Sensory stores and high-speed scanning*

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A model of scanning based on separate sensory and short-term stores was suggested and tested. The experiment used a probe recognition method, with set size varied from 1 to 8 and a fast presentation rate. A masking procedure was used to vary the number of items available in a possible sensory store. Although conditions were such as to maximize the chances of detecting an effect, none was found: the possible size of the sensory store had no effect on reaction time whatsoever. Other aspects of the data lent little support to a serial exhaustive scanning model, but a previously proposed parallel processing model fared better. Finally, not only was the function for positive probes steeper than that for negative probes but also there was a crossover effect as well. This crossover is not without precedent and may indicate the need for consideration of both accuracy and latency in high-speed scanning studies.

Since Sternberg (1967a, 1969a, b) presented his additive model of processing stages with reaction time (RT) measurements, the subtractive method has been adapted to such problems as mathematical skills (Groen & Parkman, 1972; Parkman, 1972; Parkman & Groen, 1971), linguistic performance (Chase & Clark, 1972; Clark & Chase, 1972; Olson & Filby, 1972), developmental change (Hoving, Morin, & Konick, 1970), and, most frequently, recognition memory tasks (Atkinson, Holmgren, & Juola, 1969; Briggs & Blaha, 1969; Briggs & Swanson, 1970; Burrows & Murdock, 1969; Burrows & Okada, 1971; Chase & Calfee, 1969; Clifton & Birenbaum, 1970; Corballis, Kirby, & Miller, 1972; Forrin & Morin, 1969; Morin, De Rosa, & Stultz, 1967; Morin, De Rosa, & Ulm, 1967; Williams, 1971; Wingfield & Branca, 1970). In spite of this popularity, a major controversy concerns the capacity of the model to handle this last class of problems.

In the usual high-speed scanning paradigm, S is presented with a list of items followed by a probe, and he has to answer as quickly as possible whether the probe item was or was not in the list. The typical outcome, when a negative response is appropriate, is best described by a linear function relating mean RT ($\bar{RT}$) to the size of the memory list. Such a function expresses the additivity of two parameters, the slope and the zero intercept, only the first of which is related to the independent variable (set size). If one is to use the language of information processing, this could mean that the time taken to perform the task is filled by two different (sets of) operations, only one of which is affected by the size of the list, while the other would represent any operations performed before and/or after it. The current interpretation for the slope parameter is that of a search time or the time required for sequential

comparison of the probe item to each additional target item in the list.

Another common finding is that the slopes of positive and negative $\bar{RT}$ functions are approximately equal. If one assumes that the manipulation of the probe-type variable (i.e., positive or negative probe) implies a binary decision operation, then the absence of interaction with the size variable suggests that, even for positive trials, the search is exhaustive: i.e., the decision occurs only after the whole list has been scanned. On the other hand, if such an exhaustive model is adequate, then the serial position of the probe in the list on positive trials should be inconsequential, and flat serial position curves should be expected. Sternberg (1966) used a presentation rate of one item every 1.2 sec and a delay of 2 sec or more. He found "relatively flat serial position curves," on which basis he made the claim that the serial exhaustive model was consistent.

Soon thereafter, people started finding serial position effects in memory scan tasks. Corballis (1967) varied presentation rate (0.6 sec/item and 0.3 sec/item) and delay of the probe (0.9 sec and 0.45 sec) but used fixed list length ($d = 5$), so that no estimate could be made about $\bar{RT}$ as a function of target size. The serial position curve evidenced strict recency effects for both rates, with a small (though not significant) primacy effect at the slow rate.

Morin, De Rosa, and Stultz (1967) also restricted the length factor ($d = 4$). They used a presentation rate of 2 items/sec and a short delay of 250 msec. They found fastest $\bar{RT}$ made to the last digit, while $\bar{RT}$ to the remaining items was larger and nearly equal.

Morin, De Rosa, and Ulm (1967) varied set size from 3 to 6, with presentation rate of 0.5 sec/item and probe delay of 0.25 sec. $\bar{RT}$ as a function of list length produced linear curves about parallel for negative and positive probes, though the latter showed a small significant quadratic component. They found serial position curves with recency effects on the last two or three items and little or no primacy component.

Burrows and Okada (1971) also varied target set size (from 1 to 4) and rate of presentation (0.5 sec/item and

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1.2 sec/item), the probe delays being confounded with the rate conditions. Here again, the positive and negative $\overline{RT}$ functions were approximately parallel. No significant serial position effect was found at the fast rate, but the slow rate produced a recency effect for the last item.

De Rosa and Beckwith (1971) used fixed length 4, a 0.5 sec/item rate, but varied delay of probe from 0.5 to 5 sec (0.5, 1.5, 3, and 5 sec). Again recency effects appeared at the shortest delay but had disappeared for some conditions (closed increasing set) after 1.5 sec and for all conditions after 3 sec.

An experiment by Clifton and Birenbaum (1970) suggests a way of integrating the data just reported. They varied set size from 1 to 7 but, since they actually controlled number of items preceding and following the item being probed, they only analyzed data for four serial positions. They also varied delay of probe (0.8, 2.8, and 4.8 sec) and found that $\overline{RT}$ was "faster when the probe item came near the end of the list, provided that the probe was presented within 0.8 sec after the end of the list." In that case, recency effects showed up with the last one or two items. It should also be mentioned that the $\overline{RT}$ functions for positive and negative probes were not strictly parallel, but individual data made it possible to divide Ss unambiguously into "exhaustive" and "self-terminating" types. Recency effects showed up with more than half of the exhaustive Ss but only at the shortest delay (0.8 sec). In one self-terminating S (out of three), they appeared under all delay conditions. The authors concluded that such effects, conditional upon short delay, could be attributed to retrieval from a short-term visual store of the kind suggested by Sperling (1960) or, rather, from a "refreshable image" of the kind suggested by Posner, Boies, Eichelman, and Taylor (1969).

Recently, Corballis et al (1972) reported an experiment in which they presented lists of letters (from 1 to 6) at a rate of 300 msec/item, with a delay of 600 msec between the last letter and the probe. They found a significant interaction of Set Size by Probe Type (positive or negative), the slope of the positive function being steeper than the negative function. They also found pronounced serial position effects, with a sharp primacy component and recency on the last three items or so. They too suggested that some of the items might have been searched in some kind of visual sensory store. If so, the scanning strategy involved for those items might have affected the overall scanning pattern.

Sternberg (1967b) provided some evidence that scanning through the visual image was self-terminating and at a rate quite comparable to that of scanning through a memorized list (35-40 msec/item). In fact, the slope of the positive function was about half as large as that for the negative function. This effect was also found by Burrows and Murdock (1969). Again the rate of scanning the visual image, prior to extended practice, was about that of looking through a memorized set. Finally, some data from Estes and Taylor (1966) and

Estes and Wessel (1966) on visual detection through rapidly presented visual displays also suggest the use of a self-terminating strategy. A mixture of those two strategies might then be responsible for the paradoxical findings.

Let us suppose that in the typical experiment with d items in short-term memory (STM), n of them remain accessible in a sensory store. The scanning would then proceed through that visual information storage (VIS) first and, if no match occurs, would start over in STM. Moreover, assume, as was found (Sternberg, 1967b; Burrows & Murdock, 1969), that the scanning rate b is the same for both stores but that some additional access time of the same order of magnitude ($b \cong b'$) is required on trials where switching occurs. Finally, let us consider, as most of the experiments reported above suggest, that n is rather small, typically one or two. The model thus becomes:

$$\overline{RT}(-) = (a + b') + (d + n)b \quad (1)$$

$$\overline{RT}(+) = a + \frac{n(n+1)b}{2}, d \leq n \quad (2a)$$

$$\overline{RT}(+) = a + c + \frac{n(n+1)b}{2} + \frac{(d-n)(d+n)b}{d}, d > n \quad (2b)$$

for negative and positive probes, respectively, where c represents the average amount of switching time required (between stores), that is:

$$c = \frac{(d-n)b'}{d}, n > 0$$

0, otherwise

and b' represents the time to switch between stores. If we assume that fast rate of presentation and short delays of probe allow representation of the last items in VIS, then the $\overline{RT}$ functions for the different serial positions on positive trials could be written as $a + b$ for the first item scanned through the sensory store, $a + 2b$ for the second, . . . and $(a + b') + (d + n)b$ for all the ones found only in STM.

With $n = 0$, for conditions of long delays and/or slow rate of presentation, n and b' drop from the above model, $\overline{RT}(-)$ and $\overline{RT}(+)$ become equal, and flat serial position functions are expected. This is what Sternberg (1966) did find with a rate of 1.2 sec/item and a delay of 2 sec.

Figure 1 illustrates the case for $n = 1$ with set size and serial position as the independent variables (a was set equal to 400 msec and b to 30 msec/item in accordance with the current literature; b' was also set to 30 msec). Notice that, although the best linear fits to both sets of points would have approximately the same slope, there is a difference of about $2b$ in the zero intercepts of the

two functions: $\overline{RT}(+)$ for Set Size 1 falls below the best linear fit, while $\overline{RT}(+)$ for Set Size 2 lies above it. All these features are currently reported in the literature for this type of experimental paradigm (Forrin & Morin, 1969; Clifton & Birenbaum, 1970; Burrows & Okada, 1971). In addition, if only the first three set sizes were considered, $\overline{RT}(+)$ would have a steeper slope than $\overline{RT}(-)$, another feature that has intrigued some researchers (Forrin & Morin, 1969). Finally, although the model could not handle eventual primacy effects in serial position curves, it predicts well enough the dramatic drop in the last position.

With $n=2$, almost the same features would be predicted but the peculiarities encountered at Set Sizes 1 and 2 would not show up. Also, the difference in zero intercepts would become somewhat too large with respect to the usual experimental findings.

Still, whenever such a switching between stores is involved, the positive $\overline{RT}$ function would tend to be slightly curved, its slope approaching only asymptotically that of the negative function. Data reported above from Morin, De Rosa, and Ulm (1967), Burrows and Okada (1971), and Clifton and Birenbaum (1970), all of whom used rather short probe delays, seem to favor such a prediction.

It would then seem desirable to manipulate experimentally the number of items available in a sensory store for physical match in order to test whether the paradox described above could be resolved with the scanning strategy postulated. The present experiment looks at reaction times under conditions of fast rate of presentation and short delay of probe. In addition, it was thought that a high level of practice was desirable to stabilize the data and that a broader range of set sizes than usual should be used to provide a better idea about the trend of the $\overline{RT}$ functions. Finally, masks were used after all but the last few items in order to control erasure from the visual image.

METHOD

Subjects

The Ss were five female and three male volunteers recruited from undergraduate courses and paid for their services. One S had to be rejected because he reversed the instructions in the middle of the experiment and another because of her unacceptably high rate of errors (over 30%).

Apparatus

Stimulus material consisted of digits presented sequentially on an oscilloscope, and the sense switches were used for response keys. List randomization, display of masks and digits, distribution of probe over serial positions, presentation rate and delay of probe, as well as response recording were controlled by a PDP-12A laboratory computer (Murdoch, Dufty, & Okada, 1972).

Procedure

On each trial, from one to eight digits were drawn randomly

Fig. 1. Predicted average RT as a function of set size and serial position.

without replacement from the Set 0-9 to compose the list. The probe was then selected from this list with a probability of .5. For positive probes, all serial positions were tested equally often.

There were four mask conditions. They all dealt with the number of items from the end of the list left unmasked. In the first condition, all items in the list were masked; in the second condition, all items but the last one were masked; in the third condition, all items but the last two were masked; finally, in the fourth condition, all items in the list but the last three were masked. Probability of occurrence of each condition of masking was uniformly distributed over trials.

Presentation rate was fixed at 250 msec/item, and the delay of the probe was fixed at 300 msec. More specifically, on each trial Ss were presented with the following sequence of events appearing on the oscilloscope screen: (1) a warning signal (three adjacent asterisks: ***), ON for 250 msec; (2) 50 msec OFF; (3) a digit, ON for 125 msec; (4) 75 msec OFF; (5) a mask (three adjacent asterisks), ON for 25 msec or 25 msec OFF if no mask required; (6) 25 msec OFF; (7) if more digits in the list, start over with Events 3, 4, 5, and 6; if the last digit had just been presented, warning signal again, ON for 250 msec; (8) 50 msec OFF; (9) probe digit, ON for 25 msec; (10) 5 sec OFF for response, then start over at 1.

Each S was run one session a day for 5 days. Within each session, he was presented with five runs of 110 trials, the first 10 of each run being discarded as warm-up trials. The first 2 days were regarded as practice sessions and only the last 3 were considered in the analysis, giving a total of roughly 9000 data points (100 trials $\times$ five runs $\times$ three sessions $\times$ six Ss).

RESULTS

Errors

Under the conditions of this experiment, the error rate ranged from 8.5% to 15.5% and averaged 11.7% across Ss. All incorrect trials were discarded from the analysis of response times.

RT and Set Size

Correct RTs were averaged for each S at each level of set size, probe type (positive or negative), and mask conditions. Set Sizes 1 and 2 were excluded from the

Fig. 2. Observed mean RT as a function of set size.

first ANOVA to keep the classification orthogonal; there were no possible three items unmasked at Lengths 1 and 2 and no possible two items unmasked with Set Size 1.

The only effects that were significant were set size [$F(5,25) = 17.83$, $p < .01$] and the Set Size by Probe Type interaction [$F(5,25) = 3.25$, $p < .05$]. For decision alone, mask, and all other interactions, $F < 1$. Trend analysis revealed significant linear and quadratic components for the set size effect [$F \text{ lin}(1,25) = 78.89$, $p < .01$; $F \text{ quad}(1,25) = 6.50$, $p < .05$] but no additional component: $F \text{ res}(3,25) < 1$. Decomposing the interaction showed only a significant linear component for negative probes [$F(1,25) = 12.63$, $p < .01$] but revealed both a linear and a quadratic component for positive probes [$F(1,25) = 66.55$, $p < .01$ and $F(1,25) = 9.39$, $p < .01$, respectively]. Least-squares solution gave zero intercepts of 664 and 609 msec and slopes of 8 and 19 msec/item for the negative and positive probes, respectively. Thus, the slope for positive probes was more than twice as steep as the slope for negative probes. The data are shown in Fig. 2, with separate panels for the two probe types. Standard errors of the mean RTs are 2.9 and 1.8 msec for negative and positive RTs, respectively.

Additional ANOVAs were run including Set Size 2 but dropping the three items unmasked condition or including Set Sizes 1 and 2 and dropping the two items unmasked condition; they led essentially to the same pattern of results. Since the steeper slope for positive than for negative probes was puzzling and unexpected, a look was taken at individual functions; every S showed this effect.

Serial Position Effects

Separate ANOVAs were run for Set Sizes 3-8. Serial position effects came out significantly at Set Sizes 7, 5, and 4 only [$F(6,30) = 4.93$, $p < .01$; $F(4,20) = 5.34$, $p < .01$; and $F(3,15) = 8.94$, $p < .01$, respectively]. The only other significant effect was a small Position by Mask interaction at Set Size 6 [$F(15,75) = 1.81$, $p < .05$]. Serial position curves are shown in Fig. 3.

Cumulant Analysis

Since large amounts of data had been collected under conditions of extended practice, other parameters of the RT distributions were examined in the hope that they might provide additional information about the underlying processes. All distributions were unimodal and skewed to the left. Moreover, in all cases, their moments satisfied conditions of nondegenerate probability distributions (Sternberg, 1964). Following Sternberg's (1964) and Taylor's (1965) suggestion, the first four cumulants were computed on each distribution from each S at each value of set size. Skewness and kurtosis parameters were then evaluated and each distribution plotted in this parameter space. Their position in that space could, thus, be compared with those occupied by standard theoretical distributions like the normal, exponential, geometric, gamma, and Poisson. None of the observed distributions could be assimilated to any of the theoretical distributions just mentioned nor to any simple (pairwise) convolution of them. The first four cumulants were then plotted as a function of set size. Cumulants are generated by the natural logarithm of the moment generating function (Kendall & Stuart, 1958) and cumulants of a convolution of independent probability distributions are then the sum of the cumulants of the respective component distributions. In a stage model with comparison substages, a very weak and elementary

Fig. 3. Observed mean RT as a function of serial position.

assumption is that the latency functions of these similar substages are similarly distributed (though not necessarily with identical time constants). If those substages are also independent, then each cumulant should at least be a monotonic function of the number of such substages involved, here set size. Such functions averaged across Ss are plotted in Fig. 4.

Clearly, the prediction does not hold. One could argue that extra complications due to variation in the decision or the mask conditions might have perturbed the distributions. Hence, cumulants were also computed on RT distributions for the negative probe (all items masked condition at each set and averaged across Ss). They are plotted as the dotted curves in Fig. 4 and mirror pretty well the solid ones. Truly, the third and fourth cumulants seem to vary rather wildly and are highly sensitive to contamination. But perhaps the trend depicted by the mean (first cumulant) and the variance (second cumulant) might receive some credit!

Error Analysis

Finally, the relatively high rate of errors provide additional information. Figure 5 shows the proportion of errors as a function of set size, averaged across Ss, and split into misses and false alarms (FA). An analysis of variance revealed highly significant effects of size, error (misses vs FA) and the Size by Error interaction [$F(5,25) = 21.64$, $F(1,5) = 53.90$, $F(5,25) = 13.58$, respectively, all with $p < .01$]. Neither mask nor the other interactions reached significance. All Ss showed the same trend, and all but one evidenced strictly flat FA functions.

DISCUSSION

The results did not support the initial proposal of this paper, namely, an exhaustive search in STM together with direct physical match or self-terminating scanning

Fig. 4. First four cumulants of RT as a function of set size (K_i is for the i th cumulant).

Fig. 5. Mean percentage of errors as a function of set size.

through a sensory store. The main experimental variable, number of items masked, was completely ineffectual in terms of its influence on RT. Therefore, even though the model outlined in the Introduction accords with many empirical effects in the literature, a direct attempt to substantiate it failed completely.

What are the results of this experiment that need explaining? First, there is the nonlinearity in the RT functions, more pronounced for the positive probes than for the negative probes. Second, there is the steeper slope for the positive probes than the negative probes. Third is the error data, where essentially false alarms are independent of set size but misses increase with set size. Fourth are the serial position effects, while fifth is the cumulant analysis, which fails to reveal any very striking monotonicity.

Any model that predicts exclusively linear set-size effects will clearly not do. What is needed is a model that can predict nonlinearity in the general case and reduce to linearity in the special case. One model that can meet these requirements is the parallel processing model suggested by Murdock (1971). This model says that all items are processed simultaneously, although with different rates. These processing rates vary with serial position. The primary component is linear with slope β , while the recency component is logarithmic with slope α . For negative probes, the processing or comparison time will depend upon the time taken to process the slowest item. For a self-terminating mode, the processing time will be the average over all serial positions of the different items tested. This model can account for the present data, provided some not unreasonable extensions are allowed. One is to permit forgetting, which must have occurred in the longer list lengths employed in this experiment. The other is to take cognizance of the naming latency facilitation effect reported by Kirsner and Craik (1971). They found that the rapidity with which Ss could simply name the probe when it was presented increased with serial position. In effect, the more recent the (positive) probe, the shorter

the naming latency. In a recognition task, this effect would presumably reduce the time for one of the processes preceding comparison to run its course.

The following equations were used to fit the model to the data:

$$\overline{RT}(+) = t_c(+) - NLF/d + k \quad (3)$$

$$\overline{RT}(-) = t_c(-) + k \quad (4)$$

where $\overline{RT}(+)$ and $(-)$ are mean reaction times to positive and negative probes, $t_c(+)$ and $(-)$ are comparison times for positive and negative probes as given in Eq. 3 and 5 of Murdock (1971), NLF is naming latency facilitation, d is set size, and k is the intercept constant to absorb all remaining effects. Handling NLF in this way is tantamount to assuming a one-item recency effect that the data (of Kirsner and Craik) deny. It is justified as a rough and ready expedient that will suffice as a first approximation.

A distinction between nominal and functional set size was introduced to accommodate forgetting. Nominal Set Size d was mapped into functional set size by assuming that the number of forgotten items was binomially distributed with parameters $d - 1$, $.05(d - 1)$. Notice, as Fig. 5 also suggests, that p , the probability of forgetting an item, is not constant but increases linearly with set size. For both positive and negative probes, comparison time t_c was based on functional not nominal set size. Coupled with the assumption that the S responds "no" if the probed item has been forgotten, then one can predict the error data shown in Fig. 5 quite accurately, though these assumptions would be quite unreasonable for any serial position analysis. While the computation of $t_c(+)$ and $(-)$ in Eq. 3 and 4 above were based on functional set size, no free parameters were required.

The parameter estimations were obtained by the simplex method of function minimization (Nelder & Mead, 1965), where the function to be minimized was the standard error of estimate. It is the standard deviation of the differences between observed and expected for the 16 data points (Set Sizes 1-8 for positive and negative probes). The best-fitting values were $\alpha = 75$ msec, $\beta = 26$ msec, $NLF = 33$ msec, and $k = 603$ msec. The standard error of estimate was 15 msec, and the smooth curves shown in Fig. 2 are the values predicted by the model for these parameters.

By and large, the fit of the model is not too bad. It at least captures the main qualitative features of the results. How good it is quantitatively is hard to say, since no other models except the linear scanning model have been detailed sufficiently to test. The error data cannot be credited to the model, since the forgetting functions were built in, not deduced. As for the serial position effects, since the ratio α/β is approximately 3, the curves should peak at the third from the last position (see Murdock, 1971). The data of Fig. 3 are not too discrepant here, though one would like more

information as to whether the departures are random or systematic. As for the cumulant analysis, it is really not germane, since stages varying with set size are not envisioned by this model.

In conclusion, then, this experiment would seem to decrease the credibility of a model based on scanning through separate sensory and short-term stores but increase the credibility of a parallel processing model for high-speed scanning. Finally, one empirical effect not yet mentioned might be singled out for particular notice. Not only do the present data show an interaction in the RT functions for positive and negative probes but also they show a crossover effect. Positive probes are faster than negative probes at the smallest set sizes used but slower than negative probes at the largest set sizes used. There are suggestions of such a crossover also in the data of Forrin and Morin (1969), Burrows and Okada (1971), Corballis et al (1972), and even Sternberg (1966). Perhaps this is a basic characteristic of this type of paradigm that can be accentuated by the appropriate experimental conditions. In particular, most experiments that show parallel positive and negative functions also have very low error rates, and perhaps when the error rates increase, there is a change in the relative subjective frequency of old and new items. If so, manipulating the relative frequency of the probe within the same paradigm should reinstate the parallel functions, and one might even make predictions about proportions of misses and false alarms under these conditions. More generally, perhaps it is not enough to restrict our attention to error-free performance in RT tasks. Perhaps a more general integration of accuracy and latency is required to further our understanding of high-speed memory scanning.

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