

SOME CHARACTERISTICS OF VISUAL WHOLE REPORT BEHAVIOR *

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A whole report experiment is reported that obtained joint serial position accuracy data, with probability-correct curves as functions of stimulus duration. A second experimental phase compared a condition in which the left part of the linear display was shielded from view during the last part of the stimulus exposure, with a condition in which the right part of the display was shielded from view during the early portion of the stimulus exposure interval, and with a control condition in which no shield was used. A noisy mask came on with the termination of the letter display, in both phases. The bounded performance model, possessing the characteristics of parallelness, independence and limited capacity, was in good accord with the data and fit better than the multicomponent model.

Introduction

Since the innovative work of Averbach and Sperling (1961), the traditional whole-report method of studying span of apprehension has been increasingly supplemented by partial-report and detection techniques (e.g., Estes and Taylor 1964, 1966). The designs effectively lessen the immediate memory load, thus allowing the investigation of limitations on other stages in the information processing chain.

Whole report continues to be of interest, however. The mechanisms contributing to whole report performance are far from entirely delineated. It has remained a question, for instance, as to where in the processing chain the major losses of information occur.

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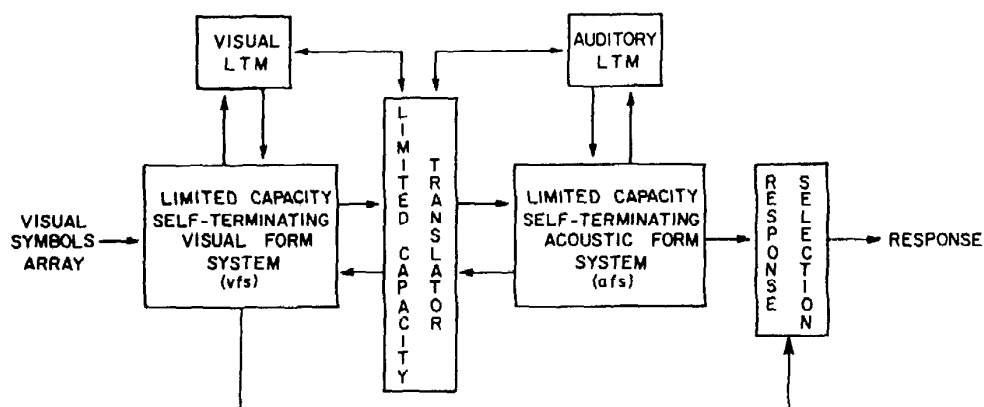


Fig. 1. A schema of selected subprocesses in visual processing. From Townsend and Roos (1973).

The intention of the present paper is to attempt to assess some of the important characteristics of whole report processing and employ them in suggesting and testing a plausible model. It will aid our exposition to have a flow-chart of the major postulated stages in whole report processing.

The schema in fig. 1 shows a flexible system that summarizes some of the functions that have been suggested to occur in a variety of visual-symbol processing tasks. It includes the visual form system (vfs), which contains a subsystem responsible for iconic storage but may also be used for matching features against incoming visual information. A translating mechanism that utilizes information garnered from correlating visual long term memory (LTM) identification with acoustic-verbal LTM to provide input to the acoustic form system (afs) follows. The translator may act as initiating a set of rehearsal instructions (Sperling 1967). The afs includes traditional immediate memory functions but also auditory icons and possibly feature alerting propensities analogous to those of vfs; acoustic inputs are not shown since the primary emphasis here is visual.

Whole report, by its very nature, must engage complete identification of the symbols (vfs-visual LTM), a linkage, possibly independent of the visual identification, with stored acoustic-verbal information (translation) and some type of storage of the consequent acoustic-verbal form of the input (afs), before report. The typical partial report procedure (Averbach and Sperling 1961) also involves these functions, but does not require that the subject process (*e.g.*, visually) as much as she or he

possibly can from the display, and translation and afs storage requirements are usually minimal. The detection paradigm, on the other hand, may involve high usage of vfs, by permitting a storage of one or more target symbols in vfs to be then matched against as much of the incoming visual information as possible, although matching may terminate (self-termination) when the target is located. Further, it is probably not necessary to completely identify each symbol in the display; probably the target can simply be matched against the display symbols. Subsequent translation to afs of the recognized target then takes place.

Because of these distinct task demands of the various paradigms the partial report and detection procedures do not establish true bounds on the capacity required to completely identify as many visually displayed symbols as possible; and the whole report task also includes a potentially higher afs load.

In addition to the actual loci of information loss in whole report, another important question concerns whether the style of processing is serial or parallel. Sperling's work has been influential with regard to this issue. He employed a whole report technique in conjunction with a noisy poststimulus mask and plotted the average-number-correct curve, as display interval varied. The results suggested a 10 msec per item scanning rate. This seems to have widely been interpreted at the time as evidence for serial processing, due to the linearity of the initial part of the curve.

However, some results reported later by Sperling (1967) appeared to suggest parallelity when serial position of the displayed letters was treated as a parameter in plotting the results. The reason is that the serial position curves were all gradually increasing, fanning out from a common origin with a negatively accelerated ascent.

The present study

The empirical goals of the work presented here were to: (1) Attempt to replicate the basic serial position functions of Sperling (1967); Experimental Phase 1 accomplishes this purpose. (2) Carry out a second experiment, with the same subjects from Phase 1, in which left-to-right serial processing would be expected to produce little or no deterioration but in which independent parallel processing should produce substantial performance decrements; this goal occupied Experimental Phase 2.

The allied theoretical goals were to (1) Ascertain some of the major characteristics of whole report behavior. These include: (a) Whether, as appears from the rather informal serial position curves of Sperling (1967: fig. 3c), there is a fairly strict upper bound on performance for durations less than around 200 ms. (b) Whether the probability of correctly reporting any given letter is correlated with the correct report of another letter, investigated by an inter-item dependence analysis. (c) Whether the Phase 2 conditions result in substantial decrements in accuracy. (2) Use these characteristics as evidence for or against the hypothesis that the major information losses in whole report occur in vfs (*e.g.*, Wolford and Hollingsworth 1974). (3) Provide suggestive evidence as to whether processing is serial or parallel. (4) Employ the above conclusions to develop a mathematical model and then test it against an alternative theoretical candidate.

Phase 1 requires no further comment at this point, but a few words are in order explaining the inter-item dependence analyses, and then the Phase 2 design. The first question concerns whether the separate letters were processed independently of one another or whether conditioning on one or more other letters being correctly processed might raise or lower the likelihood that another was correctly processed (*e.g.*, Townsend 1974; Estes and Taylor 1966). Basically, if the information lost in whole report is due to a fixed size afs short-term memory buffer, then one would expect a negative correlation among the various stimulus positions. If, on the other hand, the first information loss occurs due to less-than-perfectly accurate but independent visual channels, then the accuracy probabilities would be predicted to be independent. Finally, some models predict a positive correlation because of attentional fluctuations or the stochastic nature of the processing. Thus, a conceptualization wherein the letters are identified and sent through the translator one-at-a-time with the number of letters sent by time t described by a Poisson distribution produces such positive correlations. Mathematical models based on the three assumptions were developed and imbued with guessing structure. Guessing itself produces a slight negative correlation because each correct guess reduces the pool of correct possibilities, relative to the total remaining letters. These models were tested against the dependency statistics from Phase 1.

Phase 2 of the experiment involved an inter-display temporal manipulation to provide further information about spatiotemporal characteristics of processing. Eriksen and Spencer (1969) and Shiffrin and

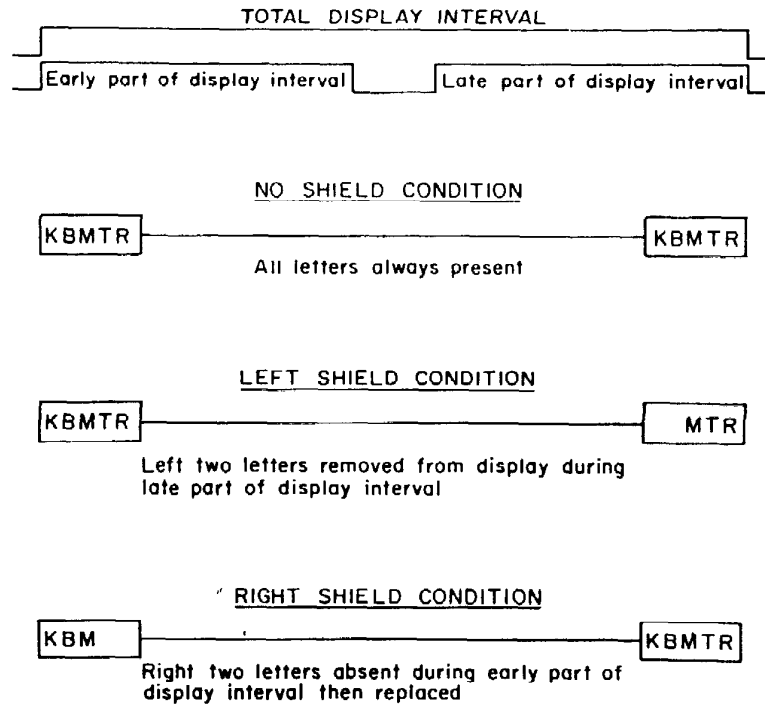


Fig. 2. A diagram of the Phase 2 paradigm.

Gardner (1972) compared the effect of presenting one symbol or part of the display for t msec followed by another symbol for t msec and so on until the entire k symbols had been shown after $k \times t$ msec, with the effect of displaying the entire array simultaneously for t msec [1]. Surprisingly, the latter condition produced accuracy about equal to that of the first. This result, of course, provides some intuitive support for parallel processing as opposed to serial processing. Both studies were of the recognition (or detection à la Estes and Taylor 1964) variety so are not directly pertinent for whole report processing. In any case, Townsend (1972) discussed this type of paradigm with respect to parallel *vs.* serial processing and proposed another of similar spirit.

The idea in the other paradigm just reverses the Eriksen and Spencer (1969) logic. If each of k symbols is presented for t msec in the sequential condition, then the simultaneous presentation is set to last for $k \times t$

[1] The former experiment (Eriksen and Spencer 1969) used a variety of sequential exposure times, the shortest being 5 msec and therefore effectively simultaneous. The Shiffrin and Gardner experiment (1972) utilized the paradigm as described with $t = 40$ msec.

msec. The modified version of this design applied in Phase 2 employed a shield on the left or right part of the linear five letter display during the early or late temporal fraction of the display duration respectively. Fig. 2 illustrates the Phase 2 paradigm. Here, if processing were parallel and independent, it was expected that the sequential (shield) type of presentation will seriously degrade performance relative to the simultaneous (unshielded), whereas if processing were serial and left-to-right, then little decrement in accuracy should be observed.

It will be shown that the data are generally supportive of independent parallel processing and the final section will test two alternative models of this type.

The experiment

Method

Stimuli

The stimuli consisted of 2,000 sets of 5 letters each. Only consonants were used. These five-letter sets were determined by programming a computer to randomly draw five letters at a time, without replacement, from the set of 20 consonants. Then, the five letters were "replaced" into the original set of 20 and the process begun again. This was done 2,000 times producing 2,000 sets of five letters each. The stimuli were typed, each set of five letters being placed on 5 X 5 cm white card. The arrays as viewed yielded letters subtending heights of 23 min with the entire five letters being about 2.5 deg visual arc.

Apparatus

A Gerbrands model T-2B 2-field tachistoscope was modified to yield three independent fields by means of solenoid switching of the first (which then became the third) stimulus field. The modifiable field could thus be either a white field with a 0.2 cm diameter fixation dot visible through a 1.8 cm high by a 3.6 cm wide aperture in the center (field 1), or the same field with a scrambled letter "visual noise" pattern visible through and filling the aperture (field 3). The stimulus field (field 2) was a white field with a 1.8 cm high by 3.6 cm wide aperture in the center. through this aperture could be seen the 5-letter stimulus pattern on any one trial. Another piece of apparatus allowed the first two letters on the left or the last two letters on the right of the stimulus to be covered for various portions of the stimulus presentation interval used only during Phase 2). It consisted of a high-speed shutter mechanism which operated either a left shield (LS) or right shield (RS) or was inoperative (no shield, NS) on any one trial. The portion of the shield in the S's view was made of the same material that the stimulus was printed on and was white and blank. The brightness of the fields was 25.35 cd/m². The ambient illumination was 19.53 cd/m² at the S's position. The opaque 2 X 2 in slides were pre-

sented via an automatic changing mechanism in randomly arranged batches of 100. A button was made available to the *S* for self-presentation of the stimulus, which occurred after a 1 sec delay.

Procedure

The total experiment required 10 days for each *S*, Phase 1 occupying eight days and Phase 2 the other two.

Phase 1. When the *S* pushed the initiation button, the white prestimulus field (field 1) with the fixation point was replaced after 1 sec by the stimulus field (field 2) containing 5 letters slightly above the locus of the fixation point. At the termination of the display duration, the stimulus field was replaced by the visual noise field (field 3) for 500 msec. The *S* was instructed to attempt to verbally report the letters in the display from left to right; that is, in their correct positions. He was then told the letters that had appeared in the display. After a day of instruction and practice, days 2 through 8 contained 200 trials each (after a set of warm-up trials), 100 trials at each of 2 stimulus durations. Day two tested 250 and 200 msec while day three tested 170 and 150 msec, and day four tested 120 and 100 msec. Days five through eight descended from 90 msec in 10 msec decrements to 20 msec during the second half of day eight. This procedure was adopted for all *Ss* in order to reduce inter-subject variability and to allow them to meet the more difficult display durations after experience with the easier displays.

Phase 2. Day nine was taken up with practicing the *S* on the shield conditions, which consisted of LS (left shield), RS (right shield), or NS (no shield) and brief testing at the 14 stimulus durations employed in Phase 1. Plots were made of each *S's* average performance on each of the 14 stimulus durations used in Phase 1 and estimates from these curves of the minimum amount of time required for 2 and 4 letters to be correctly reported were retrieved separately for each *S*. This information was compared with the day nine test results to determine the final values. The 4-letter duration (referred to as t_4 msec) was employed as the basic stimulus presentation interval for day ten and the 2-letter duration (t_2) was employed as the shield interval. It should be noted that t_4 was not constrained to be twice t_2 .

In the LS condition, all five letters were presented, then the first two on the left were covered up after the first t_2 msec had elapsed, but the right-most three letters stayed uncovered the whole t_4 msec of the presentation interval. In the RS condition, the right-most two letters of the stimulus were covered for the first part of the t_4 msec of the stimulus duration, then uncovered for the last t_2 msec of the stimulus period. The shield itself was blank to preclude additional lateral interference effects on the still visible positions 3, 4, and 5 in LS.

On day ten, in addition to warm-up trials with the various conditions, 75 trials were given at each of the 3 shield conditions (LS, RS, and NS) with their order being randomly determined for each *S*.

Subjects

Eight naive undergraduate students were run as *Ss* and were paid for their participa-

tion in the experiment. All had 20/20 acuity after correction and those wearing corrective lenses wore them throughout the study.

Results and discussion

Phase 1: the serial position curves

Fig. 3a shows the serial position curves obtained in Phase 1 averaged over all 8 subjects and fig. 3b shows them for an arbitrarily selected individual subject. As is suggested by these figures, the results were very consistent across subjects and essentially replicated Sperling's (1967) findings. In addition to the fanning out from a common origin, the

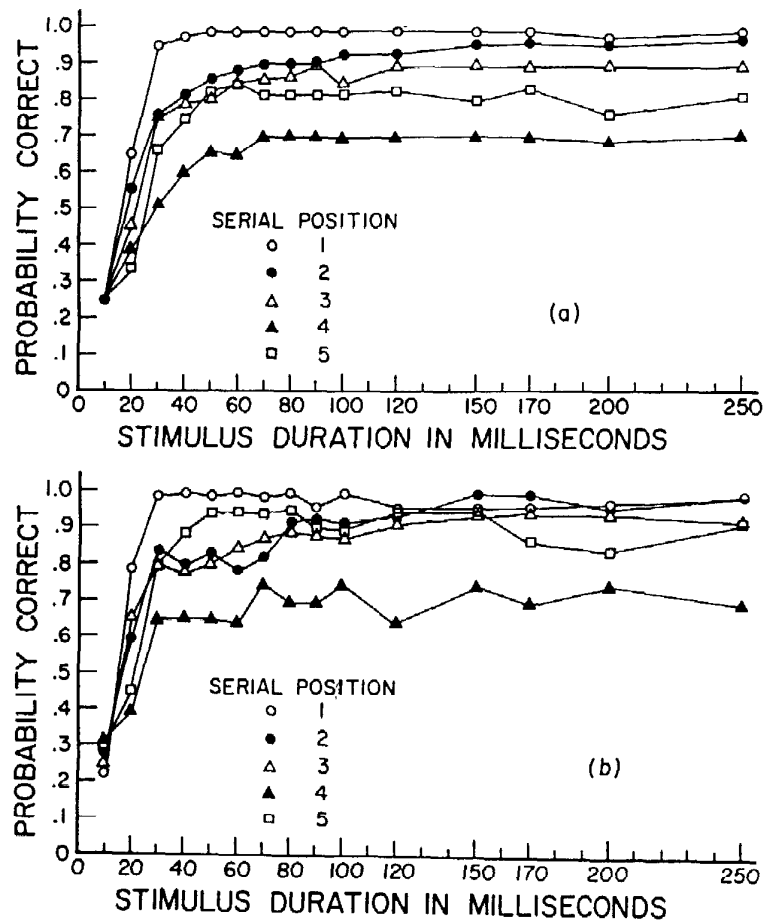


Fig. 3a. Group averaged probability correct curves for serial positions 1-5.

Fig. 3b. Probability correct curves of an individual subject for serial positions 1-5.

probability correct curves are not changing appreciably at durations longer than 100 msec. In fact, the curves of most subjects approach asymptote, but not perfect performance, by 40 or 50 msec. At about that duration, a limit appears to be reached, presumably in identification, translation, or immediate memory capacity or all three, and this limitation is not compensated for even by an extra 200 msec or so display time. The basic form of the functions was not affected by whether or not scoring a correct answer required the correct positioning of the letter in the response sequence. All the plots and analyses considered hereafter were performed for identification accuracy only, without regard to correct positioning of the letter [2].

Also, obvious in every subject's curves, was a left-to-right ordering of the curves with a reversal of serial positions 4 and 5. Thus, potentially processing might have been left-to-right and serial, or parallel with some positions being processed more accurately than others. The reversing of positions 4 and 5 may be due to an interaction between attention and lateral interference or other retinal acuity factors (*e.g.*, Townsend *et al.* 1971; Estes *et al.* 1976), or to attentional factors alone. If the subjects held their gaze at the centered fixation point, the reversal cannot have been due only to retinal factors.

The continuous fanning-out growth of the serial position curves is perhaps suggestive of parallel processing as Sperling (1967) tentatively concluded. However, serial models can also predict this type of behavior as follows directly from the general difficulties in parallel-serial identifiability (*e.g.*, Townsend 1972, 1974). Although we will not be able to draw absolute conclusions regarding parallel *vs.* serial processing in the present study, we will see that overall we can further delimit the type of model that can satisfy the data. For instance, independence of processing is more intuitively associated with parallel than serial processing, although some serial models can produce this characteristic. We therefore next analyze this issue, which is also important in its own right.

[2] Potentially, the descending stimulus duration sequence might have interacted with session number and elevated slightly the latter accuracy levels (through practice). However, the data taken in session (day) 9 on the 14 durations yielded the same basic functions, although with more variability. Further, the rapid approach to asymptote also appears in Sperling's (1967) curves.

Phase 1: independence vs. dependence of processing

In order to gain an idea of the interletter dependencies in the various positions, predictions were obtained from several diverse models and compared with the data.

As noted above, serial models based on the Poisson distribution produce positive dependencies. Such models are compatible with an overall theory positing time-limited identification and/or translation to verbal-acoustic immediate memory with these constraints being sufficiently severe that immediate memory is not taxed. On the other hand, if the primary limitation were in immediate memory (afs) and this memory were of fixed capacity, then a negative correlation would entail. The reason is that if it is known that a given letter has made it into immediate memory then the chances are lessened that space will be available for another letter. It would further seem that other theories positing output interference as the limiting factor in whole report performance might also predict negative correlations but apparently none has been sufficiently developed to make precise predictions on this issue. An independence result seems intuitively most compatible with a set of independent channels in vfs.

Two positive dependence models, a negative dependence model and an independence model were employed to make dependence predictions. Each model contained guessing structure appropriate to its particular characterization.

The processing (as opposed to guessing) part of the positive dependency models was based on a fixed order (left-to-right) serial Poisson model and a random order serial Poisson model, respectively. The negative dependence model is mathematically equivalent to the Estes and Taylor (1964) fixed sample size model and will henceforth be so designated. In contrast, the independence model assumed that each letter was processed independently of one another.

The mathematical form of these models can be indicated by the form of their probability correct ($P(C_i)$) prediction for a given display position i .

The analysis of independence below involves averaging across display positions and some of the model predictions can ignore these. However, the left-to-right Poisson model has to take position into account by its very nature, as will be seen. It will be shown how, if at all, the other models can predict serial position effects. It should be emphasized that

the $P(C_i)$ equations do not themselves exhibit the interpositional dependencies or lack thereof, and are intended simply to explain the models' structures.

For all models, n = display size and N = stimulus population size. In the present experiment, $n = 5$ and $N = 20$.

The probability correct on position i in the case of the strict left-to-right serial Poisson model is

$$P(C_i) = \sum_{j=0}^{i-1} P(j, t) \frac{n-j}{N-j} + \sum_{k=i}^{\infty} P(k, t),$$

where

$$P(j, t) = \frac{(\lambda t)^j e^{-\lambda t}}{j!},$$

is the Poisson probability that j letters have been completed during time t , and $(n-j)/(N-j)$ is the appropriate guessing factor when $j < i$ have been completed. The first sum gives the contribution of trials where the display was terminated before reaching stimulus location i . For instance, let us look at $P(C_3)$ the probability correct in stimulus position 3. Suppose that during the display time t , the first two ($j = 2$) letters were completed in the left-to-right processing path. This occurs with probability

$$P(2, t) = \frac{(\lambda t)^2 e^{-\lambda t}}{2!}$$

Because neither of these two letters will be in the guessing pool that exists for the unidentified remaining three letters, the average probability of correctly guessing the letter that was in position 3 is simply

$$\frac{5-2}{20-2} = \frac{3}{18} \approx 0.167$$

The product

$$\frac{(\lambda t)^2 e^{-\lambda t}}{2!} \cdot (0.167)$$

will therefore be the third term in the first sum above. The second sum picks up those terms wherein position 3 is completed so that the $P(j, t)$ ($j \geq 3$) is simply multiplied by 1. Adding together both sums yields the overall average probability correct. Note that this model assumes the completion time distribution for each letter is exponential with processing rate λ . Serial position effects are represented by $P(C_i) > P(C_j)$ if $i < j$.

The random order serial model predicts that

$$P(C_i) = P(C) = \frac{1}{n} \left\{ \sum_{m=1}^n \left[\sum_{j=0}^{m-1} P(j, t) \frac{n-j}{N-j} + \sum_{k=m}^{\infty} P(k, t) \right] \right\}$$

that is, $P(C)$ is an average of the possible values of probability correct across the different *processing* positions. Because the processing path through the various display positions is presumed to be entirely random, it follows that any position (i) will appear in any one of the possible n processing locations with probability $1/n$. The index m in the above equation represents this (m th) processing location. We can therefore represent the probability correct on display position i as

$$P(C_i) = \sum_{m=1}^n P(\text{position } i \text{ is processed } m\text{th}) \cdot P(\text{correct given position } i \text{ is processed } m\text{th}),$$

where $P(\text{position } i \text{ is processed } m\text{th}) = \frac{1}{n}$.

Given the processing position m , the above conditional probability is then clearly exactly the same as $P(C_m)$ in the previous formula for the strict left-to-right processing path, that is,

$$P(C_m) = \sum_{j=0}^{m-1} P(j, t) \frac{n-j}{N-j} + \sum_{k=m}^{\infty} P(k, t).$$

$P(C_i)$ then results as the weighted sum of these $P(C_m)$ terms. This model predicts a complete absence of serial position effects.

Consider next the independence model. The general form of the

probability correct formula is $P(C_i) = P(C) = p(t) + (1 - p(t)) n/N$, $0 \leq p(t) \leq 1$. The term $p(t)$ is the probability that the letter in a position is correctly processed during the display time t . With probability $(1 - p(t))$ the position is not completed and the subject must guess the entry. Because we do not know what happens in the other positions the overall average probability correct by guessing in that event is just n/N . (This can be demonstrated mathematically and is done so in many elementary probability texts.) Note that $p(t)$ is fixed for a given t , but we expect it to increase as t increases. Serial position effects can be implemented in this model by simply letting $p_i(t) \neq p_j(t)$ for $i \neq j$.

The fixed sample size model makes the prediction

$$P(C) = \frac{\binom{1}{1} \binom{n-1}{X_t-1}}{\binom{n}{X_t}} + \frac{\binom{1}{0} \binom{n-1}{X_t}}{\binom{n}{X_t}} \cdot \frac{\binom{1}{1} \binom{N-1-X_t}{n-1-X_t}}{\binom{N-X_t}{n-X_t}}, \quad 0 \leq X_t \leq n.$$

The appropriate probability distribution for this model is, as shown, the hypergeometric because it describes the probability of obtaining a certain number of items of a particular variety when a fixed sample is drawn from a set of items. When the stimulus duration is t , the fixed sample size is X_t (a positive integer) which of course must be of size $0 \leq X_t \leq n$. We are interested first in the number of ways in which the particular item of interest, namely the letter in position i , can be drawn in this selection of X_t letters out of the n . This is given by $\binom{1}{1} \binom{n-1}{X_t-1}$ and the probability the i th letter is sampled is just

$$\frac{\binom{1}{1} \binom{n-1}{X_t-1}}{\binom{n}{X_t}}$$

that is, the above term divided by the total number of ways of sampling X_t from n items. This term is then the probability of being correct on a position by actual identification.

However, if the letter in that location is not contained in the sample of X_t letters, which happens with probability

$$\frac{\binom{1}{0} \binom{n-1}{X_t}}{\binom{n}{X_t}}$$

then one may still be correct by guessing. Unlike the situation in the independence model, we know that exactly X_t of the n displayed letters have been perceived so the guessing probability must take account of this fact. The appropriate latter probability is the hypergeometric probability that a certain one (namely the one in position i) of the remaining $n - X_t$ letters is sampled from the total of $N - X_t$ possibilities. Finally, although X_t is fixed for a given t , we expect it to increase as t becomes larger. As written, this model cannot reflect serial positions, although a much more complicated fixed sample size model could by assuming that some positions can be sampled more easily than others.

A statistic that exhibits the degree of interdependence present is $\text{Ave} [P(C_i | C_j) - P(C_i)]$ where $i \neq j$ and the average is taken over i and j . By plotting this quantity as a function of $\text{Ave} P(C_i)$ it was possible to compare the data with predictions of the four models in a way that did not depend on specific parameter values. These statistics are straightforward to derive in the various models and are omitted here. Fig. 4 shows these

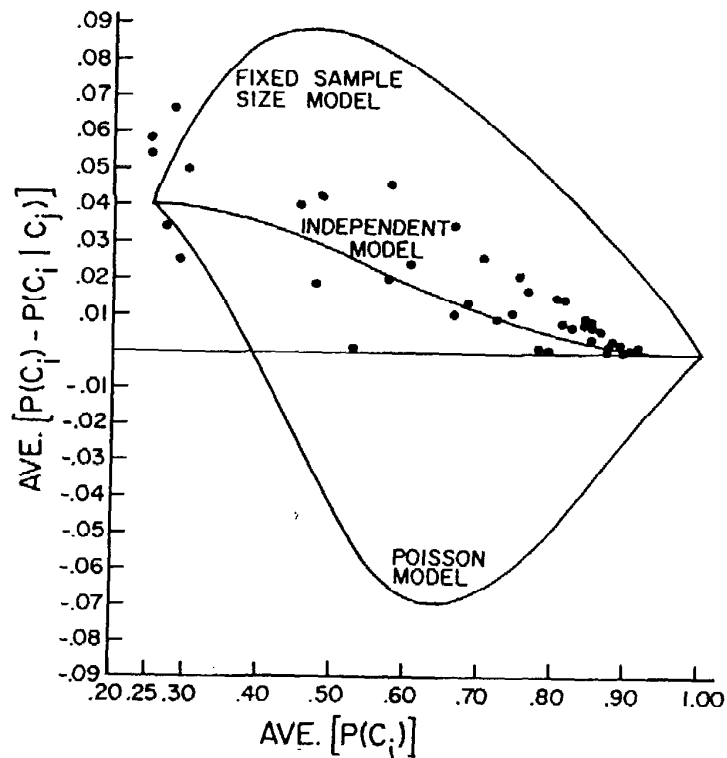


Fig. 4. An interletter dependency statistic, $P(C_i | C_j) - P(C_i)$, as a function of $P(C_i)$, averaged over serial positions (i, j) and subjects.

functions where, of course, the display time is an implicit parameter since the different display times caused Ave $P(C_i)$ to vary. The data points are those of the eight individual subjects presented as a scatter plot. The display durations were blocked into six intervals, 10 msec, 20 msec, 30 msec, 40–50 msec, 60–100 msec, and 120–150 msec and the $P(C_i)$ and $[P(C_i) - P(C_i|C_j)]$ averaged within these intervals and over stimulus positions i and $j = 1$ to 5.

Fig. 4 exhibits the fixed-sample size model prediction of a large negative correlation; the independence model of a small negative correlation due to guessing; and the Poisson model of a sizable positive correlation, at least for $P(C_i) > 0.30$. The data are much closer to the independence predictions than either of the other two model-predictions.

Individual subject's curves appeared to agree with the overall scatter plot results of fig. 4 with none showing a consistent tendency to deviate toward the positive or negative correlation predictions. For instance, when $P(C_i) \geq 0.80$, no subject possessed absolute curve values above 0.02, whereas the fixed sample size model still predicted relatively large positive deflections and the Poisson model relatively large negative deflections from zero. These tendencies also held up in the many individual subject plots of $P(C_i) - P(C_i|C_j)$ for each $1 \leq i \leq 5$ across the serial position $1 \leq j \leq 5$ within each single stimulus duration. That is, $P(C_i) - P(C_i|C_j)$ tended to go from a positive value toward 0 as the duration (and therefore $P(C_i)$) increased. A representative example is

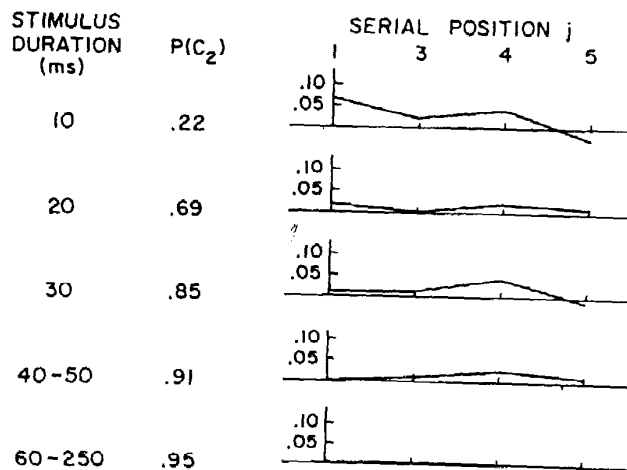


Fig. 5. $P(C_2) - P(C_2|C_j)$ plotted as a function of serial position of other letters ($j = 1, 3, 4, 5$) as stimulus duration is varied.

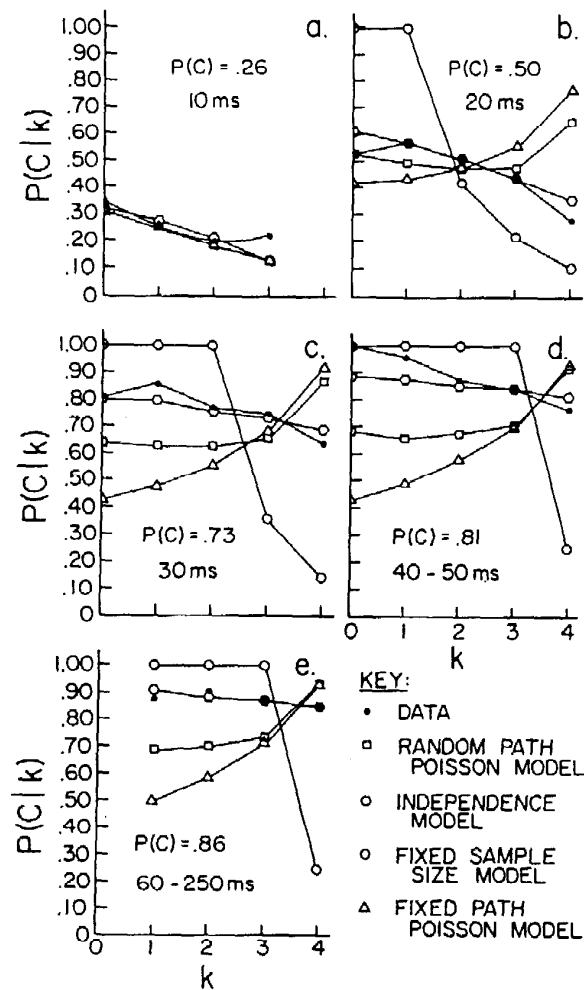


Fig. 6a-e. The interletter dependency statistic, $P(C|K)$ as a function of K , averaged over serial positions and subjects, for different marginal probability correct values.

shown in fig. 5, the data of subject 5 in the case of stimulus position $i = 2$. $P(C_2) - P(C_2|C_j)$ is on the ordinate and j is on the abscissa.

Another interesting statistic for testing independence is simply $P(C|k)$, the probability correct given exactly k of the other positions were correct, averaged again over the five serial positions, and plotted against k . The results of this analysis are shown in the panels of fig. 6a-e. Data and predictions are omitted where few trials contributed to the point. The different panels show this statistic for varying exposure duration, grouped to contain equally accurate data. Theoretical predictions were generated by selecting those parameter values yielding the

same marginal probability correct as for the particular accuracy level. Thus, each model had one parameter estimated for each graph in fig. 6, or 5 in all. Note that here, the random Poisson and the fixed path Poisson models make distinct predictions. Clearly, the data are again much closer to the independent model than to any of the others.

Phase 2: shield condition

The shield results are shown in table 1. The theoretical entries (THE) will be discussed later. Noting that the maximum standard error for any proportion in table 1 is $\sqrt{0.25}/\sqrt{75} \doteq 0.06$ from $\sqrt{p(1-p)}/\sqrt{N}$, it can be seen that the shield caused sizable effects, typically deterioration in the shielded positions. Thus, performing a sign test on the 32 differences taken from $NS - LS(i)$, $i =$ position 1 or 2 and $NS - RS(i)$, $i =$ position 4 or 5 for the individual subjects, finds significance at greater than the 0.001 level.

It was expected that the LS effects would not be so strong as the RS effects since the former type of trial was terminated by the blank shield but the RS trials were terminated by the usual visual-noise poststimulus mask (see Method section). This occurred; indeed in most cases, serial position 1 showed little information loss.

The other second order effect of note is the appearance of some individual differences in reaction to the shields. Some subjects seem to have let accuracy on the right positions suffer somewhat in LS in order to perform well on the first two positions, especially the first. Subject 4 actually improved performance on the first three positions (position 3 was not shielded in either condition) in LS with some lowered probability correct in positions 4 and 5. Some subjects seemed to compensate for the shield even in RS with more attention on one or both of the shielded positions, the most noteworthy being perhaps the substantial increase in probability correct on position 4 by subject 6 in RS; it may be observed that there was a simultaneous loss at his unshielded position 3. Thus, it seems that some subjects can alter their inter-position distribution of attention between blocks when the viewing environment is changed and may do so with some between-individual variation.

One additional point is important here. It is that the deterioration in accuracy occurred even though the design used here employed only a single shield per trial rather than two, one on each end. In that situation, the right shield would be on when the display is revealed, then

Table 1
Results of the shield conditions.

S	Serial positions															
	1			2			3			4			5			
	NS	RS	LS	NS	RS	LS	NS	RS	LS	NS	RS	LS	NS	RS	LS	
1	OBS	0.99	0.99	0.93	0.71	0.85	0.67	0.80	0.92	0.68	0.64	0.52	0.63	0.76	0.35	0.68
	THE	1.00	1.00	0.93	0.81	0.81	0.46	0.79	0.79	0.79	0.63	0.39	0.63	0.79	0.45	0.79
2	OBS	0.99	1.00	0.95	0.84	0.84	0.77	0.84	0.85	0.72	0.73	0.31	0.60	0.73	0.21	0.85
	THE	0.97	0.97	0.76	0.79	0.79	0.63	0.75	0.75	0.58	0.49	0.58	0.58	0.73	0.59	0.73
3	OBS	0.97	0.98	0.87	0.92	0.92	0.72	0.96	0.93	0.89	0.79	0.71	0.77	0.80	0.69	0.84
	THE	1.00	1.00	0.87	0.92	0.92	0.54	0.92	0.92	0.92	0.72	0.45	0.72	0.74	0.46	0.74
4	OBS	0.91	0.99	1.00	0.79	0.89	0.84	0.88	0.91	0.92	0.80	0.68	0.69	0.85	0.61	0.81
	THE	1.00	1.00	1.00	0.91	0.91	0.51	0.90	0.90	0.90	0.70	0.43	0.70	0.78	0.46	0.78
5	OBS	1.00	1.00	0.95	0.83	0.80	0.76	0.95	0.99	0.93	0.79	0.48	0.67	0.81	0.55	0.79
	THE	1.00	1.00	0.95	0.92	0.92	0.49	0.94	0.94	0.94	0.69	0.41	0.69	0.84	0.46	0.84
6	OBS	0.99	0.97	1.00	0.80	0.79	0.63	0.89	0.71	0.84	0.61	0.76	0.63	0.76	0.80	0.75
	THE	1.00	1.00	0.85	0.84	0.84	0.54	0.77	0.77	0.77	0.59	0.42	0.59	0.68	0.46	0.68
7	OBS	1.00	0.99	0.97	0.88	0.88	0.81	0.89	0.83	0.88	0.76	0.71	0.72	0.93	0.85	0.84
	THE	1.00	1.00	1.00	0.90	0.90	0.88	0.84	0.84	0.84	0.70	0.68	0.70	0.82	0.81	0.82
8	OBS	0.99	0.96	0.96	0.84	0.81	0.72	0.55	0.77	0.67	0.64	0.56	0.63	0.76	0.82	0.83
	THE	1.00	1.00	0.75	0.82	0.82	0.48	0.72	0.72	0.72	0.75	0.38	0.75	0.68	0.43	0.68
AVE	OBS	0.98	0.99	0.96	0.83	0.85	0.74	0.85	0.86	0.82	0.72	0.59	0.67	0.80	0.57	0.80
	THE	1.00	1.00	0.89	0.86	0.86	0.57	0.83	0.83	0.83	0.67	0.46	0.67	0.76	0.52	0.76

Note: OBS = observed; THE = theoretical.

shortly after it was removed, the left shield would be brought in until the entire display was terminated with the visual noise. The latter design would be expected to cause even more degradation of performance in parallel processing.

The shield effects seem most compatible with a parallel system that can adjust attention on a between-block basis. There appears to be no single subject in table 1 who gives evidence eminently compatible with a simple left-right serial model, that is, with minor or no deterioration in performance in the shield conditions and no compensatory changes in unshielded locations. Further, the serial pathways through the various positions would, in some cases, apparently have to be rather bizarre to produce the observed serial position accuracies.

A test of two parallel models

An overall parallel characterization that seems compatible with the present findings will now be outlined. It is first assumed that any given display arrayed in some retinal pattern has associated with it an upper bound on the visual clarity of the various items within it, which is due primarily to the physical characteristics of the items (*e.g.*, the font of an array of letters, the contrast, *etc.*) and to the retinal loci.

Superimposed on this "pattern of retinal integrity" is a visual attention distribution which is usually parallel and stochastically independent but may be quite nonuniform especially where well-engrained habits are influential (as in reading directions). In cases where highly unfamiliar material is employed, the attention may possibly be focused on a single item but probably cannot be refocused during a single brief exposure. This attention cannot, however, completely compensate for a low upper bound on the physical integrity, but lack of attention can make accuracy on an item worse.

It is supposed that the items to which attention is directed have part or all of their information printed in a short-term visual memory. When the information from a very well known item is quite high, visual identification of this item is probably almost automatic. If little geometric information is accrued, then this is held until a decision can be made as to what symbol it probably represents.

The visual attentional capacity seems to be sufficient to allow about four and one-half items to be processed when: displayed with reasonably high contrast, lacking severe lateral interference, for an interval of

time between 50 to 250 msec, and in the region of the fovea, when a strong noise mask (or very bright flash mask) cessates a viable visual image. A lasting icon with a high integrity display may allow somewhat more items to be correctly reported (perhaps up to the afs capacity). It seems plausible to conjecture that although all these characteristics up to here are associated with the vfs in conjunction with the visual LTM of fig. 1, later mechanisms cannot be completely ruled out at this time. The finding by Wolford and Hollingsworth (1974) that visual confusions predominated in a whole report study is compatible with the present emphasis on vfs limitations. It is also consonant with the fact that the usual estimates of afs memory capacity (for example, with auditory presentation) tend to be somewhat larger than the 4 or 5 found here (about 6 or 7; Neisser 1967).

A mathematical formulation that encompasses the major characteristics in the above account, which we call the "bounded performance model", was first suggested by Townsend and Fial (1968). Let $I_i(t)$ represent the "integrity" or quantity of stimulus information available at time t for stimulus location i and suppose that I grows monotonically with stimulus duration. Let C be a term standing for the total capacity or energy available for devotion to the letter identification task fixed for a given display size, and assume that this capacity is spread over the display according to a distribution $0 \leq a_i \leq 1$, $\sum_{i=1}^5 a_i = 1$ so that a_i is the proportion of attention given to stimulus location i . " C " can be interpreted as the amount of letter information that can be processed via the vfs-LTM system. The probability correct $p(t)$ via nonguessing events at time t is presumed to be equal to the proportion of information actually processed on the letter in position i by that time: ($p_i(t) = I_i(t)/I_i \times a_i \times C$, where $I_i = \lim_{t \rightarrow \infty} I_i(t)$ is the upper limit on obtainable information. In the present application, we make the simplifying assumption that I_i is the same for all positions so that $p_i(t) = I(t)/I \times a_i \times C$. Finally, it seems reasonable as a first approximation to suppose that the growth of the available stimulus information I is regulated by the simple first order linear differential equation $dI(t)/dt = [I - I(t)] V$ where V expresses the rate of growth, and $I = \lim_{t \rightarrow \infty} I(t)$. That is, the rate of increment to the information quantity $I(t)$ is proportional to the difference between the current level $I(t)$ and the asymptotic level. Integration yields the time function $I(t) = I[1 - e^{-(t-t_0)V}]$, and $p_i(t)$ then becomes $p_i(t) = a_i C [1 - \exp(-(t-t_0)V)]$. The quantity t_0 reflects the time at which information begins to be accumulated. Note that

potentially it might happen that $a_i C > 1$ so that $p_i(t) > 1$ as t grows large. Our interpretation here is that $a_i C > 1$ implies that more attention has been devoted to position i than is required at long stimulus durations for correct perception of the letter. When this occurs, and $a_i C \cdot [1 - e^{-(t-t_0)^V}] > 1$, the extra attention, $a_i C [1 - e^{-(t-t_0)^V}] - 1$, is wasted and, of course, $p_i(t) = 1$.

The multicomponent model of Rumelhart (1970) also seems generally compatible with the principles of the above schema. However, the limited capacity is expressed there in terms of a Poisson processing rate (expressed as r below) with the allocated attention to each letter given by some proportion of that rate. We hypothesized that this model would not be as successful as the bounded performance model because it predicts that the $p_i(t)$ curves, as t varies, increase monotonically to 1 whereas the data appear to evidence a substantial flattening out, within the durations permitted. The bounded performance model does predict this qualitative result.

The appropriate predictive formula for the multicomponent model is

$$p_i(t) = \sum_{k=K}^{\infty} \frac{[\theta_i r (t - t_0)]^k}{k!} \exp[-\theta_i r (t - t_0)]$$

where

- (i) θ_i = proportion of attention allocated to stimulus position i ,
- (ii) r = stimulus clarity factor,
- (iii) t_0 = minimal processing time,
- (iv) K = criterion number of features which must be completed to identify a (any) letter [3].

Obviously both models implicitly predict stochastic independence of processing, before guessing occurs. Each model possessed 7 parameters against the 75 data points of the basic serial position functions of

[3] The parameters $r = \mu$, $K = c$ in Rumelhart (1970) and have been altered here for less confusability with the bounded performance model's parameters. The multicomponent model has been adapted to the present experiment by taking equation (10) in Rumelhart (1970) and letting the masking be total ($\alpha_X = 0$) and $\tau = t$ (onset of the mask was coincident with the termination of the stimulus). Also, it was assumed that, as in the bounded performance model, the effective processing time was $t - t_0$. The reader is referred to that paper for more details on the multicomponent model.

Phase 1, for each subject. They were given the requisite guessing structure and then fit to the Phase 1 serial position data. The parameter estimate of t_0 that optimized the fit of the bounded performance model was between 9 and 10 msec for all subjects so was set to the minimal plausible value of 10 msec in the final version. The latter fits were virtually identical to the optimal fits.

Table 2 exhibits the χ^2 values and parameter estimates for each subject, for each model. It can be seen that the bounded performance model is substantially superior to the multicomponent model. In fact, the bounded performance model fit can be described as quite good. This can be seen by noting that for large df , the square root of χ^2 , χ , is well approximated by

$$\chi \simeq [x + \sqrt{2df - 1}] \frac{1}{\sqrt{2}},$$

where x is the unit normal variate; thus the mean or expectation of χ is $E(\chi) \simeq \sqrt{df} = 8.7$ in the present case and the standard deviation is $\sigma_x = 0.71$. Since the largest value of χ here is $\sqrt{58.9} = 7.7$, for subject 2, it follows that this model is accounting quite well for the serial position functions. On the other hand, the multicomponent model fails for all subjects at the $\alpha = 0.16$ level and for six of the eight subjects at the 0.05 level. The χ^2 values for the multicomponent model are typically several times those for the other model.

The average-number-correct curves (averaged over serial position and subjects) for the two models are shown in fig. 7, and confirm the earlier stated hypothesis that the bounded performance model would be better able to handle the upper limits on accuracy evident in figs. 3a and b.

The parameter estimates in table 2 indicate that in all cases $C < 5$ although these parameters were unconstrained in the fit program. The consistency of the parameter estimates across the subjects is striking. The fact that t_0 turned out to be about 10 msec suggests that information begins to be accumulated at the shortest display duration.

It may be noted that in some cases, $aC > 1$; for example, subject 8 exhibited $a_1C = 0.37 \times 4.6 = 1.7$. As stated earlier, we believe this to represent an excess of capacity devoted to such positions. When t is small, this benefits the favored position, but when t is large, the extra capacity could be more efficiently employed on other positions j , where $p_j(t)$ is still < 1 .

Due to the basically good fit of the bounded performance model on

Table 2
Chi-square fits and parameter estimates of the bounded performance model and multicomponent model to the serial position curves alone.

Subj	Parameter estimates								
	χ^2	C	t_0	V	a_1	a_2	a_3	a_4	a_5
Bounded performance model									
1	22.7	4.78	10.0	0.068	0.30	0.19	0.19	0.13	0.19
2	58.9	4.66	10.0	0.040	0.26	0.21	0.20	0.13	0.20
3	32.8	4.48	10.0	0.063	0.27	0.22	0.22	0.14	0.15
4	26.1	4.61	10.0	0.058	0.28	0.21	0.21	0.14	0.16
5	19.9	4.71	10.0	0.087	0.29	0.20	0.20	0.13	0.18
6	31.3	4.23	10.0	0.041	0.38	0.20	0.17	0.11	0.14
7	23.3	4.44	10.0	0.074	0.28	0.21	0.19	0.14	0.18
8	34.9	4.65	10.0	0.045	0.37	0.20	0.17	0.11	0.15
		K	t_0	r	Θ_1	Θ_2	Θ_3	Θ_4	Θ_5
Multicomponent model									
1	104.8	2	5.25	0.458	0.32	0.20	0.21	0.08	0.19
2	101.6	2	10.00	0.382	0.28	0.23	0.20	0.09	0.20
3	122.1	2	3.70	0.380	0.29	0.22	0.27	0.12	0.11
4	88.1	2	5.46	0.416	0.29	0.15	0.24	0.09	0.13
5	88.6	2	7.94	0.697	0.32	0.21	0.29	0.06	0.12
6	185.5	2	0.0	0.220	0.43	0.21	0.17	0.08	0.12
7	130.4	2	1.64	0.360	0.30	0.20	0.20	0.11	0.18
8	157.5	2	0.0	0.254	0.41	0.21	0.15	0.08	0.15

Note: $\chi^2_{0.90}(75) = 90.9$
 $\chi^2_{0.95}(75) = 96.1$

the serial position curves it was next fit to that data combined with the Phase 2 shield data of table 1. No additional parameters were estimated and t_0 was set to 10 msec so the df was raised to 91 and resulted in the predictions given by THE in table 1. The overall fit characteristics are shown in table 3. Again the outcome appears acceptable, if not quite as good, for all of the subjects. Scrutiny of the shield predictions reveal that the model, while reflecting the overall characteristics, had a tendency to over-predict the amount of decrement in accuracy under the shield condition. There are several factors that appear to have contributed to this tendency. One is the shifting of attention between conditions, resorted to by several subjects and sometimes compensating for the increased difficulty on a shielded position. Secondly, as noted

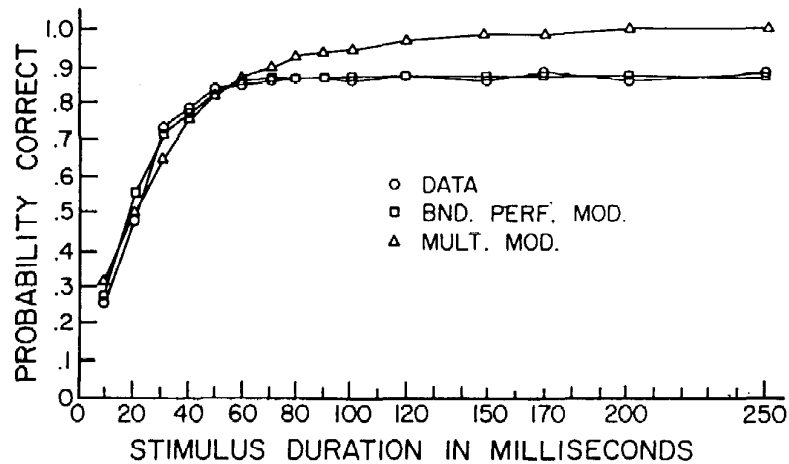


Fig. 7. Average probability correct as a function of display time compared with the bounded performance and multicomponent models.

earlier, the LS may have permitted a somewhat extended icon which aided performance on the left-most positions. Thirdly, the model seemed to simply under-predict the control NS accuracy in some cases, especially in positions 4 and 5, which would have established too low a baseline. This latter problem could have been caused by learning effects from Phase 1 to Phase 2 or an ability (not represented in the model as it stands) to come up with additional capacity under adverse circumstances. The model can be extended to encompass these possibilities

Table 3

Chi-square fits and parameter estimates of the bounded performance model fit to the combined shield data and serial position curves.

Subj	χ^2	C	t_0	V	a_1	a_2	a_3	a_4	a_5
1	45.3	6.25	10.0	0.074	0.47	0.15	0.14	0.10	0.14
2	97.7	4.77	10.0	0.042	0.28	0.21	0.19	0.13	0.19
3	89.7	5.19	10.0	0.106	0.39	0.18	0.18	0.12	0.13
4	89.2	6.05	10.0	0.094	0.46	0.16	0.15	0.11	0.12
5	47.3	5.93	10.0	0.144	0.45	0.15	0.16	0.10	0.14
6	96.0	4.18	10.0	0.066	0.39	0.19	0.17	0.11	0.14
7	76.6	4.94	10.0	1.714	0.39	0.18	0.16	0.12	0.15
8	73.8	4.74	10.0	0.062	0.40	0.19	0.16	0.11	0.14

Note: $\chi^2_{0.90}(91) = 108.9$

$\chi^2_{0.95}(91) = 114.5$

but would possess too much flexibility to allow testing with the current data.

All in all, the bounded performance model appears to give a reasonable first-order account of the data. Further work with the model, and experiments in which the shield conditions and stimulus durations are run in mixed blocks, may prove helpful in further delineating a quantitative account of whole report processing.

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