFFERENT when only one matches. In Condition G, S is never presented with two stimuli in SP-2 which match no stimuli in SP-1. Under Condition H, S responds SAME whenever only one stimulus in SP-2 matches one stimulus in SP-1 and DIFFERENT when neither matches. In Condition H, S is never presented with two stimuli in SP-2 which match both stimuli in SP-1.

For sequential exhaustive search, Condition G SAME and DIFFERENT trials require four comparisons; for SAME trials, two comparisons are "same" and two are "different," and for DIFFERENT trials, one comparison is "same" and three are "different." Similarly, for

Fig. 1. Mean correct RTs across Ss for each condition plotted as a function of sessions. RTs have been combined across the two response classes. Each data point is based on approximately 200 responses except Conditions D and G, which are based on 300.

Fig. 2. Obtained RTs across Ss and responses for the last three sessions only, and predicted RTs from each of the four search models. Predictions for the parallel models are based on distributed comparison times.

Condition H, both responses require four comparisons; for SAME trials, one is "same" and three are "different," whereas for DIFFERENT trials, all four are "different."

For sequential self-terminating search, it is assumed that stimuli in memory can be eliminated from further consideration on a trial, just as stimuli in perception are assumed to be. Condition G SAME trials require two matches. On half of the SAME trials, the first stimulus picked in perception will match the first stimulus in STM and both stimuli will be eliminated; the second stimulus in perception will match the second stimulus in memory for a total time of $2X$. For the remaining trials, the first stimulus in perception will match the second stimulus in memory, so the first match consumes a time of $X + Y$ and the second match takes only X time (because of elimination) for a total time of $2X + Y$. The average SAME time is thus $(4X + Y)/2$.

For Condition G DIFFERENT trials, only one stimulus in perception matches one in memory. For half the trials, the first stimulus in perception is the matching one, and for half of these, the first stimulus in memory

will match for a decision time of X ; the second stimulus in memory will not match the second stimulus in perception, so the total decision time for one-fourth the trials is $X + Y$. The time for the second fourth is $X + 2Y$, since the first stimulus in perception, the matching one, will not match the first stimulus in memory and will match the second. For the remaining half of the trials, the first stimulus in perception will be the nonmatching one and will fail to match either stimulus in memory for a total time of $2Y$. The average DIFFERENT decision time across the three types of trials is $(2X + 7Y)/4$.

For Condition H SAME trials, again only one stimulus in perception matches one in memory. On half of the trials, the first perceptual stimulus will be the matching one, and on half of those trials, it will match the first stimulus in memory for a time of X ; for the other half of the trials, the second stimulus compared from memory will match for a time of $X + Y$. For the remaining half of the trials, the second stimulus in perception will be the matching one; for half of these, the matching perceptual stimulus will match the

first stimulus in memory for a time of $2Y + X$, and on the other half, the second stimulus in memory will match for a time of $3Y + X$. The average SAME RT across these four types of trials is $(4X + 6Y)/4$. For Condition H DIFFERENT trials, four "different" comparisons must always be made for a total decision time of $4Y$.

Turning next to the parallel models, if we assume that comparison times are not constant but form a distribution and if we assume that the distribution of comparison times is exponential, then the time of the longest of n comparison times is proportional to the logarithm of n (Christie & Luce, 1956; Rapoport, 1959). Thus, the incremental decision time for the parallel exhaustive model for distributed times is proportional to the logarithm of the maximum number of comparisons, shown in Column 2 of Table 2, while the incremental decision time for the parallel self-terminating model is proportional to the logarithm of the minimum number of comparisons, shown in Column 3 of Table 2.

Predicted RTs for the various conditions from each of the four models will be presented in the results section with the obtained RTs.

METHOD

Stimuli

The stimuli were 5 matrix patterns selected from a larger set of 42 that had been generated by computer by systematic variation of three generation parameters. They were 9 by 9 matrix patterns consisting of approximately equal numbers of black and white squares and selected from those rated as simple by various measures. The complete set of patterns is described elsewhere in terms of objective and subjective complexity measures (Snodgrass, 1971). The 5 used in the present experiment correspond to Nos. 1, 2, 3, 4, and 8 in that paper. The 5 patterns were chosen to be as discriminable as possible from one another. Matrix No. 1 is a regular checkerboard, No. 2 is black on the bottom and white on the top, No. 3 consists of horizontal bands of black squares with a break on the diagonal, No. 4 consists of diagonal bands of black squares, and No. 8 consists of alternating black and white vertical bands of unequal widths, which are of the complementary color in the bottom half.

Subjects

Five undergraduates, four males and one female, served as Ss. All were right-handed and all were paid for their participation in the experiment.

Apparatus

The S was seated alone in darkness in one room and viewed the patterns, projected as slides on a screen, through a small 7½ x 4 in. one-way mirror opening into an adjacent room in which E operated the projection and recording equipment. The slides were presented by three Kodak Carousel slide projectors. The middle projector was used for SP-1 or SP-2 presentations consisting of a single stimulus, and the two flanking projectors were used for paired stimuli. S was seated about 3 ft from the mirror and about 14 ft from the screen in the other room. The projected size of each stimulus was 7 in. square, with 3 in. separating adjacent stimuli. Thus, a pair of stimuli subtended approximately 6 deg of visual angle in the horizontal direction.

The release of a slide in one projector used for the SP-2 presentations actuated a microswitch which started a Hunter Klockounter. S was provided with two standard telegraph keys with which to record his choice as SAME or DIFFERENT or LEFT or RIGHT. The press of one of the telegraph keys stopped the clock and RT was recorded to the nearest millisecond. A light on E's console and one on the desk at which S was seated signaled to both E and S which key had been pressed.

Procedure

Each S participated in 3 practice and 18 experimental sessions. A complete cycle of the eight experimental conditions was completed in 3 sessions. Thus, the five Ss experienced each condition once during practice sessions and six times during experimental sessions. The conditions were divided into three sets so as to minimize interference effects. The three conditions requiring location information—B, C, and D—were run in one session, A and G in a second, and E, F, and H in a third. The order in which the three sets of conditions were run and the order of conditions within a particular session were completely counterbalanced across the 18 experimental sessions and were the same for each S. Forty experimental trials were run during a given session for Conditions A, B, C, E, F, and G, and 60 were run for D and H.

For each condition, the number of SAME and DIFFERENT or RIGHT and LEFT trials was equal, no more than seven trials of one type occurred in sequence, all single and paired stimuli occurred equally often, and the spatial locations of matching stimuli were counterbalanced across locations. A single basic sequence for each

Table 3
Equations for Predicted Times for Each Condition for Serial Self-Terminating Search

			Mean	S-1	S-2	S-3	S-4	S-5
A	SAME	$t_S + X$	833	837	812	851	816	847
	DIFF	$t_D + Y$	869	888	858	882	859	859
B*	RIGHT	$t_S + \frac{X+Y}{2}$	832	816	816	868	838	822
	LEFT	$t_D + \frac{X+Y}{2}$	869	877	852	893	848	875
C*	RIGHT	$t_S + \frac{X+Y}{2}$	813	790	816	849	803	807
	LEFT	$t_D + \frac{X+Y}{2}$	832	840	821	864	798	834
D*	RIGHT	$t_S + \frac{X+Y}{2}$	835	817	817	858	829	854
	LEFT	$t_D + \frac{X+Y}{2}$	874	880	858	906	855	874
E	SAME	$t_S + \frac{2X+Y}{2}$	917	896	886	968	906	926
	DIFF	$t_D + 2Y$	942	923	924	1002	945	915
F	SAME	$t_S + \frac{2X+Y}{2}$	886	873	884	920	861	894
	DIFF	$t_D + 2Y$	943	927	936	980	954	915
G	SAME	$t_S + \frac{4X+Y}{2}$	1035	1103	967	1073	1082	951
	DIFF	$t_D + \frac{2X+7Y}{4}$	1043	1079	1014	1091	1020	1009
H	SAME	$t_S + \frac{2X+3Y}{2}$	1025	1032	1032	1096	981	980
	DIFF	$t_D + 4Y$	1133	1145	1117	1199	1154	1059

Note—Obtained times are based on the last three sessions only. (t_S = base time for SAME or RIGHT RTs and t_D = base time for DIFFERENT or LEFT RTs. X = time for a single "same" comparison and Y = time for a single "different" comparison.)

*Predictions based on the assumption that S always checks right stimulus (in memory or perception) first are: RIGHT: $t_S + X$; LEFT: $t_D + Y$.

condition was constructed subject to the above constraints, and then was permuted in three ways to yield four distinct sequences.

Ten practice trials, selected randomly from the experimental sequence, were run prior to the experimental trials in order to familiarize S with each condition. In addition, Ss were provided with schematic diagrams of the conditions, which were visible during each session. A typical session lasted approximately 1 h. Ss were paid \$1.50 for participating in each session and in addition won 2c for each response faster than 500 msec and lost 10c for each error. Although Ss were given neither error nor time feedback, they were usually aware of when they had made an error because the stimulus or stimuli remained on after they had responded.

The interstimulus interval between SP-1 and SP-2 was approximately 2½ sec, and SP-1 was exposed for approximately 2½ sec. The intertrial interval was approximately 6 sec. These intervals were only approximate because the stimulus presentations

were actuated manually by E.

Because the experimental procedure was relatively complex, no counterbalancing of hands and responses was attempted. Instead, each S used the apparently natural mapping of right hand for a RIGHT and SAME response and left hand for a LEFT and DIFFERENT response.

RESULTS AND DISCUSSION

Figure 1 presents RTs for each condition plotted as a function of sessions. The RTs are averages of both responses. It is apparent that fairly large decreases took place across sessions and that the decrease was larger for the more complex conditions such as G and H than for the simpler conditions such as A, B, C, and D. Because the last three sessions appeared to be relatively stable for all conditions, only data from those were used in subsequent data analyses.

The initial step was to determine how well each of the models predicted the overall RT data. The exact predictions depend upon the relationship between X , the time for a "same" comparison, and Y , the time

Table 4
Predicted Values of X (Time for a Single "Same" Comparison) and Y (Time for a Single "Different" Comparison) Based on Differences Among SAME and DIFFERENT RTs for Conditions A, G, H, and the Average of E and F (EF)

		Mean	S-1	S-2	S-3	S-4	S-5
<i>Predictions from SAME RTs (in Msec)</i>							
Y	$2[\overline{EF} - A]$	137	95	146	186	135	126
	$H - \overline{EF}$	124	148	147	152	98	70
	$2/3[H - A]$	128	130	147	163	110	89
	Mean	130	124	147	167	114	95
X	$G - \overline{EF}$	134	218	82	129	198	41
	$[G - A] - 1/2 Y$	137	204	82	138	209	56
	$[G - H] + Y$	140	195	82	144	215	66
	Mean	137	206	82	137	207	54
<i>Predictions from DIFFERENT RTs (in Msec)</i>							
Y	$\overline{EF} - A$	74	37	72	109	90	56
	$1/3[H - A]$	88	86	86	106	98	67
	$1/2[H - \overline{EF}]$	95	110	94	104	102	72
	Mean	86	78	84	106	97	65
X	$4[G - A] - 3Y$	219	265	186	259	176	202
	$4[G - \overline{EF}] + Y$	244	348	210	252	190	220
	$4[G - H] + 9Y$	207	219	172	261	168	192
	Mean	223	277	189	257	178	205
X - Y (Based on SAME RTs)		7	82	-65	-30	93	-41
X - Y (Based on DIFFERENT RTs)		137	199	105	151	81	140

for a "different" comparison. The simplest relationship, that $X = Y$, was assumed in order to make the predictions. For the parallel models, predictions were derived for distributed comparison times, since the predictions for constant comparison times are that all conditions will yield identical average RTs, a prediction which is obviously contradicted by the data.

The predictions of the four models are presented in Fig. 2, along with the empirical data. It is clear from Fig. 2 that the predictions from the parallel self-terminating model are almost indistinguishable from those for the serial self-terminating model and that the only difference between the parallel and serial exhaustive models is that the latter predicts twice the difference between Conditions G and H than the former.

The obtained RTs obtained from the last three sessions, combined across responses and Ss, are shown in the lower part of Fig. 1. Regardless of the actual relationship between X and Y, both parallel exhaustive and serial exhaustive models predict that $A < B = C = D$ and $E = F$, whereas both parallel and serial self-terminating models predict that $A = B = C = D < E = F < G$; the other relationships among conditions depend upon the

relationship between X and Y. Thus, the data very clearly reject both exhaustive models and provide preliminary support for both self-terminating models.

The question of distinguishing between a serial and parallel model is one that has received increasing attention. Townsend (1971) has shown that it is, in principle, very difficult to distinguish between serial and parallel models once the possibility of distributed comparison times is admitted. Furthermore, Atkinson et al (1969) have shown that a parallel exhaustive model accounts for the data they obtained in a 1:n visual search experiment if the assumption is made that comparison stages are not independent. Because the predictions from the serial self-terminating model are relatively straightforward and the predictions from a parallel model are not so obvious, the implications of the serial self-terminating model are here pursued as far as possible.

Table 3 presents averaged and individual S mean RTs for each response. The equations are based on the serial self-terminating model and the assumption that the base time for a SAME or RIGHT response (t_S) may differ from the base time for a DIFFERENT or LEFT response (t_D).

Considering, first, the symmetrical Conditions B and C, which involve searching for location information through perception and memory, respectively, and E and F, which involve searching for identity information through perception and memory, respectively, the average times, as predicted, are quite close. Condition C is somewhat faster than Condition B, suggesting that search through memory may be faster than search through a perceptual display; similarly, Condition F is faster overall than Condition E, although the advantage occurs for SAME responses, whereas DIFFERENT responses across the two conditions are identical.

Across all conditions, SAME RTs are generally faster than DIFFERENT RTs, although this difference is quite large for Condition H (108 msec) and quite small for Condition G (8 msec). Furthermore, RIGHT RTs are faster than LEFT RTs for Conditions B, C, and D, and the average difference (32 msec) is about equal to the difference between SAME and DIFFERENT RTs for Condition A (36 msec). Since RIGHT and SAME RTs were made by the same hand for all Ss, one could account for this difference by a response selection bias. It is also possible, however, to account for this difference by a bias in comparison strategies. Suppose it were the case that in Conditions B, C, and D, S always made his first comparison with the stimulus on the right (either in memory or perception); if a "same" comparison resulted, S would respond with the right hand, whereas if a "different" comparison resulted, S would terminate his search and respond with the left hand. If "same" comparisons take approximately 30 msec less than "different" comparisons, i.e., if $Y - X = 30$, one could also account for the difference between RIGHT and LEFT responses on the basis of comparison strategies. We will return to this issue after estimates of X and Y have been derived.

Tests of Predictions of the Serial Self-Terminating Model

(1) $A = B = C = D$. This prediction is about equality between RTs averaged across the two responses and not about equality within each response class. Accordingly, a repeated measures one-way ANOVA was performed on the mean RTs for each S, averaged across the two responses. The results indicated that the means of the four conditions were significantly different [$F(3,12) = 18.50, p < .01$], presumably because Condition C produced lower RTs than the other three conditions. Separate ANOVAs on SAME or RIGHT and DIFFERENT

or LEFT RTs indicated that the former were not significantly different across the four conditions [$F(3,12) = 3.23$], whereas the latter were highly significant [$F(3,12) = 29.53$, $p < .01$].

(2) $E = F$. This prediction is about separate responses: SAME and DIFFERENT RTs should be the same between Conditions E and F. SAME RTs were significantly higher for Condition E than for Condition F [$t(4) = 3.60$, $p < .05$], whereas DIFFERENT RTs were not [$t(4) = -1.10$].

(3) $ABCD < EF < G$. It is obvious that E and F produce longer RTs than A, B, C, or D, and that G is longer than either E or F.

(4) Estimates of X and Y. It is possible to obtain several estimates of X (time for a single "same" comparison) and Y (time for a single "different" comparison) by subtracting mean times in the various conditions. Specifically, SAME and DIFFERENT RTs from Conditions A, E, F, G, and H were used. Although E and F have significantly different SAME RTs, averaged data for Conditions E and F were used, providing four independent estimates for each S for SAME RTs and four for DIFFERENT RTs. All six possible differences were computed among the four condition sets A, EF, G, and H for SAME and DIFFERENT RTs separately, although only two of these six differences are independent.

Table 4 presents predicted values of X and Y computed by subtraction. It was possible to solve for Y independent of estimates for X for both SAME and DIFFERENT RT differences. However, only one difference, that based on differences between G and EF for SAME RTs, gives an estimate of X independent of a Y estimate. All other estimates of X are dependent on a value for Y; for these, the average value of Y from the particular response class was used for each S. All estimates of X include the condition G, whereas there is no condition which contributes to all estimates of Y; thus, X estimates are more interdependent than Y estimates.

Table 4 reveals the following points: First, X is generally estimated to be longer, rather than shorter, than Y, although the magnitude of the difference is much greater based on SAME than on DIFFERENT RTs. Secondly, the two sets of estimates for X and Y based on SAME RTs are substantially different from those based on DIFFERENT RTs. Thirdly, estimates based on data from individual Ss show relatively good agreement.

Although the qualitative predictions of a serial self-terminating model are generally supported, attempts to apply

Table 5
Equations for Predicted Times for Each Condition Under the Assumption that the Comparison Order is RP-RM, RP-LM, LP-LM, LP-RM, Where R = Right, L = Left, P = Perception, M = Memory, and the Search is Self-Terminating*

				Mean	S-1	S-2	S-3	S-4	S-5
E	SAME	$\begin{bmatrix} 1 \\ 2 \end{bmatrix}$	(1) $t_S + X$	882	843	847	925	886	908
		$\begin{bmatrix} 1 \\ 1 \end{bmatrix}$	(2) $t_S + X + Y$	956	951	930	1012	931	947
			$Y = (2) - (1)$	74	108	83	87	45	39
F	SAME	$\begin{bmatrix} 2 \\ 1 \end{bmatrix}$	(3) $t_S + X$	867	840	845	927	831	906
		$\begin{bmatrix} 1 \\ 1 \end{bmatrix}$	(4) $t_S + X + Y$	905	907	924	915	894	885
			$Y = (4) - (3)$	38	67	79	-12	63	-21
G	SAME	$\begin{bmatrix} 1 \\ 1 \end{bmatrix}$	(5) $t_S + 2X$	980	966	939	1034	1052	911
		$\begin{bmatrix} 1 \\ 2 \end{bmatrix}$	(6) $t_S + 2X + Y$	1109	1286	1007	1127	1126	1003
			$Y = (6) - (5)$	129	320	68	93	74	92
G	DIFF	$\begin{bmatrix} 1 \\ 1 \end{bmatrix}$	(7) $t_D + 2Y$	1052	1050	1056	1107	1014	1022
		$\begin{bmatrix} 2 \\ 1 \end{bmatrix}$	(8) $t_D + 2Y$	989	1058	949	1016	994	930
			$0 = (8) - (7)$	-63	8	-107	-91	-20	-92
G	DIFF	$\begin{bmatrix} 2 \\ 1 \end{bmatrix}$	(9) $t_D + X + Y$	1060	1128	1027	1144	1028	988
		$\begin{bmatrix} 1 \\ 1 \end{bmatrix}$	(10) $t_D + X + 2Y$	1059	1090	1015	1096	1034	1063
			$Y = (10) - (9)$	-1	-38	-12	-48	6	75
H	SAME	$\begin{bmatrix} 2 \\ 1 \end{bmatrix}$	(11) $t_S + X$	962	974	980	1010	882	960
		$\begin{bmatrix} 1 \\ 1 \end{bmatrix}$	(12) $t_S + X + Y$	1038	1108	1038	1004	1061	979
	SAME	$\begin{bmatrix} 1 \\ 2 \end{bmatrix}$	(13) $t_S + X + 2Y$	1054	1044	1064	1120	1025	1017
		$\begin{bmatrix} 2 \\ 1 \end{bmatrix}$	(14) $t_S + X + 3Y$	1065	1032	1064	1281	993	961
			$Y = (12) - (11)$	76	134	58	-6	179	19
			$Y = (13) - (12)$	16	-64	26	116	-36	38
			$Y = (14) - (13)$	11	-12	0	161	-32	-56

*Obtained times are based on last three sessions.

the model quantitatively by obtaining estimates of individual comparison times are not as successful.

Search Order Effects

If Ss search through stimuli in STM and perception in a serial self-terminating fashion, and if they always conduct their search in a particular spatial order, it should be possible to derive explicit equations for certain classes of trials in various conditions. Preliminary inspection of the search order data suggested that Ss searched through items in memory for each item in perception, searched right to left in memory when an item on the right in perception was being compared and left to right in memory when an item on the left in perception was being compared, and always began the search with the right item in perception. These assumptions predict the following comparison order: right in perception—right in memory; right in perception—left in memory; left in perception—left in memory; left in perception—right in memory. With these assumptions, it is possible to

write explicit equations for each class of SAME and DIFFERENT trials. Classes of trials were analyzed within Conditions E, F, G, and H. For example, in Conditions E and F, SAME trials consisted either of cases in which the single stimulus in memory (or perception) matched the right stimulus in perception (or memory), or vice versa.

Table 5 presents examples of each of the types of trials analyzed, the prediction equations, and the obtained RTs across Ss and for each individual S. Subtraction of mean RTs for certain classes of trials produce new estimates of Y, the time to make a "different" comparison. The predicted values of Y are fairly good (although lower than the estimates from Table 4) for Conditions E and F, Condition G for Trial Types 5 and 6, and Condition H for Trial Types 11 and 12. The remaining predicted values of Y are unreasonable, in particular those for G in which 0 is the predicted difference and those for H involving Trial Types 12, 13, and 14. Of course, the assumptions upon which the

Table 6
Obtained and Predicted Rates (Percent) for Each Condition With the Prediction Equations,
Where x = Probability of an Error in a Single "Same" Comparison and
 y = Probability of an Error in a Single "Different" Comparison

Condition	Obtained Error Rate	Predicted Errors Based on Condi- tion A	Predicted Errors Based on $x = 8y$	Prediction Equation
A SAME	1.33	—	6.40	x
DIFF	1.00	—	0.80	y
B RIGHT	0.67	1.16	3.60	$\frac{x + y}{2}$
LEFT	1.00	1.16	3.60	$\frac{x + y}{2}$
C RIGHT	0.67	1.16	3.60	$\frac{x + y}{2}$
LEFT	2.33	1.16	3.60	$\frac{x + y}{2}$
D RIGHT	1.11	1.16	3.60	$\frac{x + y}{2}$
LEFT	2.44	1.16	3.60	$\frac{x + y}{2}$
E SAME	5.00	1.82	6.77	$\frac{2x + y - xy}{2}$
DIFF	1.00	1.99	1.59	$2y - y^2$
F SAME	6.67	1.82	6.77	$\frac{2x + y - xy}{2}$
DIFF	2.33	1.99	1.59	$2y - y^2$
G SAME	6.33	3.13	12.74	$\frac{4x + y - 2x^2 - 2xy + x^2 y}{2}$
DIFF	6.67	2.40	4.56	$\frac{2x + 7y - 3xy - 3y^2 + xy^2}{4}$
H SAME	6.89	2.80	7.52	$\frac{4x + 6y - 6xy - 4y^2 + 4xy^2 + y^3 - xy^3}{4}$
DIFF	3.33	3.94	3.16	$4y - 6y^2 + 4y^3 - y^4$

predictions are made are exceedingly strong, based as they are on the assumption that all Ss always follow a particular comparison order. In fact, the differences are always positive when they should be except for Condition G. It would be more realistic to assume that the comparison order assumed is the dominant strategy but that Ss may adopt other strategies from trial to trial or session to session, so that the obtained estimates of Y are underestimates of true Y. Furthermore, the estimates shown for individual Ss are based on as few as 10 RTs and would be expected to show a fair amount of variability. In fact, the present model does fairly well on all conditions except G. It is possible, of course, that Ss adopt various strategies of search, depending upon the particular condition.²

Returning now to a question raised earlier, that of the possibility that, for Conditions B, C, and D, RIGHT responses were faster both because S checked the right stimulus first and because "same" comparisons are faster

than "different" comparisons, the data clearly support the first notion while failing to support the second. The search order data clearly support the idea that S has a definite search order, one biased toward the right stimulus. However, estimates of X and Y from the condition means reveal that X is estimated as *longer* than, rather than shorter than, Y. Thus, it must be the case that the base time, t_S , for a RIGHT or SAME response is faster than the base time, t_D , for a LEFT or DIFFERENT response. This accounts for the fact that SAME RTs are faster than DIFFERENT RTs in Condition A, as well as the fact that RIGHT RTs are faster than LEFT RTs in Conditions B, C, and D.

The estimation of X as slower than Y is contrary to many published studies of memory 1:1 tasks, i.e., those in which a single stimulus in memory is compared with a single stimulus in a visual display and S must respond SAME if they are identical and DIFFERENT if they are not. A number of investigators have reported

that SAME RTs are faster than DIFFERENT RTs when the hand used to response SAME is counterbalanced across Ss, suggesting that "same" comparisons are faster than "different" comparisons (e.g., Nickerson, 1967; Bamber, 1969; Snodgrass, 1972).

Analysis of Error Rates

Table 6 presents the obtained error rates for all eight conditions across Ss, for the last three sessions. It is clear that error rates are relatively low and constant across the first four conditions, but that they increase rather markedly for the last four conditions, particularly for SAME RTs and for DIFFERENT RTs for Condition G. It is a widely held belief that, in order to apply the "subtraction method" to the results of RT experiments, error rates should be low and constant across the various conditions in which a varying number of stages occur (Sternberg, 1969), a condition which the results of the present experiment clearly violate. However, if a particular comparison stage is subject to some small, finite probability of error, one should obtain increases in the error rates as the number of comparison stages is increased, as long as these stages are independent, an assumption that is necessary for the subtraction method for RTs to be valid anyway. Furthermore, it should be possible to predict error rates for conditions with more stages from a knowledge of the error rates for a single stage.

Error rates were estimated under the assumption that Ss conducted a serial self-terminating search, as the results from RTs would indicate, and under the assumption that stages were independent. In order to estimate error rates for a single "same" and "different" comparison stage, error rates for Condition A were employed, yielding an error rate of 1.3% for "same" comparisons and 1.0% for "different" comparisons. If Ss begin their comparisons randomly in Conditions B, C, and D, for which location information is required, then one would predict an average of 1.16% for both RIGHT and LEFT responses, since only one comparison is required for each condition, and half the time it will be a "same" comparison and half the time a "different" comparison.

For Conditions E, F, G, and H, the number of comparisons increases and so ought also the error rate, in conformity with the equations shown on the right in Table 6. To illustrate how the equations were derived, a DIFFERENT RT in Condition E requires two "different" comparisons; an error can arise from a single error in either comparison or one in both, and

the probability of this, under independence, is $2y - y^2$. A SAME RT in Condition E occurs half the time with a single "same" comparison, for an error rate of x , and half the time with a single "different" comparison, for an error rate of $x + y - xy$, so the average error rate is $(2x + y - xy)/2$.

The predicted error rates, based on the base rates estimated from Condition A and the prediction equations, are shown in Column 2 of Table 6. It is clear that the predicted error rates are not very close to the obtained error rates; in particular, SAME responses for the more complex conditions are predicted to have lower error rates than were actually obtained. In fact, there is no single adjustment in the base error rates x and y that will do a good job of predicting error rates for the more complex conditions. Error rates for E, F, and H are accounted for rather well by assuming that $x = 8y$, i.e., that the probability of error for a "same" comparison is eight times the probability of error for a "different" comparison. These predicted error rates, based on a value of y of .008 and, hence, a value for x of .064, are shown in Column 3 of Table 6. Although the predicted error rates for E, F, and H are not bad, the predicted error rates for G are too high for SAME responses and too low for DIFFERENT responses, and the error rates for the simpler conditions, A, B, C, and D, are generally overestimated.

The problem may be that errors occur not because of some basic error probability in an underlying comparison stage, but rather, for purely fortuitous reasons, and, hence, no particular order in the error data would be expected. The purpose of the present analysis was to point out the possibility, in cases where it seems reasonable to assume that comparison stages would contribute some small error probability, that just as times are theoretically estimable from assumptions of serial processes and independence of stages, so also are error rates. Thus, one hopes for both an increase in RT and an increase in error rate as the number of

hypothetical stages in the experiment is increased.

SUMMARY AND CONCLUSIONS

The present experiment was designed to vary the number of theoretical comparison stages between items in perception and those in STM, by varying the nature of the task, rather than by varying explicitly the number of items in STM and in perception. The RT data clearly support a serial or parallel self-terminating model; because predictions were easier to make for the serial model, that one was used to derive predictions for the finer grain of the data. Although the serial self-terminating model was not perfectly consistent in the predictions of the underlying comparison times X , time for a "same" comparison, and Y , time for a "different" comparison, the estimates were not unreasonable except for the data from Condition G. Analyses of particular types of trials indicated that S_s appeared to scan from right to left in both perception and memory and to scan through memory for each item in perception. It was shown that error rates should, in principle, increase as the number of stages increases, a result that was obtained in the present experiment. However, the quantitative error rate estimates were poor predictors of the obtained error rates.

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.
- BAMBER, D. Reaction times and error rates for "same"-different judgments of multidimensional stimuli. *Perception & Psychophysics*, 1969, 6, 169-174.
- 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.
- CHRISTIE, L. S., & LUCE, R. D. Decision structure and time relations in simple choice behavior. *Bulletin of Mathematical Biophysics*, 1956, 18, 89-111.
- EGETH, H. Parallel versus serial processes in multidimensional stimulus discrimination.

- Perception & Psychophysics*, 1966, 1, 245-252.
- NEISSER, U. Decision time without reaction time: Experiments in visual scanning. *American Journal of Psychology*, 1963, 76, 376-385.
- NEISSER, U., NOVICK, R., & LAZAR, R. Searching for ten targets simultaneously. *Perceptual & Motor Skills*, 1963, 17, 955-961.
- NICKERSON, R. "Same"-different response times with multi-attribute stimulus differences. *Perceptual & Motor Skills*, 1967, 24, 543-554.
- O'CONNOR, N., & HERMELIN, B. Seeing and hearing and space and time. *Perception & Psychophysics*, 1972, 11, 46-48.
- RAPOPORT, A. A study of disjunctive reaction times. *Behavioral Science*, 1959, 4, 299-315.
- SNODGRASS, J. G. Objective and subjective complexity measures for a new population of patterns. *Perception & Psychophysics*, 1971, 10, 217-224.
- SNODGRASS, J. G. Matching patterns vs. matching digits: The effect of memory dependence and complexity on "same"-different reaction times. *Perception & Psychophysics*, 1972, 11, 341-349.
- STERNBERG, S. High-speed scanning in human memory. *Science*, 1966, 153, 652-654.
- STERNBERG, S. Two operations in character recognition: Some evidence from reaction-time measurements. *Perception & Psychophysics*, 1967a, 2, 45-53.
- STERNBERG, S. Scanning a persisting visual image versus a memorized list. Paper presented at the annual meeting of the Eastern Psychological Association, 1967b.
- STERNBERG, S. Memory-scanning: Mental processes revealed by reaction-time experiments. *American Scientist*, 1969, 57, 421-457.
- TOWNSEND, J. T. A note on the identifiability of parallel and serial processes. *Perception & Psychophysics*, 1971, 10, 161-163.

NOTES

1. The convention is followed here to use capitalization when referring to overt observable responses and the RTs associated with them, and to use quotation marks to indicate the underlying comparison processes.
2. An unpublished study by Nickerson and Pew (Nickerson, R. S., & Pew, R. W. Visual pattern matching: An investigation of some effects of decision task, auditory codability and spatial position), employing similar types of tasks to the ones used here, also concluded that their data did not support the Sternberg model when the additional assumption was made that search was from left to right in perception and memory.

(Received for publication June 5, 1972; revision received July 5, 1972.)