High-Speed Scanning in Human Memory

Saul Sternberg

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the typical range of stimulation levels and environments of the species; perhaps it would be most relevant for studying evolution of behavior. The second approach, however, enables systematic analysis of the influence of various environments and test situations on behavior of the species.

The existence of interactions between variables does not imply that general statements cannot be made about genetic, age, or environmental factors per se. Significant main effects may still be the primary concern of the investigator and may frequently emerge. The value of such results increases considerably, however, if it is known that the effect occurs over a wide range of conditions and if the investigator is aware of specific interactions.

NORMAN D. HENDERSON

Department of Psychology,
Oberlin College, Oberlin, Ohio

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Abstract. *When subjects judge whether a test symbol is contained in a short memorized sequence of symbols, their mean reaction-time increases linearly with the length of the sequence. The linearity and slope of the function imply the existence of an internal serial-comparison process whose average rate is between 25 and 30 symbols per second.*

How is symbolic information retrieved from recent memory? The study of short-term memory (1) has revealed some of the determinants of failures to remember, but has provided little insight into error-free performance and the retrieval processes that underlie it. One reason for the neglect of retrieval mechanisms may be the implicit assumption that a short time after several items have been memorized, they can be immediately and simultaneously available for expression in recall or in other responses, rather than having to be retrieved first. In another vocabulary (2), this is to assume the equivalence of the "span of immediate memory" (the number of items that can be recalled without error) and the "momentary capacity of consciousness" (the number of items immediately available). The experiments reported here (3) show that the assumption is unwarranted.

Underlying the paradigm of these experiments is the supposition that if the selection of a response requires the use of information that is in memory, the latency of the response will reveal something about the process by which the information is retrieved. Of particular interest in the study of retrieval is the effect of the number of elements in memory on the response latency. The subject first memorizes a short series of symbols. He is then shown a test stimulus, and is required to decide whether or not it is one of the symbols in memory. If the subject decides affirmatively he pulls one lever, making a positive response; otherwise he makes a negative response by pulling the other lever. In this paradigm it is the identity of the symbols in the series, but not their order, that is relevant to the binary response. The response latency is defined as the time from the onset of the test stimulus to the occurrence of the response.

Because they are well learned and highly discriminable, the ten digits were used as stimuli. On each trial of experiment 1, the subject (4) saw a random series of from one to six different digits displayed singly at a fixed locus for 1.2 seconds each. The length, s, of the series varied at random from trial to trial. There followed a 2.0-second delay, a warning signal, and then the test digit. As soon as one of the levers was pulled, a feedback light informed the subject whether his response had been correct. The trial ended with his attempt to recall the series in order. For every value of s, positive and negative responses were required with equal frequency. Each digit in the series occurred as a test stimulus with probability $(2s)^{-1}$, and each of the remaining digits occurred with probability $[2(10-s)]^{-1}$.

Each subject had 24 practice trials and 144 test trials. Feedback and payoffs were designed to encourage subjects to respond as rapidly as possible while maintaining a low error-rate. The eight subjects whose data are presented pulled the wrong lever on 1.3 percent of the test trials (5). Recall was imperfect on 1.4 percent of the trials. The low error-rates justify the assumption that on a typical trial the series of symbols in memory was the same as the series of symbols presented.

Results are shown in Fig. 1. Linear regression accounts for 99.4 percent of the variance of the overall mean response-latencies (6). The slope of the fitted line is 37.9 ± 3.8 msec per symbol (7); its zero intercept is 397.2 ± 19.3 msec. Lines fitted separately to the mean latencies of positive and negative responses differ in slope by 9.6 ± 2.3 msec per symbol. The difference is attributable primarily to the fact that for $s = 1$, positive responses were 50.0 ± 20.1 msec faster than negative responses. Lines fitted to the data for $2 \leqq s \leqq 6$ differ in slope by an insignificant 3.1 ± 3.2 msec per symbol.

The latency of a response depends, in part, on the relative frequency with which it is required (8). For this reason the frequencies of positive and negative responses and, more generally, the response entropy (8), were held constant for all values of s in experiment 1. However, the test-stimulus entropy (predictability) was permitted to co-vary with s.

Both response and test-stimulus entropies were controlled in experiment 2, in which the retrieval process was studied by an alternative method similar to that used in more conventional experiments on choice-reaction time. In experiment 1, the set of symbols associated with the positive response changed from trial to trial. In contrast to this varied-set procedure, a fixed-set procedure was used in experiment 2. In each of three parts of the session, a set of digits for which the

positive response was required (the positive set) was announced to the subject (4); there followed 60 practice trials and 120 test trials based on this set. The subject knew that on each trial any of the ten digits could appear as the test stimulus, and that for all the digits not in the positive set (the negative set) the negative response was required. Each subject worked with nonintersecting positive sets of size $s = 1$, 2, and 4, whose composition was varied from subject to subject.

Stimulus and response entropies were both held constant while s was varied, by means of specially constructed populations of test stimuli. Let x_1, y_1, y_2, z_1, . . . , z_4 and w_1, . . . , w_3 represent the ten digits. Their relative frequencies in the population were x_1, 4/15; each y, 2/15; each z, 1/15; and each w, 1/15. The three sequences of test stimuli presented to a subject were obtained by random permutation of the fixed population and assignment of x_1, the y_i, or the z_i to the positive response. Thus, the population of test stimuli, their sequential properties, and the relative frequency of positive responses (4/15) were the same in all conditions (9).

A trial consisted of a warning signal, the test digit, the subject's response, and a feedback light. Between a response and the next test digit, 3.7 seconds elapsed. As in experiment 1, feedback and payoffs were designed to encourage speed without sacrifice of accuracy. The six subjects whose data are presented pulled the wrong lever on 1.0 percent of the test trials (5).

The results, shown in Fig. 2, closely resemble those of experiment 1. A positive set in experiment 2 apparently played the same role as a series of symbols presented in experiment 1, both corresponding to a set of symbols stored in memory and used in the selection of a response. As in experiment 1, linear regression accounts for 99.4 percent of the variance of the overall mean response-latencies (6). The slope of 38.3 ± 6.1 msec per symbol is indistinguishable from that in experiment 1; the zero intercept is 369.4 ± 10.1 msec. In experiment 2, the relation between latencies of positive and negative responses when $s = 1$ is not exceptional. Lines fitted separately to latencies of the two kinds of response differ in slope by an insignificant 1.6 ± 3.0 msec per symbol.
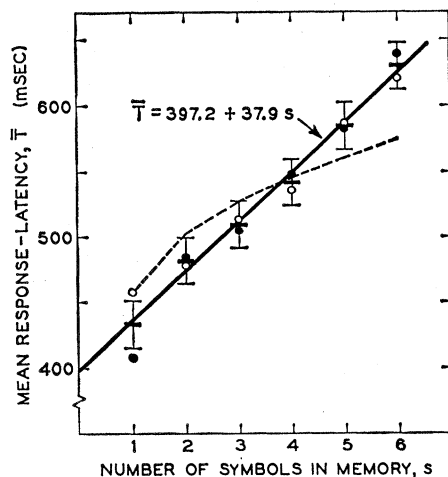
The linearity of the latency functions

Fig. 1. Relation between response latency and the number of symbols in memory, s, in experiment 1. Mean latencies, over eight subjects, of positive responses (filled circles) and negative responses (open circles). About 95 observations per point. For each s, overall mean (heavy bar) and estimates of $\pm\ \sigma$ are indicated (6). Solid line was fitted by least squares to overall means. Upper bound for parallel process (broken curve).

suggests that the time between test stimulus and response is occupied, in part, by a serial-comparison (scanning) process. An internal representation of the test stimulus is compared successively to the symbols in memory, each comparison resulting in either a match or a mismatch. The time from the beginning of one comparison to the beginning of the next (the comparison time) has the same mean value for successive comparisons. A positive response is
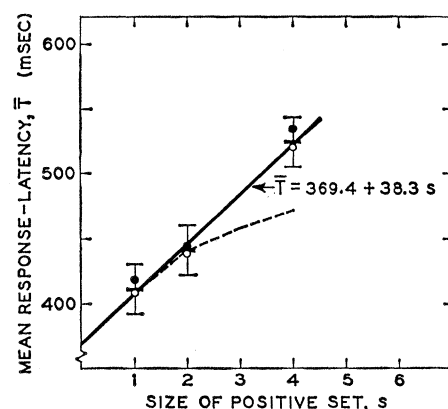

Fig. 2. Relation between response latency and the size of the positive set, s, in experiment 2. Mean latencies, over six subjects, of positive responses (filled circles) and negative responses (open circles). About 200 (positive) or 500 (negative) observations per point. For each s, overall mean (heavy bar) and estimates of $\pm\ \sigma$ are indicated (6). Solid line was fitted by least squares to overall means. Upper bound for parallel process (broken curve).

made if there has been a match, and a negative response otherwise.

On trials requiring negative responses, s comparisons must be made. If positive responses were initiated as soon as a match had occurred (as in a self-terminating search), the mean number of comparisons on positive trials would be $(s + 1)/2$ rather than s. The latency function for positive responses would then have half the slope of the function for negative responses. The equality of the observed slopes shows, instead, that the scanning process is exhaustive: even when a match has occurred, scanning continues through the entire series. This may appear surprising, as it suggests nonoptimality. One can, however, conceive of systems in which a self-terminating search would be inefficient. For example, if the determination of whether or not a match had occurred were a slow operation that could not occur concurrently with scanning, self-termination would entail a long interruption in the scan after each comparison.

On the basis of the exhaustive-scanning theory, the zero intercept of the latency function is interpreted as the sum of the times taken by motor response, formation of the test-stimulus representation, and other unknown processes whose durations are independent of the number of symbols in memory. The slope of the latency function represents the mean comparison-time. The two experiments, then, provide a measure of the speed of purely internal events, independent of the times taken by sensory and motor operations. The average rate of between 25 and 30 symbols per second is about four times as high as the maximum rate of "subvocal speech" when the words are the names of digits (11). This difference suggests that the silent rehearsal (12) reported by subjects in both experiments should probably not be identified with high-speed scanning, but should be thought of as a separate process whose function is to maintain the memory that is to be scanned.

In view of the substantial agreement in results of the two experiments, one difference in procedure merits particular emphasis. A response in experiment 1 was the first and only response based on a particular series, made about three seconds after the series had been presented. In contrast, the positive set on which a response was based in experiment 2 had been used on an average of 120 previous trials. Evidently,

neither practice in scanning a particular series nor lengthening of the time it has been stored in memory need increase the rate at which it is scanned.

In accounting for human performance in other tasks that appear to involve multiple comparisons, theorists have occasionally proposed that the comparisons are carried out in parallel rather than serially (13, 14). (This perhaps corresponds to the assumption mentioned earlier that the momentary capacity of consciousness is several items rather than only one. Are the present data inconsistent with such a proposal? Parallel comparisons that begin and also end simultaneously (14) are excluded because the mean latency has been shown to increase with s. A process in which multiple comparisons begin simultaneously is more difficult to exclude if the comparison times are independent, their distribution has nonzero variance, and the response is initiated when the slowest comparison ends. A linear increase in mean latency cannot alone be taken as conclusive evidence against such a process. The magnitude of the latency increase that would result from a parallel process is bounded above, however (15); it is possible to apply the bound to these data (16). This was done for the negative responses in both experiments, with the results shown by the broken curves in Figs. 1 and 2. Evidently, the increase in response latency with s is too great to be attributed to a parallel process with independent comparison times (17).

Other experiments provide added support for the scanning theory (16). Two of the findings are noted here: (i) variation in the size, n, of the negative set ($n \geqslant s$) had no effect on the mean latency, indicating that stimulus confusability (10, 18) cannot account for the results of experiments 1 and 2; (ii) variation in the size of a response-irrelevant memory load had no effect on the latency function, implying that the increase in latency reflects the duration of retrieval and not merely the exigencies of retention.

The generality of the high-speed scanning process has yet to be determined, but there are several features of experiments 1 and 2 that should be taken into account in any comparison with other binary classification tasks (14, 19): (i) at least one of the classes is small; (ii) class members are assigned arbitrarily; (iii) relatively little practice is provided; (iv) high accuracy is required and errors cannot be

corrected; and (v) until the response to one stimulus is completed the next stimulus cannot be viewed.

SAUL STERNBERG

Bell Telephone Laboratories,
Murray Hill, New Jersey

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6. For both experiments the data subjected to analysis of variance were, for each subject, the mean latency for each value of s. So that inferences might be drawn about the population of subjects, individual differences in mean and in linear-regression slope were treated as "random effects." Where quantities are stated in the form $a \pm b$, b is an estimate of the standard error of a. Such estimates were usually calculated by using variance components derived from the analysis of variance.
7. The analyses of variance for both experiments provided a means of testing the significance of differences among individual slopes. Significance levels are .07 (experiment 1) and .09 (experiment 2), suggesting true intersubject differences in slope; the population distribution of slopes has an estimated standard deviation of 8.0 msec per symbol.
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20. Supported in part by NSF grant GB-1172 to the University of Pennsylvania. I thank D. L. Scarborough for assistance, and J. A. Deutsch, R. Gnanadesikan, and C. L. Mallows for helpful discussions.

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Anxiety Levels in Dreams: Relation to Changes in Plasma Free Fatty Acids

Abstract. *Blood samples for determination of plasma free fatty acids were obtained throughout the night by means of an indwelling catheter. The first sample was drawn at the onset of rapid eye movements and a second after 15 minutes of these movements. Subjects were then awakened and asked to relate their dreams; a third sample was drawn 15 to 25 minutes later. Anxiety scores derived from 20 dreams of nine subjects had significant positive correlations with changes in free fatty acids occurring during REM sleep. No statistically significant relation was found between anxiety and the changes in free fatty acids occurring from the time just before awakening to 15 to 25 minutes later. Presumably, anxiety in dreams triggers the release of catecholamines into the circulation, and these catecholamines mobilize proportional amounts of free fatty acids from body fat.*

A previous study of the relation of emotions and blood lipids during the waking state revealed a significant positive correlation between low levels of arousal of anxiety, as determined from a 5-minute period of free associative speech (1), and concentrations of free fatty acids (FFA) in plasma. No essential correlation was found in this study between hostility and concentrations of FFA. The positive correlation between anxiety levels and FFA raised the question whether a similar relation might occur while subjects are in a dream state. Our study was undertaken to explore such a possibility.

Nine paid volunteer male subjects, ranging in ages from 19 to 25, were asked to sleep overnight in a dream laboratory, arranged to appear as a hospital room. Subjects slept 1 or 2 nights in the laboratory but were not given preliminary periods in which to become accustomed to sleeping in this room. They were told that we were investigating sleep, dreams, and changes in body chemistry. Subjects were instructed not to eat after their evening meal at 6:00 p.m. and to report to the laboratory at 11:00 p.m. At this time a venipuncture was performed in the left antecubital vein with a No. 18 thin-