# VISUAL DETECTION IN RELATION TO DISPLAY SIZE AND REDUNDANCY OF CRITICAL ELEMENTS[1]

by

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Abstract

Visual detection was studied in relation to displays of discrete elements, randomly selected consonant letters, distributed in random subsets of cells of a matrix, the subject being required on each trial to indicate only which member of a predesignated pair of critical elements was present in a given display. Experimental variables were number of elements per display and number of redundant critical elements per display. Estimates of the number of elements effectively processed by a subject during a 50 ms. exposure increased with display size, but not in the manner that would be expected if the subject sampled a fixed proportion of the elements present in a display of given area. Test-retest data indicated substantial correlations over long intervals of time in the particular elements sampled by a subject from a particular display. Efficiencies of detection with redundant critical elements were substantially lower than those expected on the hypothesis of independence of response to different elements of the display and were relatively invariant with respect to distance between critical elements. The overall pattern of results was in substantial agreement with predictions from a serial processing model of visual detection.

In a previous article (Estes and Taylor, 1964) we have presented a detection method for assessing the amount of information assimilated by an observer from a tachistoscopically presented visual display. In many essentials the procedure corresponds to that of a two alternative, forced-choice signal detection experiment. On each trial the subject is shown for a short interval, 50 ms. in the previous study, a display containing a number of symbols. Two symbols are designated as critical elements and the rest as noise elements, each display containing exactly 1 of the 2 critical elements. The subject's task on each trial is simply to observe the display and indicate which of the 2 critical elements he believes to have been present.

One of our purposes in developing this technique was to provide estimates of the number of elements perceived from a brief display with minimal perturbation by retention loss. This procedure may be more sensitive than either the sampling method of Sperling (1960) or the indicator method of Averbach and Coriell (1961). With the detection method there is minimal retention loss during the time required for the subject to give his response and the visual field immediately following a display is not disturbed by the appearance of an indicator mark. A question of considerable theoretical interest which arises in connection with comparisons of these various techniques for assessing perceptual span is that of whether the perceptual response which a subject must make to an element of a display in order to categorize it as signal or noise is the same as the response required to permit the subject to designate the symbol by name in a subsequent report. While recognizing that the alternative methods for assessing perceptual span cannot be satisfactorily compared for sensitivity until this question is answered, we defer further consideration of it until the behavior involved in the detection task has been studied in greater detail.

The two experiments to be reported in this paper were designed to provide information bearing on alternative theoretical assumptions regarding the process of sampling the elements in a display. From results of our preliminary experimentation, (Estes and Taylor, 1964) it is clear that with displays of the order of 5 to 10 elements (random samples of consonants printed in linear arrays) the average number of elements per display effectively processed by adult subjects is appreciably greater than that revealed by the classical verbal report procedure with similar materials, but still significantly less than should be possible on the basis of psychophysical considerations alone. Under our conditions, a display of up to 10-12 elements should be expected to generate an image falling well within the area of clear vision on the retina. With substantially longer exposure times, an observer has no difficulty in reporting all of the elements of one of these displays while fixating on a point in the center, and consequently there would seem to be no explanation in terms of the visual system for the fact that our subjects were able to use information from no more than about 70% of the displayed elements during 50 ms. exposures. The simplest explanation which comes to mind, to the effect that the amount of information utilizable from a display is restricted by a fixed upper limit on the number of elements which can be registered in a temporary memory storage of some sort, appears to be excluded by the forms of the functions obtained in our previous study relating estimates of elements perceived to size of the display. These functions were, however, quite compatible with predictions from a serial processing model, which will be discussed in more detail below. The first of the two experiments to be reported was planned to obtain more information on the process responsible for the upper limit on the amount of information obtainable from a display of a given size; it deals with probability of correct detection as a function of display size under conditions differing in some important respects from those of the preceding study. The second experiment has to do with the independence of response to different elements of a display, the experimental variable of principal interest being the introduction of redundant critical elements.

## Experiment 1

### Detection as a function of Number of Elements in Displays of Constant Area

On the basis of much accumulating data concerning information processing by human subjects, (see Broadbent, 1958) we believe it essential to assume that at some point in the subject's response system the elements of a tachistoscopic display must be reacted to singly; figuratively speaking, the elements, though initially registered in parallel on the retina, must pass at some point through a channel which permits passage of only one element at a time. The serial processing model, proposed in our earlier paper, has this characteristic. The principal assumptions of the model are:

(1) When a display containing D elements is exposed for a short interval, a subset of elements is registered in the receptor apparatus. In the present study we have chosen experimental conditions such that we should expect all of the elements in the display to be so registered.

(2) Following the exposure, the traces of the display in the nervous system fade exponentially in such a way that, during each successive interval of time $\Delta t$ (taken just long enough for scanning of a single element) following the display, there is some fixed probability $s$ that the traces of the display will have passed below the threshold level at which they can influence behavior.

(3) During and following the display, until the stimulus traces pass below threshold, the registered elements are scanned one at a time. As each element is scanned, it is classified either as signal or as noise; and if the former, it leads to a report as to the critical element detected.

(4) If the stimulus traces fade below threshold before the critical element is scanned, the subject gives a report at random.

The probability of scanning any number k of elements from a display is, then, given by

$$p_k = \begin{cases} 0 & \text{if } k < m \\ s(1-s)^{k-m} & \text{if } m \leq k < D \\ (1-s)^{D-m} & \text{if } k = D \end{cases} , \qquad [1]$$

where $\underline{m}$ , the number of elements scanned during the stimulus exposure, is assumed to be a linear function of exposure time.

According to this formulation the mean number of elements effectively processed is expected to be an increasing function of display size simply because, up to the limiting number of elements that can be registered on the retina, the larger the display the larger is the possible number of elements scanned on a trial.

A principal alternative interpretation to that of the scanning model, which is in some respects more parsimonious, is the following, which might be termed a differential perceptibility model. - It is well known that when a subject fixates his gaze on the central point of a display area, such as that of our tachistoscope, there exists a probability distribution over the area of the potential display such that elements appearing at the center have highest probabilities of being seen clearly, the probabilities falling off in all directions toward the periphery. Assuming that this probability-of-seeing distribution is determined by the conditions of area, brightness, and exposure duration of a given experiment, we might suppose that in our previous study conditions were such that for the smallest displays nearly all of the elements fell in the central area of high probability but that with increasing display size the added elements fell in the peripheral areas, thus increasing the total mean number of elements seen per display. Since, in that study, the elements were presented in linear arrays with constant distances between elements, and the center of each display was at the fixation point, this interpretation could account nicely for the results obtained.

In order to obtain evidence which might be more useful in deciding between the two types of interpretation mentioned above, the displays were prepared according to a different principle in the present study, the plan being to vary number of elements per display while holding the area over which these elements were spread approximately constant. The plan followed was to embed each display, regardless of size, in a 4 x 4 matrix approximately one inch square. For the largest display used, 16 elements, the 16 cells of the matrix were simply filled by a random sample of 16 consonant letters. For the smallest display size, 8 elements, half of the cells were filled, but with the restriction that each row and each column of the hypothetical matrix contain 2 elements; in the intermediate display size, 12 elements, the matrix was filled similarly, but with the restriction that each row and each column contain exactly 3 elements. Thus the vertical and horizontal distances from the fixation point spanned by the elements of a display were constant while the number of elements per display varied from 8 to 16. Now, according to the interpretation of the display size function in terms of differential perceptibility, the number of elements perceived per display should on the average be a constant proportion of the number of elements presented in the display. According to the serial processing model, on the other hand, the <u>mean number</u> of elements effectively processed should increase as a function of display size, but the <u>proportion</u> should decrease in a negatively accelerated fashion with linear increases in display size.

## Method

Apparatus. The front of the tachistoscope[2] appeared to S as a wooden panel 17-1/2 in. square surrounded by a dark hood 8 in. deep. Centered in the panel at a height of 9-1/2 in. from the bottom was a window of half-silvered glass, 2 in. high by 5-1/2 in. wide. Below this was a sloping black shelf, extending from the panel to the edge of the hood, such that its reflection rather than those of objects in the experimental room appeared in the glass.

Stimulus exposure was effected by turning on a cold-cathode fluorescent tube in the left-hand (from S's point of view) of two equal sized compartments behind the window; this light provided even illumination of the stimulus display which was positioned 2-1/2 in. behind the window. The light was controlled by means of an external control, power supply, and waveform generator[3]. In the present experiments the stimulus presentation interval was always 50 ms. (.05 sec.).

The S was allowed to hold his head at that distance from the window at which he could most comfortably read sample material, but in no case closer than 8 in. to the window. A fixation point was provided in the form of a small round spot of white paper positioned by each S on the sloping shelf below the window so that its reflection, seen only while the exposure light was not on, appeared on the center position of a sample display.

The stimulus field reflected 14.5 ft.-lamberts during exposures and less than .1 ft.-lambert between exposures, as determined with a Macbeth illuminometer.

Stimulus materials. The stimulus materials were arrays of consonant letters typed, by means of an IBM electric typewriter, in large capitals on white cards in the following manner: Potential 16-cell matrices, 4 letters wide and 4 letters high, were filled with either 8, 12, or 16 letters. The size of the type used and the spacing were such that each display was 1 in. high and 7/8 in. wide.

For each display size, D, a complete set of displays consisted of 32 cards. These were two parallel sets of 16 which differed only in the signal, i.e., the member of the critical letter pair, B and F, which was present. Each critical letter appeared once in each cell of the 4 x 4 matrix, always accompanied by the same D-1 noise letters. For a given display size, the set of noise elements was drawn randomly without replacement from the set of 18 available consonants. The matrices were filled randomly within the severe constraints imposed by the foregoing rule and a rule that each row and each column contain the same number of letters. Thus at D = 8 each row and column contained 2 letters; at D = 12 each row and column contained 3 letters, and at D = 16 each row and column contained 4 letters. In this way the area on the card covered by the matrices was independent of the number of letters, while the density of letters in this area increased with increasing D. These stimulus materials were typed in IBM Executive Directory style, .14 type, code 66, pk, type-style.

Procedure. Subjects were 20 Stanford students, paid for participation. The experimental room was illuminated by a 150-w bulb encased in a white globe mounted on the ceiling; this was adjusted to about 1/3 normal brightness by means of a wall dimmer switch.

After a 5 min. allowance for adaptation to room brightness, each S was seated at the apparatus and given a sample display with which to find a comfortable observing position and then to adjust the fixation spot. He was then instructed to report whether each display contained a "B" or an "F", guessing whenever unsure. The 8-letter cards were now exposed, in a different random order for each S. A new stimulus exposure followed the response to the previous display by about 2 sec. and was preceded by 1/2 sec. by a 5 ms. flash of the exposure light to ensure alertness.

When the 8-letter cards had all been exposed, the 12-letter displays were then shown, then the 16-letter displays. At the conclusion of this series S was given a 5 min. rest while the cards were reshuffled; they were then presented again in the same fashion, reshuffled, and presented once more. Thus a total of 3x32 = 96 determinations was obtained for each display size.

## Results

Statistics for the 20 Ss pooled over the three replications at each display size are given in Table 1. About all that can be concluded from these data is that, as would be anticipated, proportion of correct detections decreased significantly with increasing display size, and that there was substantial variability among Ss in efficiency of detection. If there were no individual differences, and if trials were independent, the standard deviations in Table 1 should have run from approximately .042 at $D = 8$ to .048 at $D = 16$. The tendency for standard deviations to decrease toward the standard deviation of the appropriate binomial distribution as $D$ increases is to be expected, for with increasing display sizes increasing proportions of the obtained successes must be achieved by guessing and the probability of success by guessing is the same for all subjects.

For most theoretical purposes it is desirable to convert the raw data in terms of proportions of correct responses into estimates of numbers of elements effectively processed at the various display sizes. To do this, we proceed as in our previous study, correcting for successes achievable by guessing according to the formula

$$p_C = \frac{P}{D} + \left(1-\frac{P}{D}\right)\frac{1}{2} \qquad [2]$$

where $p_C$ represents probability of a correct response, $P$ the number of elements effectively processed, and $D$ the number of elements in the display. The basis of this relation is that, since the critical elements are randomly placed in the displays, the probability that the critical element falls among the P elements perceived is P/D ; and whenever the critical element does not fall among those perceived the probability of a correct response is 1/2 since both critical elements occurred equally often in random sequence. Replacing $p_C$ by the observed proportion of correct detections at a given display size, we can solve the equation above for P and thus obtain an estimate of this theoretical quantity in terms of observables:

$$\hat{P} = (2p_C - 1) D. \qquad [3]$$

Using this procedure, the estimates of mean number of elements processed per display have been computed for each of the three tests given on each display size and these, together with estimates averaged over the three tests, are given in the left-hand three columns of Table 2. Two conclusions immediately emerge from consideration of these values. Firstly, except perhaps for the first test, $T_1$ , given before the Ss had reached their limit of improvement as a function of practice, the mean number of elements processed increased as a function of display size. For the pooled data, a signed ranks test shows the increases from D = 8 to D = 12 and from D = 8 to D = 16 to be significant at the .02 level; the differences between values for D = 12 and D = 16 were not significant. However, the increases in number of elements processed are far from proportional to increases in display size as D goes from 8 to 12 to 16; consequently there would seem to be no support for the hypothesis that the dependence of detection rate on display size can be accounted for entirely, or even primarily, in terms of the factor of differential perceptibility. The parameter *s* of the serial processing model has been estimated from the data by least squares and theoretical predictions for mean numbers of elements processed at each display size are given in the right-hand side of Table 2. For the second and third tests and for the pooled data, these predicted values exhibit reasonably satisfactory correspondence with the observed data.

Since each subject was tested on each display three times at widely spaced intervals, data on changes of response to a given display over successive tests may be expected to provide information concerning the scanning process. If the order in which the elements of a display are scanned were entirely random, then the probability of a correct response to a given display on a later test should be the same regardless of whether *S*'s response to that display on an earlier test was correct or incorrect. If, on the other hand, scanning follows a relatively fixed path, for example beginning at the fixation point and proceeding outward in some orderly fashion, then correct detection to a given display on an earlier test will tend to be followed by correct detections on later tests and failures on early tests by failures on later tests. Probability of a correct detection on a later test following a correct detection on an earlier test should, then, be greater than the overall probability of a correct detection. However the probability of correct given correct should be less than unity for two reasons: Firstly, some successes will occur by chance and these will be followed by successes on later tests on the same displays only to the extent that chance would allow; secondly, even though the "scanning path" were precisely the same from trial to trial on a given display, there would still, according to the serial processing model, be variation in the distance travelled along this path. Also, it is a consequence of the assumptions of the serial processing model that, for the parameter values of this study, the divergence between probability of correct given correct and probability of correct given incorrect should increase as display size increases. It can be shown that, in general, the difference between probability of correct given correct and probability of correct given incorrect should start at 0 for the smallest displays, increase to a maximum and then decrease to 0 as display size increases. For the particular parameter values of this experiment, the difference should be smallest at $\underline{D} = 8$ increase considerably at $\underline{D} = 12$ , and increase only slightly further as $\underline{D}$ goes from 12 to 16. On the whole, the pattern exhibited in Table 3 appears to bear out expectations on the basis of our assumptions. At the very least, it can be concluded with confidence that there is substantial positive correlation over successive tests in the particular elements processed by a subject from a given display even when the tests are separated by long time intervals and much interpolated activity. Although mechanisms differing in some details from that of the serial processing model could account for the observed pattern, they must all have in common the property that the order in which the elements of the display are scanned is relatively constant and determined at least to substantial extent by the positions of the elements in the display.

Since the exposure time in the present study was too short to permit Ss to move their eyes and obtain more than one fixation of the presented material on any trial, this orderly scanning of the elements must be a central process, but whether its characteristics are determined entirely by the structures involved or are modifiable by learning remains a problem for future investigation.

Although not particularly germane to the hypotheses leading to the present experiment, data on response biases may be of some interest. In Table 4 are presented the proportions of trials on which Ss made B responses (that is, reported B rather than F as a critical element), proportions of correct responses on trials when B was the critical element in the display, and proportions correct when F was the critical element. The gist of these data is that there was a slight overall bias in favor of the B over the F response and a significant differential in correct responding to B displays over F displays. Since this disparity in correct responding to the two types of displays decreased with increasing display size, whereas the amount of guessing must have increased as a function of display size, it appears that the differential accuracy must have been due to differential perceptibility of the two cues rather than to a bias in guessing habits.

## Experiment 2

### Detection with Matrix Displays Containing Redundant Critical Elements

In order to obtain somewhat more direct evidence concerning the degree of within-display correlation among responses to different elements, this experiment was designed with displays each of which contained only one of the two critical elements (B or F) but with the critical element appearing sometimes once and sometimes more than once in a display. If responses to different elements of a display were independent of one another, accuracy of detection would be optimal. According to the serial processing model, detection with displays containing redundant elements should be substantially less than optimal; the reason, in brief, is that on trials when the scanning process happens to continue until all or nearly all of the displayed elements have been scanned, S will gain little or no advantage from the presence of redundant critical elements. A number of alternative models that have been considered, including the fixed sample size model and the differential perceptibility model discussed above, yield expectations of efficiency intermediate between the optimal and that prescribed by the serial processing model. It was possible conveniently to provide an additional source of information about the scanning process in this experiment by treating distance between redundant critical elements as a second independent variable.

## Method

Apparatus. The experimental room, apparatus, and stimulus display cards were identical to those of the preceding experiment in all respects except for details of the displays which are described below.

Stimulus materials. All of the stimulus displays were arrays of 16 consonant letters arranged in 4 x 4 matrices according to the same format as that of the $\underline{D}$ = 16 condition of the preceding experiment. Each display was composed of a number of randomly drawn "noise" consonants and either 1, 2, or 4 instances of one of a pair of critical consonants (B and F). There were three sets of cards:

1. There were 32 cards containing but one instance of the critical letter; these were two parallel sets differing only in the member of the B/F pair that was present. In this set both the critical letter and each of the 15 filler letters appeared once in each of the 16 cells of the matrix.

2. There were 48 cards containing two instances of the critical letter; these were parallel sets of 24 each differing only in the member of the B/F pair that was represented. The critical letters did not appear in the 4 corner cells of the matrix; they appeared with equal frequency in the remaining 12 cells. On 1/3 of the cards the two redundant cases of the critical letter appeared in adjacent rows ( or columns); on 1/3 they were separated by one row (or column); on the remaining 1/3 they were separated by two rows (or columns). On 1/2 of all the cards the two appeared in the same column (or row); on the other half, they appeared in adjacent columns (or rows). In every case, one member of the pair appeared in one of the outer, or edge cells. The 14 filler letters were filled in randomly.

3. There were 32 cards containing four instances of the critical letter; these were two parallel sets of 16 each differing only in the member of the B/F pair that was represented. The critical letters did

not appear in either the 4 corner cells or the 4 central cells of the matrix. In one of the 2 cells of each of the remaining 4 pairs (one on each edge of the matrix) appeared one of the four cases of the critical letter. The set of these cards was exhaustive with respect to these groupings. The 12 filler letters were randomly inserted in the remaining cells.

Procedure. Subjects were 8 Stanford students, paid for participation. After a 5 minute allowance for adaptation to room brightness, each S was seated at the apparatus and given a sample display with which to find a comfortable observing position and then to adjust the fixation spot. He was then instructed to report whether each display contained a "B" or an "F", guessing whenever unsure. All the cards with 4 cases of the critical letter were now exposed, in a different random order for each S. A new stimulus exposure followed the response to the previous display by about 2 sec. Each exposure was preceded by a flash, 0.8 sec. in length, of a green light mounted at the bottom of the panel; 0.6 sec. intervened between the termination of this alerting signal and the stimulus exposure.

When the 4-case cards had all been exposed, the 2-case displays were now shown, then the 1-case ones. At the conclusion of this series S was given a 5 minute rest while the cards were reshuffled. The cards were now presented, with the same procedure, in the order 2-case, 1-case, 4-case. After another reshuffling, they were presented a third time, now in the order 1-case, 4-case, 2-case.

## Results

Proportions of correct detections for each of the 8 Ss on displays with 1, 2, or 4 critical elements are given in Table 5. The first question to be answered in connection with these data is whether the proportions of detections for 2 and 4 critical elements deviate significantly from the values that would be expected if detections of multiple critical cues were independent events. Using the proportion obtained from displays with 1 critical element to estimate the probability of detecting a single critical element in any display, we can quickly obtain rough estimates of the proportions to be expected on the 2 and 4 critical element displays, on the hypothesis of independence, by a simple probabilistic calculation: Taking the mean proportion of .714 from the first column of Table 5, we obtain

$$1-(1-.714)^2 = .918;$$

similarly for 4 critical elements, we obtain

$$1-(1-.714)^4 = .993.$$

Clearly the calculated values are distinctly larger than the corresponding observed values, .831 and .906, respectively, for the 2 and 4 critical element displays. When similar calculations are performed for each of the 8 individual subjects, it is found that, for the 2 critical element displays, 6 of the 8 Ss fall short of the values predicted on the hypothesis of independence and, again, 6 of the 8 Ss fall short on the 4 critical element displays. Only one of the 8 Ss yields values satisfying the hypothesis of independence on both of the multiple element displays. Thus, on the whole, the hypothesis of independence can be rejected for these data and we may conclude that there is significant correlation between the responses of an S to different elements of a given display. In order to see whether the magnitude of this correlation is in line with that predictable from the serial processing model, we have estimated the parameter s of the model for each of the 8 Ss by least squares and calculated the theoretical proportions of correct detections for all 3 display conditions. Although there is a slight overall tendency for the theoretical values to fall short of those observed for the 2 and 4 critical element conditions, considering that only one degree of freedom has been used from the data of each S in generating the 3 predictions, the pattern of the theoretical values appears to reflect that of the observed values well enough to be compatible with the hypothesis that the scanning process is substantially that envisaged by the model.

The other principal aspect of this experiment has to do with efficiency of detection as a function of distance between critical elements in a display. It will be recalled that in the 2 critical element displays, the two instances of B or F were separated by 0, 1, or 2 cells horizontally or vertically in the display matrix. For these three conditions, the observed mean proportions of correct detections were a .815, .849, and .828, respectively. We have not been able to calculate theoretical values for the serial processing model in order to provide a quantitative test of the model against these data. It can, however, readily be shown that the surprisingly small amount of variation in efficiency of detection as a function of distance between critical elements is much more nearly compatible with the process assumed in the serial processing model than with that in any model assuming a relatively constant number of elements sampled per exposure. Taking an 8 element display for illustrative purposes, and assuming on the basis of our data given earlier that about 4 elements are effectively processed, it can readily be seen that according to a fixed sample size model there should have been sharp variation in proportion of correct detections as a function of distance. This can be seen most readily if we simplify the situation a bit by imagining that the 8 elements are arranged in a line. When the 2 critical elements are adjacent, it is possible to draw a sample of 4 adjacent elements which contains neither of the critical elements in 42 different ways; when the critical elements are separated by 1 space, this can be done in but twelve different ways; and when the critical elements are separated by 2 spaces this can be done in only two ways. Since S would have to guess, and would be wrong half of the time, on all trials on which the sample did not include either critical element, it is clear that proportion of errors would vary several fold over the three distance conditions.

According to the serial processing model, S makes a correct detection on any trial if, beginning from his point of fixation and scanning elements successively, he reaches one of the critical elements before the scanning process stops on that trial. Assuming that the scanning process starts from some specified point, say the left-hand end of the line, the first of the two critical elements to be reached, moving from left to right, would be the first element scanned with probability 1/7, the second element scanned with probability 1/7, etc., up to the seventh position. The probability that S would reach the critical element in his scanning process would be 1-s if the first of the two critical elements were in the first position, $(1-s)^2$ if it were in the second position, and so on. Thus, letting $\varphi_i$ represent the probability that S effectively processes at least one of the two critical elements when they are separated by i cells, we have

$$\varphi_o = \frac{1}{7}[(1-s) + (1-2)^2 + \ldots + (1-s)^7]$$

$$= \frac{(1-s)}{7s}[1-(1-s)^7] \quad .$$

Similarly,

$$\varphi_1 = \frac{(1-s)}{6s}[1-(1-s)^6]$$

$$\varphi_2 = \frac{(1-s)}{5s}[1-(1-s)^5] \quad .$$

Substituting in these equations the value $s = .11$, taken from the mean value in Table 5, we obtain for the three $\varphi$ values .65, .68, and .71, respectively. Then, since on trials when the subject does not process a critical element he guesses with probability 1/2 of being correct, we obtain the expected proportions of correct responses by adding the quantity $\frac{1-\varphi}{2}$ to each of these values, obtaining .825, .84, and .855. These exact values should not be taken too seriously, but it can be seen that they are of the right order of magnitude and that the differences between values for different inter-critical-element distances are also of the right order of magnitude. This result would seem to be, in some respects, the most cogent evidence we have so far obtained in support of the type of scanning process envisaged in the serial processing model.

## Discussion

The principal results of these two experiments may be summarized as follows:

1. The mean number of elements effectively processed increases with the number of elements in the display. The function relating number of elements processed to display size differs considerably from those prescribed either by a fixed sample size model or by one which assumes a probability distribution of probabilities-of-seeing over elements of area in the visual field; but it is compatible with the relation derivable from the serial processing model.

2. Test-retest results show relatively high correlations over widely separated 50 ms. exposures with respect to the particular elements sampled by a subject from a particular display.

3. The efficiency of detection with multiple, redundant critical elements falls distinctly short of expectations on the hypothesis of independence of response to different elements of a display.

4. Probabilities of detection are relatively invariant with respect to distance between redundant critical elements in a display, a result which tends to support the serial processing model over various alternatives considered.

Although it has functioned rather pleasingly in guiding the design of the present experiments and integrating the results, the serial processing model should not be taken as more than a provisional and incomplete prototype of a theory which may handle behavior involved in abstracting information from brief visual displays. Although our assumptions concerning the main features of the hypothesized scanning and categorizing processes appear to be well supported, there is considerable room for modification of these assumptions in quantitative details. Further elaboration of the model will be necessary before we can attempt a quantitative account of the role of figure-ground contrast (Eriksen, 1964) or of visual after-images (Teichner and Wagner, 1964).

Our interpretation of behavior in the detection situation has involved no concepts of short-term memory or visual information storage (Sperling, 1963), unless the latter notion merely denotes the persistence of visual excitation beyond the terimination of a display. This outcome is hardly surprising in view of the fact that our aim in developing the detection method was to minimize the role of memory in assessments of perceptual span. Assumptions concerning learning and memory will be required in a detailed theoretical account of the differences in estimates of perceptual span obtained with report and detection procedures, but discussion of these is beyond the scope of the present paper.

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## Footnotes

[1] This research was supported in part by Grant G-24264 from the National Science Foundation.

[2] Built by Iconix, Inc., of Menlo Park, California.

[3] Rise and decay times for light intensity output have been described in a previous report (Estes and Taylor, 1964).

[4] For simplicity, the parameter _m_ in equation [1] has been taken equal to zero for all theoretical calculations given in this paper.

Table 1

Statistics for Proportions of Correct Detections

from Displays with Single Critical Elements

(Data Pooled over 20 Subjects and 3 Replications)

| | Display Size | | |
|---|---|---|---|
| | 8 | 12 | 16 |
| Mean | .777 | .722 | .673 |
| S.D. | .076 | .073 | .062 |
| $S.E._M$ | .017 | .016 | .014 |

Table 2

Estimates of Mean Number of Elements Processed

for each Display Size

| | Observed | | | Theoretical | | |
|---|---|---|---|---|---|---|
| | Display Size | | | Display Size | | |
| Test | 8 | 12 | 16 | 8 | 12 | 16 |
| $T_1$ | 3.82 | 5.09 | 4.10 | 3.88 | 4.50 | 4.80 |
| $T_2$ | 4.72 | 5.20 | 6.24 | 4.55 | 5.53 | 6.10 |
| $T_3$ | 4.58 | 5.81 | 5.82 | 4.58 | 5.56 | 6.13 |
| Pooled | 4.43 | 5.33 | 5.57 | 4.36 | 5.22 | 5.70 |

Table 3

Test-retest Data [ $P(C_j: C_i)$ and $P(C_j: I_i)$ Denoting Proportion of Correct Detections on Test $T_j$ Given a Correct or an Incorrect Response, Respectively, to the Same Display on Test $T_i$ ]

| Display Size | $P(C_2:C_1)$ | $P(C_2:I_1)$ | $P(C_3:C_2)$ | $P(C_3:I_2)$ | $P(C_3:C_1)$ | $P(C_3:I_1)$ |
|---|---|---|---|---|---|---|
| 8 | .797 | .790 | .792 | .763 | .795 | .760 |
| 12 | .744 | .652 | .789 | .624 | .778 | .652 |
| 16 | .734 | .630 | .742 | .549 | .694 | .664 |

Table 4

Response Bias in Relation to Display Size

| | Display Size | | |
|---|---|---|---|
| | 8 | 12 | 16 |
| Prop. of B Responses | .535 | .509 | .515 |
| Prop. correct on B Displays | .808 | .733 | .688 |
| Prop. correct on F Displays | .738 | .715 | .657 |

Table 5

Observed and Theoretical Proportions

of Correct Detections in Relation to

Number of Critical Elements Per Display

| | Number of Critical Elements | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | | 2 | | 4 | | |
| Subject | obs. | th. | obs. | th. | obs. | th. | $\hat{s}$ |
| 1 | .844 | .862 | .896 | .909 | 1.000 | .950 | .045 |
| 2 | .812 | .862 | .965 | .909 | 1.000 | .950 | .045 |
| 3 | .635 | .663 | .757 | .743 | .854 | .837 | .185 |
| 4 | .750 | .797 | .896 | .861 | .948 | .921 | .075 |
| 5 | .854 | .850 | .903 | .900 | .938 | .945 | .050 |
| 6 | .515 | .531 | .514 | .563 | .604 | .626 | .995 |
| 7 | .614 | .693 | .806 | .773 | .927 | .860 | .150 |
| 8 | .688 | .779 | .910 | .847 | .979 | .912 | .085 |
| Av. | .714 | .740 | .831 | .815 | .906 | .891 | .110 |