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by

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Abstract

In a search task similar to that used by Sternberg (1966), Ss were presented with one of three alternative representations of a given stimulus and were required to state whether or not that stimulus was present in a previously memorized list. For each type of stimulus representation and each response (positive or negative), reaction time was recorded.

Functions relating reaction time to the size of the memorized list were both qualitatively and quantitatively different from those usually obtained with the Sternberg paradigm. In particular, the form of the functions did not correspond to predictions based on an exhaustive scanning process.

MEMORY SCANS BASED ON ALTERNATIVE TEST STIMULUS REPRESENTATIONS

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INTRODUCTION

In a series of experiments, Sternberg (1966, 1967a, 1967b, 1968) has used a search paradigm to study the retrieval of information stored in memory. In a typical search task, _S_ sees a _memory set_ of letters, presented in sequence. After a short delay, a warning signal is given, and _S_ is then shown a _test stimulus_ (letter) and required to pull a lever indicating whether or not the test stimulus was a member of the memory set (a positive or negative response, respectively). The dependent variable in this task is response latency, defined as the time between the onset of the test stimulus and _S_'s response. Two reaction-time functions, which relate latency to the size of the memory set, are plotted, one for positive and the other for negative responses. These functions serve to indicate the nature of the processes involved in the search task. It is assumed that _S_ stores a representation of the memory set in short-term memory at the beginning of each trial. When he is presented with the test stimulus, he searches through this representation, seeking a match for the stimulus, and the results of this search determine his response.

Since S's responses are required to be virtually error-free, the reaction-time functions may be interpreted as giving accurate information about his search process.

The results of Sternberg's experiments with the task described above have led to several important conclusions. In particular, he has found that the reaction-time functions for both positive and negative responses are linear; that is, each addition of an element to the memory set causes an identical increment in response time (Sternberg, 1966). This has led him to a theory of the search process in which three components may be identified. During the first component, S processes the test stimulus, transforming it into the form used for subsequent comparisons with the memory set. During the second component, S searches through short-term memory, comparing the test stimulus representation to the memory set which has been stored there. The third component occurs when S makes his response, based on the results of his search of short-term memory. If this search has been successful, that is, if he has matched the test stimulus with one of the elements in the memory set, he makes a positive response. Otherwise, his response is negative. The slope of the reaction-time function for each type of response is interpreted as a measure of the time used for the second component of this three-part process, while the intercept of the function measures both the time used for pre-processing the test stimulus and that necessary for responding once the answer is known.

Another important finding concerns the nature of the comparison task. Two hypotheses about this task have been presented: exhaustive search and self-terminating search. That S searches exhaustively means that he compares every member of the memory set to the test stimulus before making a response, regardless of whether or not a match has been made. In contrast, a self-terminating search is one in which only as many comparisons as necessary are made; that is, *S* responds as soon as a match is made in the case of a positive response and searches the entire set in the case of a negative response. In the exhaustive case, the same number of comparisons are made for both a positive and negative response, so the slopes of the reaction-time functions for the two responses should be equal. In the self-terminating case, on the other hand, *S* must search, on the average, only half the memory set before making a positive response, whereas he must search the entire set before making a negative response. This leads to the prediction that the slope of the function for a positive response will be half the slope for a negative response. In particular, reaction time (RT) for the exhaustive case is

$$RT(d) = \begin{cases} (\pi + \rho_y) + d\kappa & \text{for a positive response} \\ (\pi + \rho_n) + d\kappa & \text{for a negative response.} \end{cases}$$

For the self-terminating case,

$$RT(d) = \begin{cases} (\pi + \rho_y) + \frac{1}{2}(d+1)\kappa & \text{for a positive response} \\ (\pi + \rho_n) + d\kappa & \text{for a negative response.} \end{cases}$$

In the above equations, d = size of memory set, π = processing time, and κ = time for a single comparison. Also, ρ = response time, and the subscripts y and n on ρ denote positive and negative responses, respectively. Sternberg (1966) has found that the slopes for the positive and negative functions are equal, which supports the exhaustive search hypothesis. He has also found that the intercepts are approximately equal for the two responses.

Search experiments of the Sternberg type have usually used the same symbols for test stimuli and memory set elements. The present experiment, in contrast, was concerned with the case in which the test stimulus was not directly comparable to the memory set. While members of the memory sets were letters of the alphabet, the test stimulus on any trial could be a letter, a word, or a picture. If the test stimulus was a letter, S made a positive response only if that letter was a member of the memory set. This is precisely the task used by Sternberg for digit stimuli (1966). If the test stimulus was a word, S made a positive response only if the first letter of that word was a member of the memory set. Finally, if the test stimulus was a picture, S made a positive response only if the first letter of the name of that picture was a member of the memory set.

In this experiment, the search paradigm involved retrieval of information from long-term memory. It is for this reason that picture stimuli were used. If the test stimulus was a picture, a direct comparison with the memory set was impossible. Instead, the picture test stimulus served to instigate a search of long-term memory, a search essential to obtaining a symbol comparable to the representation of the memory set stored in short-term memory. It was assumed that given a picture stimulus, S had to retrieve the name of that picture from long-term memory, translate that name to its first letter, and then transform the letter into a form which could be compared to the memory set representation before searching for a match. If the test stimulus was a letter, the first two steps of this process were unnecessary. In this case, S could immediately begin transforming the test stimulus into the form used for comparisons. Finally, word stimuli were used to represent an intermediate stage in S's search process. Given a word stimulus, S had to ~~abstract the first letter of the word and then transform it before~~ beginning his search of short-term memory. One might hypothesize that the time necessary to translate the retrieved name of a picture stimulus into a representation of its first letter would correspond to the time necessary to change a word stimulus into a similar representation, although this is a rather tenuous hypothesis.

The data of interest in this study are the slopes and intercepts of the reaction-time functions for each type of test stimulus and each type of response. The form of these functions may be used to evaluate several hypotheses. For example, if the stimulus representations ultimately compared to the memory set were the same for each type of test stimulus, there should be no differences among these stimuli in the time required for a single comparison (κ). This leads to the prediction that for both positive and negative responses, the slopes of the reaction-time functions for letters, words, and pictures should be identical. If these slopes were not identical, a difference in comparison time and a corresponding difference in the representations of the test stimulus would be implied. Intercept differences among the reaction-time functions for letters, words, and pictures may be interpreted as representing differences in initial processing time (π), response time (ρ), or both. If the time required to obtain a representation of the picture stimulus comparable to the representation of the memory set in short-term memory includes both the processing time normally required for letter stimuli and the time required to retrieve the name of the picture from long-term memory, the intercepts of the reaction-time functions for letters should be less than the intercepts for pictures. However, such intercept differences could also be interpreted in terms of different response times (ρ) for the two types of stimuli. (Moreover, in the case of a self-terminating search, the intercept of the function for a negative response includes the term $\frac{1}{2}\kappa$, so differences in comparison times would contribute to differences in the intercept of that function.) Of course, both slope and intercept differences could be present, indicating that both comparison time and pre-comparison processing or response procedures are not the same for the two types of stimuli. Finally, a comparison of the slopes of the reaction-time functions for positive versus negative responses for each type of stimulus serves to indicate whether the search process for that stimulus is exhaustive or self-terminating. It is possible, of course, that the process used could vary with the type of test stimulus. This experiment was conducted in order to test these various predictions.

METHOD

Subjects

The Ss were 10 girls who were in grades 11 or 12 in high schools in the vicinity of Stanford University. They were paid $1.75 for each of the five experimental sessions.

Stimuli

The memory sets consisted of two or four capital letters typed with an IBM Executive Registry electric typewriter and separated by a single space. No letter was duplicated within a memory set. Each set was displayed on a 5 in x 8 in white file card, with the center of the display located at the center of S's visual area. The set of letters whose elements were used will be called the <u>letter set</u>; this consisted of all letters but the five vowels and V, S, and Y.

~~Eighteen letters, 18 words, and 18 pictures were used as test stim-~~uli. Each test stimulus was displayed on a 5 in x 8 in white file card with the center of the stimulus at the center of <u>S</u>'s viewing area. The letter stimuli consisted of single members of the letter set, one corresponding to each letter set element. Each letter was typed in capitalized form with the same typewriter as that used for memory set displays. To each letter stimulus, there corresponded a word test stimulus beginning with that letter. These word stimuli were common nouns (e.g., s = snake, w = whistle, etc.) whose length ranged from 3 to 7 letters. Since the center of the word coincided with the center of <u>S</u>'s visual area, the position of the first letter relative to the center varied. The words were typed in capitals, again with the same typewriter as that used for the memory sets and letter stimuli. Picture test stimuli were black-and-white drawings, copies of illustrations used in <u>The Golden Happy Book of ABC</u> (Golden Press), a children's picture book. The height and width of these pictures varied from $1\frac{1}{4}$ in to $3\frac{1}{4}$ in and $1\frac{3}{8}$ in to 4 in, respectively. Each picture represented one of the common nouns used as word stimuli.

<u>Apparatus</u>

The apparatus consisted of an Iconix tachistoscope and exposure box (System 153). Displays were placed by <u>E</u> in a slot at the rear of the box. The visual area exposed to <u>S</u> measured 7 in x $3\frac{1}{2}$ in, and the viewing distance was approximately 2 ft. Between stimulus exposures, the viewing area was illuminated by a light of 1.4 ft lamberts, while the display brightness averaged 39 ft lamberts. A black dot marked the center of the pre- and post-exposure field.

On a table to the right of *S*, three telegraph keys were placed in an arc, separated by a distance of 4.3 cm. The *S* rested her right arm on the table and depressed the keys with both her forefinger and second finger; previous experiments have shown that the use of two fingers makes the response easier and more natural for *S*. One half of the *S*s were randomly chosen to depress the key on the right for a positive response and the key on the left for a negative response; for the remainder, these conditions were reversed. The *S* was instructed to depress the center key until she made her response; this procedure prevented her from biasing that response by maintaining a hand position closer to one of the response keys than the other. A light on the control panel monitored by *E* enabled her to ensure that *S* was following this instruction.

Procedure

Each *S* participated in five sessions of 54 trials; a session lasted from 25 to 40 min. At the beginning of each session, *S* viewed and named each member of the set of picture stimuli before beginning the series of trials.

Each memory set size (2 or 4), each response (positive or negative), and each serial position for a correct response was used equally often in a session. In addition, letter, word, and picture test stimuli were used equally often for each set size, response, and position. Each of the 54 test stimuli was used once per session. Within these limits, the order of presentation of trials and the particular stimuli used were randomized.

Each trial lasted approximately 15 sec and involved the following sequence of events:

1. S depressed the center key and held it down.

2. E exposed the memory set for study until S verbally informed ~~E that she was ready to be tested.~~

3. E removed the memory set, inserted the test display, and verbally informed S that she had done so. (This procedure lasted about 3 sec.)

4. S pushed a button held in her left hand, and after a .4 sec delay, the test stimulus was exposed for 400 msec. The onset of the stimulus exposure coincided with the onset of a latency counter.

5. Using her right hand, S made the appropriate response by releasing the center key and depressing the key to the right or left. This response stopped the latency counter.

6. S told E the particular letter, word, or picture which had been used as the test stimulus.

7. If S made an error, E informed her of this fact.

RESULTS

The mean latencies in milliseconds for the group of 10 subjects are presented in Fig. 1. The error rate for each S was low (with a mean error over Ss of 2.2% and a range over Ss from .5% to 5%), and analysis was based only on the data for correct responses. The data from the first session were discarded in order to allow for the possibility that S had not fully understood the task. In addition, the first six trials of subsequent sessions were considered warm-up trials, and the data from these trials were also omitted from the analysis. Although an improvement in mean performance over sessions was found, when the data for sessions 2 and 3 were compared to the data for the last

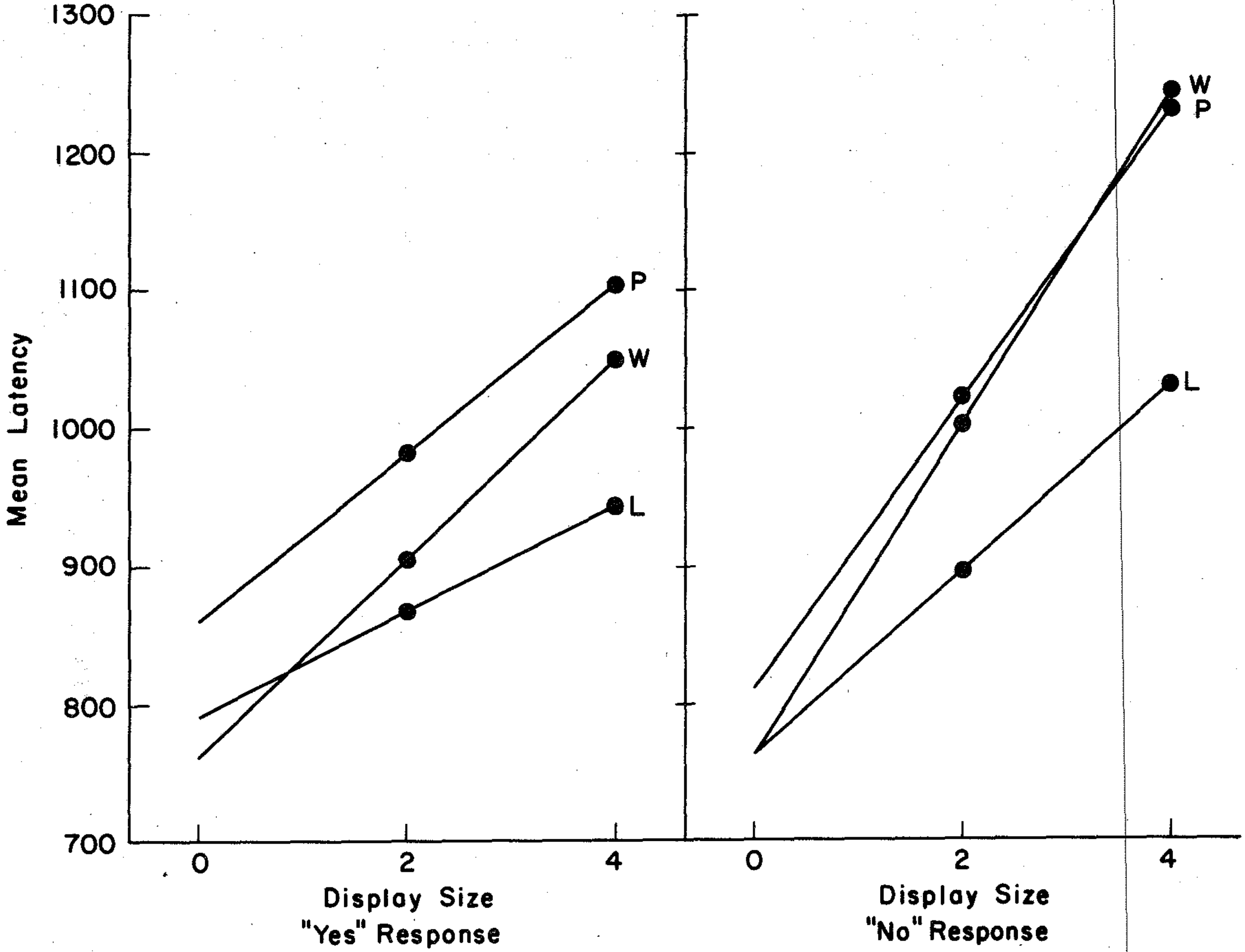

Fig. 1. Latency in milliseconds of positive (left panel) and negative (right panel) responses to each type of stimulus as a function of the size of the memory set, averaged over Ss and Sessions 2 to 5. (L = letters, W = words, and P = pictures.)

two sessions, there was no difference in the form of the reaction-time functions. This suggests that, although *S*s learned to respond more quickly, the nature of the search process itself did not change over sessions.

Figure 2 presents the serial position curves. These show mean latency in milliseconds for correct responses as a function of the position of the test stimulus in the memory set. For example, the latency for serial position one is the mean reaction time over all *S*s for those trials in which the test stimulus corresponded to the first element of the memory set.

Tables 1 and 2 present the data for individual *S*s. (It should be noted that for *S*s 1-5, the telegraph key on the right corresponded to a positive response and the key on the left to a negative response, while for *S*s 6-10, the situation was reversed.) Table 1 shows the mean latency over days for each type of stimulus and each response. In Table 2, the slopes and intercepts of the reaction-time functions for each *S* and for the mean over *S*s are given. In addition, this table shows the ratio of the slope of the function for negative responses to the slope for positive responses. (For the mean over *S*s, this ratio corresponds not to the average of the individual slope ratios, but to the ratio of the average slopes.) For a given function, the value of the slope given in the table was calculated by the formula: Slope = $\{RT(4) - RT(2)\}/2$. In terms of the equations we have presented, the slope value represents κ in the case of negative responses, while for positive responses, it represents κ or $\frac{1}{2}\kappa$ for exhaustive or self-terminating hypotheses, respectively. The ratio of the slope for

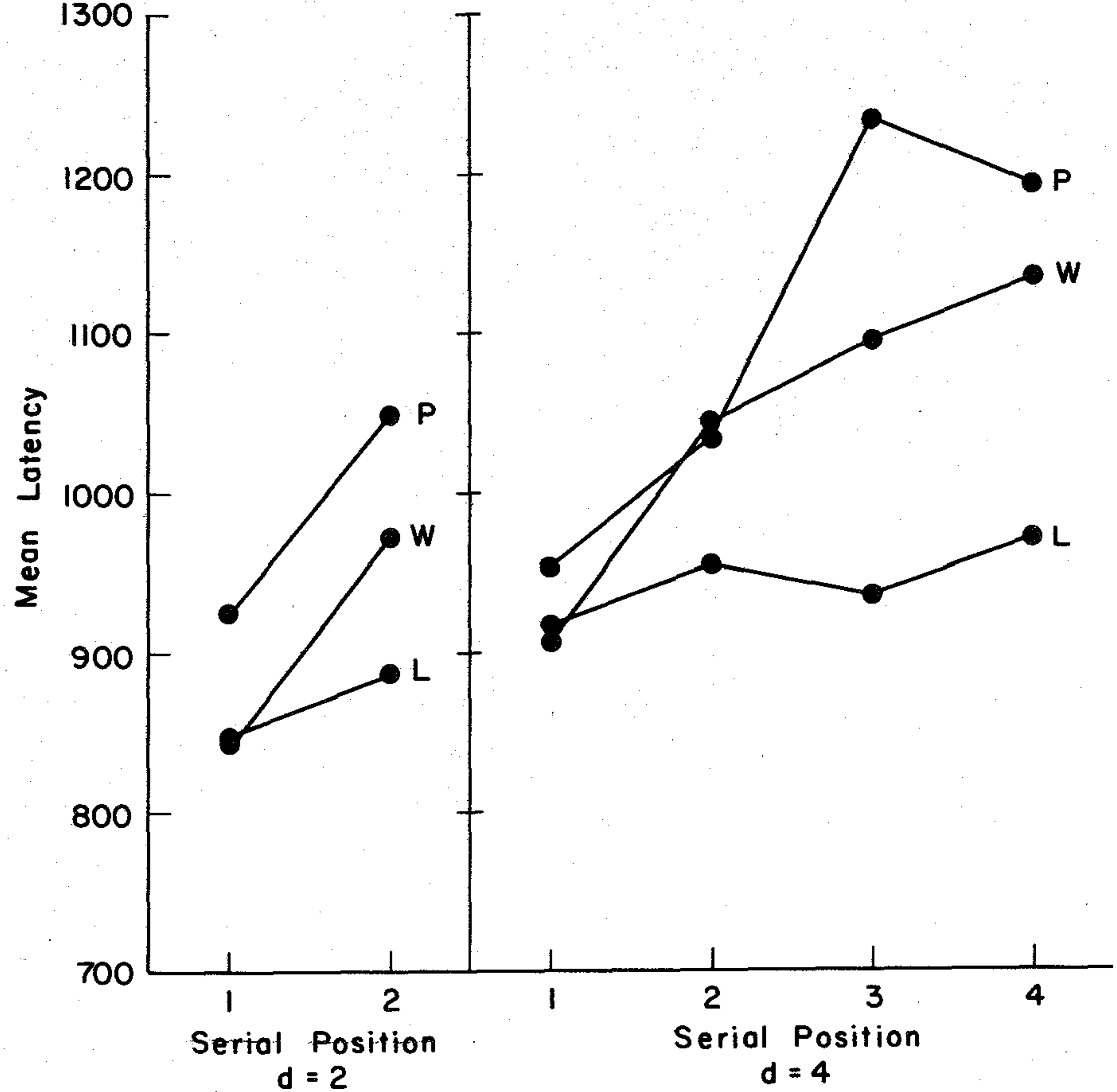

Fig. 2. Latency in milliseconds of positive responses as a function of the serial position of the test stimulus in the memory set for sets of two (left panel) or four (right panel) elements, averaged over Ss and Sessions 2 to 5. (L = letters, W = words, and P = pictures.)

Table 1

Mean latencies in milliseconds over sessions 2 to 5 for each subject and for the group; d denotes the size of the memory set.

Stimulus

Subj. No.	Letter				Word				Picture			
	d = 2		d = 4		d = 2		d = 4		d = 2		d = 4	
	yes	no	yes	no	yes	no	yes	no	yes	no	yes	no
1	788	827	828	845	832	920	932	1109	844	910	957	1042
2	1046	1138	1062	1144	1124	1257	1171	1305	1208	1209	1254	1278
3	819	793	894	993	826	865	999	1234	910	907	1100	1307
4	879	866	892	895	860	908	980	1022	930	917	1027	992
5	770	737	927	946	836	940	1159	1108	916	1032	1104	1165
6	781	892	873	1069	853	995	1065	1365	952	960	957	1118
7	730	801	800	958	853	928	870	1124	922	922	1002	1172
8	1242	1253	1366	1644	1262	1422	1505	2064	1350	1538	1568	2106
9	659	702	733	811	667	717	840	968	805	808	1008	1045
10	976	962	1066	1003	972	1070	1042	1166	1006	1054	1074	1134
Group Mean	869	897	944	1031	908	1002	1050	1246	984	1026	1105	1236

Table 2

Slope and intercept values in milliseconds of the reaction-time functions for each subject and for each group mean. The symbols S and I denote slope and intercept, respectively; the subscripts y and n denote yes and no responses, respectively.

		1	2	3	4	5	6	7	8	9	10	Mean, All Ss
Letter	S_y	20.0	8.0	37.5	6.5	78.5	46.0	35.0	62.0	37.0	45.0	37.5
	I_y	748	1030	744	866	613	689	660	1118	585	886	794
	S_n	9.0	3.0	100.0	14.5	104.5	88.5	78.5	195.5	54.5	20.5	67.0
	I_n	809	1132	593	837	528	715	644	862	593	921	763
	S_n/S_y	.45	.38	2.67	2.23	1.33	1.92	2.24	3.15	1.47	.46	1.79
Word	S_y	50.0	23.5	86.5	60.0	161.5	76.0	8.5	121.5	86.5	35.0	71.0
	I_y	732	1077	653	740	513	701	836	1019	494	902	766
	S_n	94.5	24.0	184.5	57.0	84.0	185.0	98.0	321.0	125.5	48.0	122.0
	I_n	731	1209	496	794	772	625	732	780	466	974	758
	S_n/S_y	1.89	1.02	2.13	.95	.52	2.43	11.53	2.64	1.45	1.37	1.72
Picture	S_y	56.5	23.0	95.0	48.5	94.0	2.5	40.0	109.0	101.5	34.0	60.5
	I_y	731	1162	720	833	728	947	842	1132	602	938	863
	S_n	66.0	34.5	200.0	37.5	66.5	79.0	125.0	284.0	118.5	40.0	105.0
	I_n	778	1140	507	842	899	802	672	970	571	974	816
	S_n/S_y	1.17	1.50	2.10	.77	.71	31.60	3.12	2.60	1.17	1.18	1.74

negative responses to the slope for positive responses thus represents either κ/κ (for the exhaustive case) or $\kappa/\frac{1}{2}\kappa$ (for the self-terminating case). Thus, if the search process were exhaustive, we would expect this ratio to be 1.0, while a self-terminating search would result in a ratio of 2.0. Finally, the intercepts given in Table 2 were calculated by the formula: Intercept = RT(d) - (d x slope). For positive responses, these intercepts represent the value $(\pi + \rho_y)$. For negative responses, they represent $(\pi + \rho_n)$ or $(\pi + \rho_n + \frac{1}{2}\kappa)$ for the exhaustive case or self-terminating case, respectively.

DISCUSSION

Using digit stimuli, Sternberg (1966) obtained a mean reaction-time function of the form: RT(d) = 397.2 + 37.9 d. Furthermore, functions obtained for digits and other stimuli (e.g., faces, nonsense forms) all gave qualitatively similar results; that is, linear functions with the same slope for both positive and negative responses, although scanning rates varied somewhat among stimulus materials. On the basis of these findings, similar functions for letter stimuli would be expected, and experiments conducted in our laboratory do conform to these expectations. However, in the present experiment, the Sternberg paradigm for letter stimuli was imbedded in a more complex task. That is, when presented with a letter test stimulus, S's task was precisely the same as that required in Sternberg's (1966) experiment, but letter trials were mixed with trials involving word and picture stimuli. The resulting data for letter stimuli are qualitatively different from those usually obtained.

In this experiment, both the slopes and intercepts of the reaction-time functions for all three types of test stimuli are larger than those typically found, indicating that the search process is different from that used by Ss in the usual Sternberg task. In particular, the increased slope indicates that more time is required for comparisons. One possible explanation for this result is that the representation of the test stimulus which is used for comparisons has changed, and this hypothesis is supported by the intercept data, which imply that pre-comparison processing and/or response time, even for letter stimuli, has also increased. Sternberg (1968) has stated that his experiments indicate that comparisons are made on the basis of visual rather than acoustic material. For example, the stimulus 8 is compared to members of the memory set in terms of its physical features (e.g., rounded top and bottom) rather than its name, "eight." In our experiment, however, one might suspect that comparisons are made in terms of verbal material. This might occur especially for word and picture stimuli, which require pre-processing of a verbal nature; and it is possible that this verbalization carries over to the case of letter stimuli as well.

Another feature of our data is that the slopes for letter stimuli are less than those for words and pictures. This may indicate that the representation of the stimulus which is used for comparison with the memory set in the case of letters is different from that used for word and picture stimuli. If the representations are identical for all three types of stimuli, the reaction-time functions should be parallel, with the lowest intercept corresponding to letters. This would imply that the only difference in the search processes for the three stimulus types is the amount of pre-processing conducted. However, this is not the case.

On the other hand, the lower slope for letters could result from the mixing of two different search strategies, one exhaustive and one self-~~terminating, a hypothesis discussed in more detail below.~~

In addition, we found that equality of slopes for positive and negative responses does not hold in this experiment. The ratio of the slope for negative responses to the slope for positive responses is approximately 1.75 for all three types of stimuli instead of the 1.0 ratio found by Sternberg. This implies that at least some Ss depart from an exhaustive strategy, even in the case of letter stimuli.

The serial position curves also indicate that Ss may not be searching exhaustively. In an exhaustive search, all members of the memory set are compared to the test stimulus, with the result that reaction time is independent of the position of the test stimulus in the set. Thus, serial position curves should be flat if an exhaustive search is used. Flat serial position curves would also be found in the case of a self-terminating search if either the order or the starting point of comparisons were random, since the search would require on the average an equal amount of time for each serial position. However, if comparisons always began with the leftmost member of the memory set and proceeded from left to right, a self-terminating search would result in linearly increasing serial position curves. In Fig. 2, the serial position curves are increasing, which gives additional support to the hypothesis that self-terminating searches are occurring.

Sternberg (1968) has proposed a model which attempts to explain why exhaustive scans occur. According to his model, a "homonculus" operates a scanner, which delivers material for comparison to a comparator, and examines a match register, to which the comparator sends a signal if a match is made. Since the homonculus cannot perform both of these functions simultaneously and switching from one function to the other takes time, it acts so as to minimize the total time involved in the search process. If it takes longer to make a check of the match register after each comparison than to check the register only once, after all comparisons, the homonculus operates exhaustively. On the other hand, if the time required for a single scan and comparison is large relative to the time required to switch functions and check the match register, a self-terminating process is more efficent. In fact, Sternberg (1967a) has found that self-terminating scans occur when the comparison rate is slow (approximately 124 msec).

In the present case, comparison time (κ) is much greater than in Sternberg's (1966) experiment, perhaps because the basis for comparison is no longer visual. Thus, a self-terminating search might be advantageous. Moreover, if this self-terminating process were carried over to the case of letter stimuli for a portion but not all of the trials, this would account for the fact that the slope of the reaction-time function for letters is less than that for words and pictures. It would also explain the fact that the letter slope for negative responses is approximately twice that found by Sternberg for digits. (The slope for negative responses gives a more accurate estimate of comparison time because it covers the case in which a comparison is made for each memory set stimulus.) Possibly, comparisons of letter stimuli are sometimes based on visual representations and sometimes on verbal representations, and the search process is varied accordingly.

In an attempt to clarify the results of this experiment, another study is presently being conducted. In this study, word stimuli have been eliminated, and the test stimuli for a given session may be pictures only, letters only, or a mixture of pictures and letters. For sessions which involve only letters as test stimuli, the task is the same as that used by Sternberg (1966) with digits, and a replication of his results is expected. On the other hand, the results of picture only and mixed picture and letter sessions should be more similar to those obtained in the present experiment. Moreover, additional memory set sizes are being used in the study currently in progress. Because the data obtained in the first experiment are very different from the usual results of the Sternberg procedure, there is a possibility that the reaction-time functions depart from linearity, and the use of several values of d will indicate whether or not these functions are in fact linear. Hopefully, as a result of these changes, this second experiment will serve to present a better picture of search processes which involve in part a retrieval of information from long-term memory.

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