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INFORMATION UNDERLOAD: RECOGNITION OF SLOWLY-PRESENTED ALPHABETIC CHARACTERS*

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The accuracy of identification of alphabetic letters was examined under three experimental procedures: slowly plotting all of the dots associated with a given display of letters in their correct spatial positions, but in a random temporal order; rapidly plotting one half of the dots associated with a display, and after a variable delay, rapidly plotting the other half of the dots; and rapidly plotting only a fraction of the total number of dots associated with the display. The accuracy of identification suffers as the rate of plotting is decreased and as the interval between the successive fields is increased. Therefore, a failure of spatial-temporal integration is inferred. The results of the separate procedures are partially consistent with an interpretation of a discrete, non-synchronized perceptual moment of 120–150 msec duration, assuming no accumulation of information across successive moments.

1. Introduction

In most information-processing tasks, the accuracy of performance typically decreases as the rate of presented information is increased. Nevertheless, there are several classes of experiments which demonstrate *poorer* performance at slow rates of presentation than at rapid rates.

The prototype demonstration of information underload is the vigilance decrement in monitoring signals of low probability. Depending upon the specific task parameters, there may be a decrement in sensitivity or a change in criterion over the duration of the signal detection task (Mackworth 1970a, b).

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In auditory pattern recognition, Garner and Gottwald (1968), for example, have shown that the accuracy of identification of repeated patterns of binary-coded auditory elements suffers slightly at presentation rates below two elements per second. Phenomenally, at slow presentation rates, the individual elements are verbally encoded and the pattern of encoded elements is sought. At more rapid presentation rates, the pattern is 'heard', in that an emergent property associated with the repeated pattern is available.

In visual pattern perception, several effects have been demonstrated by Mayzner and his associates (e.g., Mayzner et al. 1967a, b), depending upon the rate of presentation. Elements of the display (usually alphabetic characters within a word) are presented in their correct spatial positions, but the timing and order are controlled. At extremely fast rates of presentation, the entire display appears to be presented simultaneously, and order effects are absent. At intermediate rates, about 40 msec per letter for five-letter words, interior letters may appear to be absent (sequential blanking) or appear to be shifted in the display (sequential displacement). And, at slow rates of presentation, the letters of a word are separately appreciated, but word recognition of the randomly-ordered sequence may suffer (Pollack 1971). Mayzner interpreted his interesting findings in terms of a 'gating' model upon the stream of visual information.

A related paradigm for studying spatial-temporal interactions in visual perception is that of Eriksen and Collins (1967, 1968). The individual dots contributing to a display of three letters and to a random noise background were randomly assigned to one of two displays. Each display was briefly flashed, and the interval between the two displays was varied. Accuracy of identification suffers as the interval between the two displays is increased. Presumably, there is a failure to integrate the spatially distributed elements over time. Eriksen and Collins discuss their findings with respect to several interpretations, including a discrete-moment model of visual perception.

The present study re-examines the spatial-temporal integration of visual displays, using a variety of procedures. Specifically, the present study asks how the accuracy of identification of displays of alphabetical characters varies with the rate of presentation of elements of the display. The study also asks whether the obtained performance is consistent with a perceptual moment theory of visual perception.

2. Method

2.1. Illustration

On a 5 X 7 grid, the letter 'T' may be approximated by 11 dots, as shown on the right side of fig. 1. If the 11 dots are scrambled in order of presentation, but presented extremely rapidly, all dots will appear to be presented simultaneously and the character is clearly identified. If the rate of presentation is somewhat slower, modulations in apparent brightness may be reported, but the letter can still be clearly identified. If the rate of presentation is markedly reduced, the individual dots will appear one-at-a-time and dance over the display. The observer may infer a character by remembering the plotted positions, but he reports that the letter is not 'seen' directly. The present tests attempt to trace the identification of alphabetic characters as the rate of presentation of successive dots is controlled.

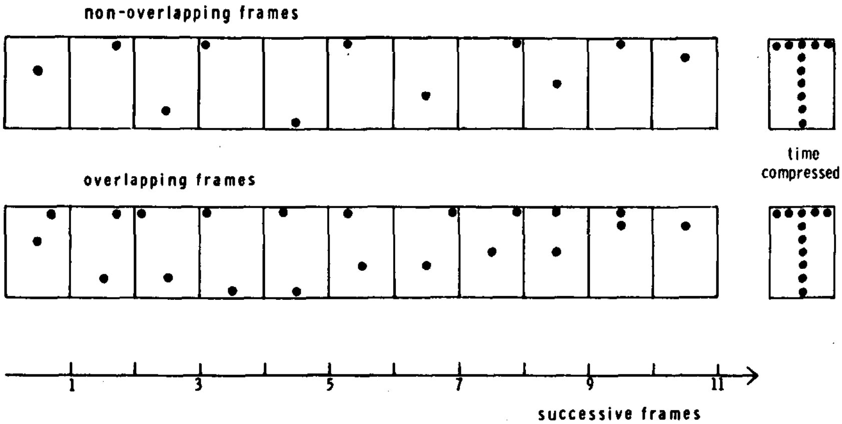

Fig. 1. Schematic illustration of distributed mode of plotting. Under rapid rates of plotting, individual letters are seen, as shown on the right (time compression). At slow rates of presentation, the individual dots making up the letters are seen. The top line represents the non-overlap plotting of the letter 'T', one dot at a time. The second line represents the overlap plotting of the same letter, two dots at a time, with one dot overlapping two successive frames.

A 'time-frame' defines a time period in which a defined number of dots is rapidly plotted. In the top line of fig. 1, one dot per frame was plotted. More than one dot per frame also may be plotted. When a given dot is plotted within only a single time-frame, the method will be termed 'non-overlapping frames'. When the same dot is plotted over successive time-frames, the method will be termed 'overlapping frames'. The second line of fig. 1 illustrates two dots per frame with 50% overlap (one dot) between successive frames.

2.2. Performance measures

The task of the observer was to report the letters presented upon the display. The most obvious measure of performance is the proportion of correct observations, P(C). However, because of momentary lapses of attention, eye blinks, etc., the present tests employed up to two presentations per observation. If the observer's response was correct upon the first presentation, a score of '1' was assigned, the observer was notified that he was correct, and a new display was presented on the following observation. If the observer's response was incorrect on the first presentation, he was notified, and the previous display was presented again. If the response was correct upon the second presentation, a score of '2' was assigned; and if the second response was incorrect, a score of '3' was assigned. From the assigned '1, 2, or 3' scores, a mean weighted score, W.S. was calculated.

There is obviously a close relation between P(C) and W.S. When P(C) approaches 1.0, W.S. approaches 1.0; when P(C) approaches 0, W.S. approaches 3.0. For each of 855 combinations of display conditions and target letters, P(C), W.S., and the variance of W.S. were calculated with a median of 17 observations per combination. A polynomial regression analysis was performed between pairs of measures. The proportion of the variance accounted for by the regression is presented in table 1.

Table 1
Polynomial regression analysis for selected performance measures.

			R_1^2	R_2^2	R_3^2
Weighted scores	vs	Percent correct	0.971	0.980	0.980*
Variance of wtg. score	vs	Weighted score	0.094	0.908	0.908
Variance of wtg. score	vs	Percent correct	0.122	0.807	0.839

* cubic term insignificant.

The linear regression between the two mean performance scores P(C) and W.S. accounted for all but 3% of the total variance (0.971). The regression was only slightly improved upon the further introduction of a quadratic regression term (0.980). The increment produced by the cubic regression term was insignificant. Because the mean weighted score extracts more of the total information from the tests, it will be used, hereafter, to describe average performance. It will be convenient later to set up a performance scale, where 0, 50, and 100 correspond with weighted scores of 3.0, 2.0, and 1.0, respectively. The least-squares relation between the weighted score, W.S. and the percentage correct on the first observation, P(C), is:

$$\text{W.S.} = 2.93 - 0.0261\,P(C) + 0.680 \times 10^{-4}\,[P(C)]^2, \text{ or approximately,}$$
$$\text{W.S.} = 2.93 - 0.0191\,P(C)$$

The variance of the weighted scores relates to the two performance measures in the same manner as binomial error: little variance is associated with extreme mean scores and maximum variance is associated with intermediate scores. The principal contribution to the regression is, therefore, the quadratic term with 91% of the variance accounted for between the variance of W.S. and W.S., and 81% between the variance of W.S. and P(C).

2.3. Methods of presentation

2.3.1. Random scrambling of individual dots

A single character consisted of dots drawn upon an imaginary 5 X 7 grid. The number of dots within a character varied from 11 (I, L, T) to 20 (B) with a mean of 15 and a standard deviation of 2.6 dots. The inter-grid distance was 1.25 mm, so that the outline of a letter occupying the entire grid would be 5 X 7.5 mm. The width of each dot was about 0.5 mm. Corresponding positions between adjacent letters were spaced horizontally at 8.75 mm, unless specified otherwise, resulting in an inter-letter spacing of 3.75 mm. Unless specified otherwise, the positions of the individual dots within the entire string of letters were presented in a randomly-scrambled order. In all cases, the dots were plotted in their correct spatial position. Mayzner and his associates (1967a, b) have used this paradigm in plotting the individual letters within words in a scrambled order.

To achieve visible dots, each dot was plotted twice for a duration of 80 μsec, separated by a wait interval, equal to one-half the interval between successive dots, IDI. It will be convenient, however, to consider each dot as if plotted only once with an onset-to-onset inter-dot interval equal to IDI. Unless specified otherwise, single dots were separated by successive IDI's.

2.3.2. Frame plotting

More than one dot may be plotted in a single temporal interval, or frame, as illustrated in the lower row of fig. 1. Actually, the time between successive dots within the same time frame was 0.04 msec/dot and will be ignored.

2.3.3. Two-flash plotting

One-half of the dots associated with a display were randomly selected and plotted within a single burst (actually at an IDI of 0.2 msec/dot). The remaining half of the dots were plotted in a second burst; and the delay between successive burst onsets, or the inter-burst delay, IBD, was varied. This method has been used intensively by Eriksen and Collins (1967, 1968).

2.3.4. Irregular temporal plotting

Temporal irregularities were introduced by means of non-plotted letters (*) with the same number of points as the average letter. The points of non-plotted letters were scrambled along with the plotted points. The net result is an irregular temporal distribution between successive dots.

The introduction of non-plotted letters also permitted the display of a constant number of letters with different degrees of spatial and temporal separations, as shown in the middle section of table 2.

2.3.5. Deletion plotting

A fixed proportion of the dots, P(D), from the pool of dots associated with a display was randomly sampled and was displayed in a single burst (actually at an IDI of 0.2 msec/dot). The remaining dots, 1.0 – P(D), were not plotted.

2.3.6. 'Redundant'plotting

The same letter was painted on the display, e.g., 'BBB'. The individual points were randomly scrambled, as in multi-letter displays.

2.3.7. 'Stroke' plotting

Alphabetic characters were also plotted in a 'stroke' mode. For example, the seven dots associated with the left vertical of an H were plotted top to bottom, then the seven dots associated with the right vertical of the H, then the three dots associated with the horizontal of the H were plotted left to right. No temporal break marked each 'stroke'.

2.3.8. Spatial factors in plotting

As noted in 2.3.4, the non-plotted letter (*) introduced temporal irregularity and spatial separation. In the same manner, different spatial separations were introduced with spaces (–) without temporal irregularity. The lowest section of table 2 illustrates a display of three-letter words with different spatial spacings, but without affecting temporal irregularities.

Smaller horizontal spatial separations were obtained by adjusting the spatial distance between successive letters in units of the intra-letter grid of 1.25 mm. An inter-letter spacing of 1.25 mm, for example, represents no additional inter-letter spacing between successive letters.

2.4. Apparatus and procedure

A PDP-9 (Digital Equipment Corp.) served as the experimental controller. The display was a Tektronix 602, equipped with a fast P15 phosphor. Displays were centered on an 8 X 8 cm display area. The distance of the observer to the display was adjusted for maximum comfort, with a typical distance of 160 cm. Natural binocular viewing was employed with a dim background room level. The observer controlled the onset of the display sequence. After presentation of the displayed sequence, he attempted to identify the display by hitting the appropriate keys on a teletypewriter. He was encouraged to guess, but if he felt that he had missed the display, no guess was required.

Separate test series were identified to the observers as 'words', 'non-words', redundant letters, etc. Letter strings of a given number of letters were typically run in order of increasing IDI so that uncertainty of the length of the letter string was minimal. Words were selected from the Thorndike-Lorge Word List (1944) of most frequent words. Because of the limited pool of two-letter words, two-letter words were repeated in different tests. Non-words consisted of letter strings in which all letters were equally likely.

*S*s had previously had intensive experience in previous auditory and visual psychophysical testing (100–2000 hrs). The number of pooled responses contributing to each condition is noted within each figure legend.

3. Results

We shall first consider results associated with temporal factors in plotting (Section 3.1). We shall then consider results associated with spatial factors (Section 3.2). The latter may be considered secondary to the primary purpose of the paper.

3.1. Temporal factors

3.1.1. Random scrambling of individual dots

The left panel of fig. 2 represents scores for non-words as a function of the number of letters in the letter-string (parameter) and of the duration between successive dots (abscissa). The performance scale on the left ordinate is the derived measure described under 'Method', the performance scale on the right ordinate is the average number of display sequences required for a correct response, where '3' signifies an incorrect response or a miss following the second display sequence. In general, performance deteriorates as the interval between dots is increased and as the number of displayed letters is increased. Unless specified otherwise, all smooth curves were fitted visually to the data and do not represent theoretical predictions.

The right panel of fig. 2 rescales the abscissa of the left panel in terms of the

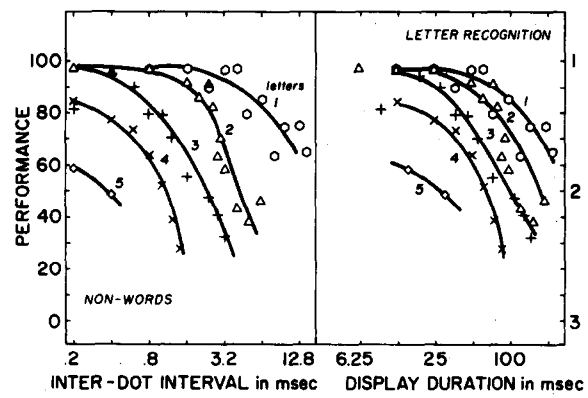

Fig. 2. Identification performance associated with non-word letter strings. The left panel represents the effect of the inter-dot interval, IDI; the right panel replots the data in terms of the total display duration. The parameter is the number of letters in the string. The right ordinate is the average number of display sequences required for a correct identification, where '3' represents an incorrect response following the second presentation; the left ordinate is a transform. Each point represents 15–26 (median: 20) observations contributed by ten subjects for each of nine sequences of letters. In figs. 2, 3, and 8, successive dots were painted, one at a time, in a randomly scrambled order.

total display duration. In essence, the data of the left panel were shifted horizontally in terms of the number of letters. The role of string length is reduced in terms of the total display duration, although performance still systematically decreases with string length. Performance changes little until display durations of 30 msec are encountered. Rapid changes in performance are obtained for display durations of about 60–80 msec. Random strings of five alphabetic characters are subject to misidentification even under excellent display conditions (c.f. Sperling 1960).

The organization of fig. 3 parallels that of fig. 2 for words of 2–9 alphabetic characters. Again, differences in performance for words of different length, when expressed as a function of IDI (left panel), become substantially reduced when expressed in terms of total display duration (right panel). Indeed, with only minor violence to the data, a single function reasonably represents words of 2–9 letters. The latter result suggests that factors which led to poorer performance with longer non-words are relatively absent in the perception of words. Still, there remains a slight advantage for the shortest words. Rapid changes in performance are obtained for display durations of about 100 msec.[1]

The superior performance associated with the shorter letter sequences – large in the case of non-words (fig. 2) and small in the case of words (fig. 3) – may have resulted from several factors: better integration of spatial information over a small display area, better visual acuity over a small display area, greater temporal regularity in the painting of dot elements within each character, and, with words, differences in the size of the pool of available words for each length.

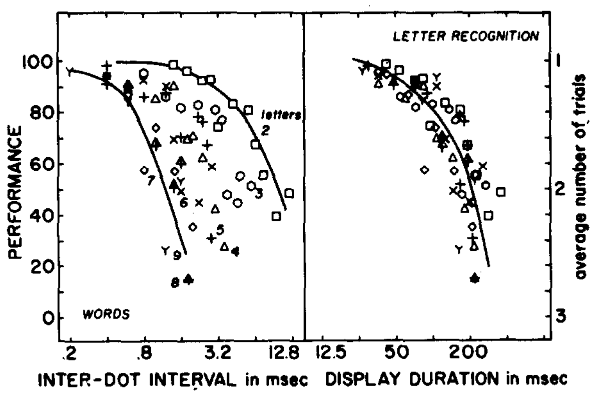

Fig. 3. Identification performance associated with words. Organization as in fig. 2. Each point represents 15–26 (median: 17) observations contributed by 11 subjects for each of seven words.

3.1.2. Frame plotting

The left panel of fig. 4 represents displays of five-letter words with non-overlapping sequences in which each dot is painted only once with bursts of 1, 2, 4, 8, and 16 dots per frame as shown on the abscissa. The top line of fig. 1, for example, represents one new dot per frame. With non-overlapping sequences, the number of

[1] The major features of figs. 2 and 3 were replicated when dot duration was nearly equal to the inter-dot interval, and, thus, where apparent brightness increased with IDI. In the tests of figs. 2 and 3, on the other hand, dot duration was independent of IDI, and apparent brightness decreased with IDI. It seems reasonable that critical features of performance are not likely to be identified with apparent brightness.

frames required is the total number of plotted dots divided by the number of dots per frame. The average $\overline{IDI}$, the inter-dot interval divided by the number of dots per burst, is the parameter of fig. 4. Thus, for example, an $\overline{IDI}$ of 1 msec/dot can be achieved by rapidly plotting frames of 16 dots, with waits between frames of 16 msec; by plotting frames of four dots with waits between frames of 4 msec; or by plotting frames of only one dot with waits between frames of 1 msec. If the fine temporal structure of successive dots were crucial, differences in performance should be associated with the number of dots per frame. If the average $\overline{IDI}$ were the crucial variable, performance should be independent of the number of dots per frame for a constant $\overline{IDI}$. Although the variability about the mean is large at intermediate plotting rates, performance appears to be relatively independent of the dots per frame.

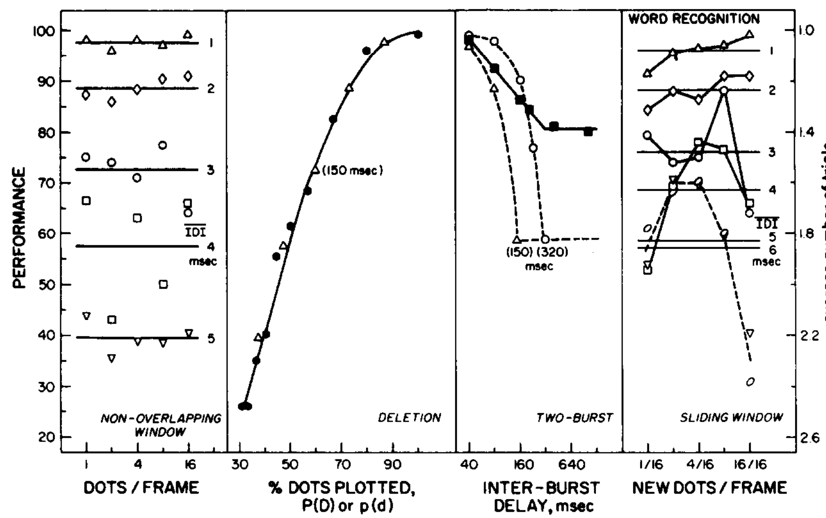

Fig. 4. Performance associated with five-letter words under several testing procedures. The left panel represents multi-dot plotting without overlap between successive frames; the parameter is the average inter-dot interval, $\overline{IDI}$, or the inter-dot interval divided by the dots per frame. The second panel represents the observed effects of deletion in terms of the proportion of the dots presented, P(D) (filled points); or, in terms of the inferred proportion of registered dots, $p(d)$ from the results of the first panel (open points), based upon an assumed moment duration of 150 msec. The third panel represents the observed effect of a delay interposed between two bursts, each employing a random half of the total number of dots (filled points); or, the predicted performance (open points) based upon assumed moment durations of either 150 or 320 msec. The fourth panel represents multi-dot plotting with overlap between successive frames of 16 dots each; the parameter is the average inter-dot interval, $\overline{IDI}$, or the inter-frame interval divided by the number of newly-introduced dots per frame. Each point represents 14–22 (median: 19) observations contributed by six subjects for each of ten words.

The right panel of fig. 4 represents results obtained with displays with overlapping dot sequences with 16 dots plotted in each frame. The middle line of fig. 1, for example, represents overlapping sequences with two dots per frame, but with only one new dot per frame. The number of frames required is roughly the total number of plotted dots divided by the number of new dots per frame. The fraction of newly introduced dots per frame is shown on the abscissa of fig. 4. It is noted that the apparent brightness of the display, and the apparent width of the dots, also increases as the proportion of new dots per frame is decreased. For example, with one new dot per frame of 16 dots, some dots were painted 16 successive times, and the time between successive plottings was 1/16 that of non-overlapping display of the same average $\overline{\text{IDI}}$. The parameter is the average $\overline{\text{IDI}}$, or the inter-frame interval divided by the number of newly introduced dots per frame. Successive points representing the same IDI are connected, with a dashed line between the average results for IDI's of 5 and 6 msec. At fast rates of presentation, there is little change in performance with the number of new dots per frame and the average results are comparable with the non-overlapping presentation of the left panel of fig. 4. At slower rates of presentation, there appear to be sharp gains in performance with moderate degrees of overlap and the average performance is superior to that obtained under the non-overlapping presentation, represented in the left panel of fig. 4. The decrement at the highest degree of overlap at the three slowest plotting rates (with one new dot introduced to a frame of 16 dots) may be due to brightness factors.

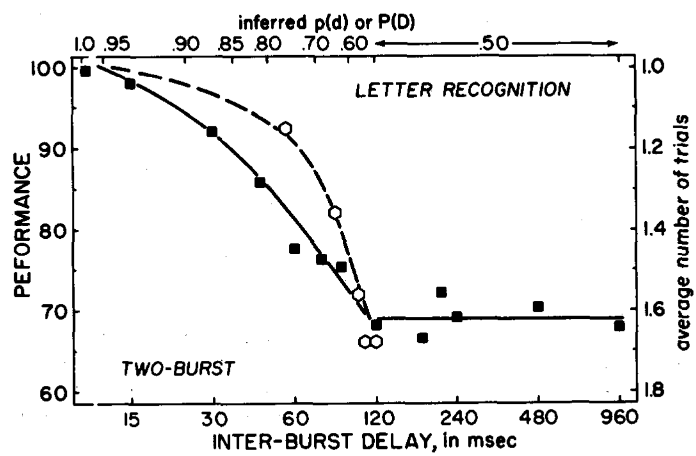

Fig. 5. Performance within the Eriksen-Collins mode of plotting as a function of the delay between the two bursts, IBD. The observed points are shown by the filled points and solid curve. Note the sharp break at about 120 msec. The upper abscissa, open points, and dashed curve reflect the inferred $p(d)$ based upon a non-triggered discrete model of perceptual moment. A moment of 120 msec is assumed. Each of the filled points represents 33 observations contributed by ten observers for each of 26 letters.

3.1.3. Two-flash plotting

The solid points and unbroken curve of fig. 5 present the effect of a delay between two dot fields, each representing half of the dots associated with a single letter. Performance falls as the delay is increased, at least to 120 msec. Delays greater than 120 msec yield nearly constant performance. There is no suggestion of a sharp improvement in performance at longer delays, as might be suggested by a transfer of information via a verbal encoding of the separate bursts. We shall defer consideration of the open points, dashed curve, and upper abscissa until the Discussion.

The solid points and unbroken curve of the third panel of fig. 4 present corresponding results for tests with five-letter words. Performance falls as the delay is increased, at least to about 320 msec. Delays greater than about 320 msec appear to yield equivalent performance, but the number of conditions is too sparse. Again, we shall defer discussion of the open points and dashed curve.

3.1.4. Irregular temporal plotting

The top section of table 2 considers the irregular plotting of a single letter at an average inter-display interval of 8 msec per displayed point. With a single displayed letter, there appears to be a slight gain in performance associated with the most irregular mode of presentation. Presumably, related local features may be blocked within irregular bursts of dots.

3.1.5. Deletion plotting

The filled dots and unbroken curve of fig. 6 show the effect of rapidly plotting only a fraction of the dots associated with single letters, P(D). Performance smoothly improves with the percentage of dots plotted. The filled dots and unbroken curve of the second panel of fig. 4 show the same effect with five-letter words. In each case, discussion of the open dots will be deferred.

3.2. Spatial factors

3.2.1. Redundant plotting

One factor in the poorer performance associated with longer non-word letter strings is the limited memory for unrelated letters. Redundant strings of the same letter preserve the spatial characteristics of multi-letter displays, but minimize the problem of memory for the presented materials.

Displays of 1–9 letters (0–8 redundant letters) were presented at display durations of 45, 90, and 135 msec. There were clear significant differences associated with the three display durations (weighted scores of 1.4, 1.8, and 2.0, respectively, $F = 303$, $p < 0.001$). However, there were no effects of the number of redundant letters ($F < 1.0$), nor of the interaction of duration and the number of redundant letters ($F = 1.01$, $p > 0.20$). This result suggests that the penalty introduced by distributed plotting was balanced by local features highlighted in the redundant presentation.

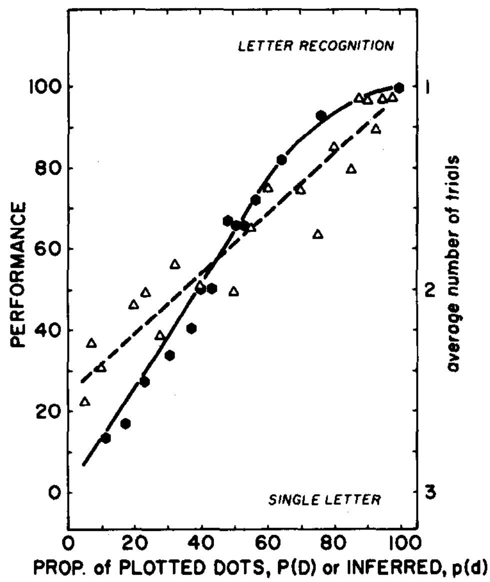

Fig. 6. Performance under random deletion (solid curve and filled points) at a rapid presentation rate (IDI = 0.2 msec) as a function of the proportion of deleted dots, P(D). The obtained results are compared with the proportion of effective dots (dashed curve and open points), *p(d)*, inferred from a discrete, non-overlapping perceptual moment theory, on the assumption of a perceptual moment of 120 msec. Each point represents 14–18 (median: 15) observations contributed by four subjects for each of 26 characters.

3.2.2. Stroke plotting

Fig. 7 considers two modes for the plotting of single alphabetic characters: a randomly scrambled sequence (open points and dashed curve) and a non-random 'stroke' (filled points and solid curve) sequence. Performance is superior with the non-random sequence, especially with longer inter-dot intervals. At short inter-dot intervals, where there is poor appreciation of the order of plotting, we expect, and find, little difference in performance for the two modes of plotting. At longer inter-dot intervals, the order of plotting becomes better appreciated, and large differences in performances are obtained in favor of 'stroke' characters. The intermediate plateau for the non-random sequences appears to be related to the appreciation of the order of the 'printing' strokes.

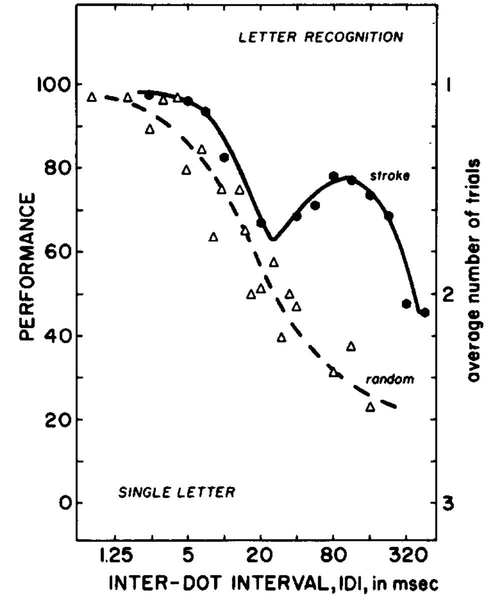

Fig. 7. Comparison of a random (open points) and a non-random (filled points) plotting sequence for single alphabetic characters. Data from random sequences are identical with fig. 2. Each point for the non-random sequences represents 8–13 (median: 10) observations contributed by five subjects for each of 26 characters.

Table 2
Effects of spacing and/or irregular plotting.

	Sample	IDI msec	Av. # trials	σ
Single letter	L	8.0	1.35	0.32
(n=11)	G*	4.0	1.36	0.32
	*C**	2.0	1.29	0.23
	B*	1.0	1.21	0.33
Three-letter words	HIS	3.0	1.58	0.24
(n=11)	L*E*D	1.8	1.58	0.50
	O**U**T	1.2	2.00	0.53
	A***C***T	1.0	2.31	0.49
Three-letter words	MAY	3.0	1.58	0.24
(n=11)	S–H–E	3.0	1.91	0.53
	F––L––Y	3.0	1.84	0.35
	B–––I–––T	3.0	1.94	0.59

* ≡ non-plotted character.
– ≡ space.

3.2.3. Spatial factors in plotting

The lowest section of table 2 shows that accuracy of performance is related to gross differences in spacing of letters within a three-letter word. For larger spacings, the average number of required presentations increases.

The middle section of table 2 shows that the further addition of temporal irregularity does not consistently add to the effect of increased inter-letter spacing.

The effect of small-to-large spacings between successive letters is shown in fig. 8 for two sets of materials: three-letter words and two-letter non-words. (The left-most point represents a horizontal inter-letter spacing equal to the intra-letter grid.) For the present letters, plotted upon a 5 × 7 matrix with a horizontal center-to-center intra-letter spacing of 1.25 mm and a letter width of 5 mm, the optimal inter-letter spacing under random scrambling is about 5 mm.

Spacing effects were also examined for redundant letter displays of five letters. Since there was no requirement to integrate materials over the display, performance might be expected to improve as the inter-letter spacing is increased. It did significantly (df 4, 75; F = 10; p< 0.001). The average number of required trials was 1.92, 1.87, 1.81, 1.66, 1.60 for inter-letter spacings of 1.25, 2.5, 3.74, 6.25, and 10 mm, respectively.

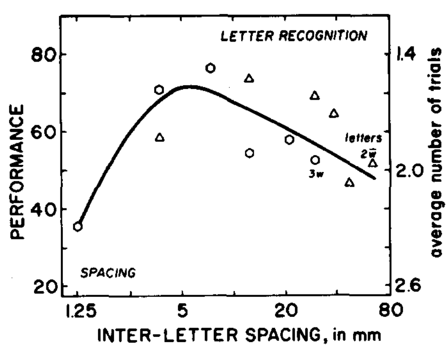

Fig. 8. Effect of the spacing between adjacent letters in three-letter words, 3w, and in two-letter non-words, 2w̄. Each point represents 13–21 (median: 15) observations contributed by ten subjects for each of 11 sequences.

4. Discussion

4.1. Failure of spatial-temporal integration with non-word letter strings

With distributed random plotting, there is little change in performance with longer words (fig. 3), but there is a greater change in performance with longer non-word strings (fig. 2). The latter result cannot be assigned entirely to deficits for the memory of independent strings because clear differences are obtained between 1- and 2-letter non-word strings. Nor can the result be assigned entirely to the proximity of neighboring elements, because the loss in performance is not found with redundant letter strings. The important result is not the word vs non-word difference, which is commonly observed. Rather, it is the failure to integrate distributed spatial information over the display in the case of non-words, and the successful integration of distributed spatial information for words.

4.2. Individual letters

Large differences are observed in scores associated with individual letters. Some of the differences are due to the particular display format employed: for example, the 'U' and 'V' differed by only two dot locations in the 5×7 matrix; some of the differences are associated with the greater ease in identifying letters consisting of straight strokes. Table 3 presents a rank-ordering among the letters for four methods of plotting. Since each letter was not employed at each duration for each method of plotting, letters were rank-ordered within each basis for comparison and an average rank was determined. The rank-order correlation among the four methods of plotting for the entire alphabet is presented in the top half of table 4. Also presented is the correlation with the number of dots per letter. Except for 'stroke plotting,' the three sampling plotting procedures yield high inter-correlations among themselves and with the number of dots per letter. Rank-order correlations within the indicated subsets of letters are shown in the lower half of table 4. Reasonably high correlations are obtained within subsets, but only a few reach statistical significance because of the small number of letters per subset.

4.3. An oversimplified, but interesting, model

It is tempting to view the observer's visual system in the manner of a motion picture camera, in which each successive frame captures only that visual information available during the frame. Essentially, this view is that of the discrete non-overlapping moment (Stroud 1954) and has found some support by a number of investigators. A critical analysis of overlapping vs non-overlapping moment theories has been provided by

Allport (1968, 1970) for visual patterns. Auditory masking has also recently been examined in terms of moment theory (e.g. Robinson and Pollack 1971; Pollack 1973). Qualitatively, the moment view is sensible for the present tests, at least in extreme cases. If successive dots are painted rapidly enough, all dots are encompassed within a single moment or perceptual time-frame, there is little appreciation of their random ordering, and the entire display is 'seen' as a unit. If successive dots are painted slowly enough, the dots are extended over several frames, and there is a failure to integrate the spatial information over time.

Before considering different classes of moment models in detail, it is important to regard the data base against which the models are evaluated. The most exacting test of such models is based upon brightness threshold measurements by individual observers (extensive discussions comparing different models may be found in Blackwell (1963) and in Shallice (1967)). The variability of scores among letters and the variability among observers makes the present data base a less-than-critical test among competing models. (Table 3 shows inter-letter variability.) Moreover, the reasonableness of the models has not been tested against the extensive literature on the behavior of the visual photoreceptors (see Blackwell (1963) and Shallice (1967) for such comparisons). The reason is that, presumably, letter identification is not limited at the receptor level. A further complication is that at slow presentation rates, the observer's eyes move almost reflexively with the individual dots, thereby distorting their relative spatial positions upon the retinal mosaic. With an intensive training program in maintaining fixation (Steinman et al. 1967), despite the changing display, the dots might have registered more nearly in their correct spatial positions upon the retinal mosaic.

Two opposing classes of models of the perceptual moment may be distinguished. The first class of models is that of the triggered non-overlapping moment, where the onset of the display triggers a sequence of discrete perceptual moments. In terms of the motion picture camera, the onset of the display triggers the camera. An alternative to the triggered moment is that of a series of overlapping moments in which the delay between the onsets of overlapping moments is small relative to the duration of the moment. In terms of the analogy, a battery of motion picture cameras is driven at the same rate, but the frame onsets are staggered. An extreme version of the overlapping moment obtains when the delay between successive moments approaches zero. One then has a sliding window. The sliding window, or moving average, can be regarded as a separate model. It is not considered in further detail here because the rectangular sliding window, at least, permits no forward or backward masking (Pollack 1973). A continuous oscilloscope recorder plus display persistence may reflect this operation. The second class of models is that of a non-triggered, or independent, non-overlapping sequence of moments. It is assumed that the onset of the display occurs independently of the occurrence of the boundaries of successive moments.

The two classes of models lead to different predictions for two modes of display plotting, as illustrated in fig. 9. Consider first the non-overlapping distributed mode of plotting, as previously considered in figs. 2–3, and illustrated in the top line of fig. 9. Individual dots are successively painted in time over a specified duration of plotting, D. If the onset of the sequence of perceptual moments is triggered by the onset of the display, all displays whose duration, D, is equal to or less than the duration of the moment, m, will be entirely 'registered' within the triggered moment. Displays longer than the duration of a moment will 'spill over' to the adjacent moment. In this case, the proportion of dots within the triggered moments is m/D. We shall assume that no information is accumulated over successive moments and shall be concerned only with $p(d)$, the greatest proportion of the total number of dots registered within any one moment. Predictions for the triggered moments are shown in the upper left box of fig. 9; those for the non-triggered, or independent moment are shown in the upper right box of fig. 9. The latter derivation is considered in more detail in Appendix I. It is noted here that $p(d)$ is identical for the two models when $D \geqslant 2m$. The reason is that, irrespective of the time of display onset, relative to the onset of an underlying train of moments, one moment will be entirely occupied when $D \geqslant 2m$ and $p(d)$ will be equal to m/D.

Another mode of plotting is that of the Eriksen-Collins paradigm where 50% of the dots are rapidly presented in each of two bursts separated by a delay interval, Δ. The predictions of the two models are shown in the lower half of fig. 9. For the triggered moment, all delays shorter in duration than the moment will register all of the dots in the triggered moment; and all delays longer in duration than the triggered moment will register only one burst, or 0.50 of the dots. For $\Delta > m$,

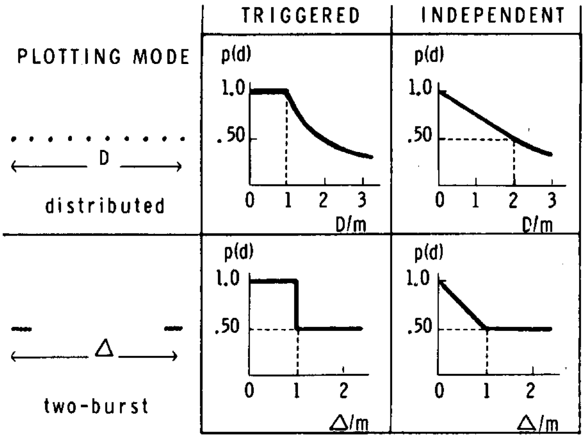

Fig. 9. Schematic representation of predictions from two models of the perceptual moment. The top two boxes reflect a scrambled, distributed mode of plotting; the bottom two boxes reflect a two-burst mode of plotting. The two left boxes reflect a triggered perceptual moment; the two right boxes reflect a non-triggered, or independent, perceptual moment. Within each block is the predicted largest proportion of dots which is registered within a single perceptual moment.

the same result is obtained for both moment models, since the second burst will always occur in a different moment, irrespective of the initial onset. For the independent moment, all dots will register in the same moment when $\Delta = 0$, and the transition will be uniform between $0 \leqslant \Delta \leqslant m$ for a uniform distribution of independent moment onsets.

We are thus able to distinguish between two classes of perceptual moment theories. There remain three difficulties: the predictions of fig. 9 are made with respect to $p(d)$, the inferred proportion of dots registered within any one moment; no variability of the perceptual moment is included and, the assumption that information is not accumulated across successive moments is untested.

The latter assumption appears to be untenable, at least on a phenomenal level: at long delays, for example, the first burst may yield the hypothesis P; the second burst may yield the hypothesis K; and the verbal combination of the hypotheses may yield the hypothesis R. In order to obtain specific quantitative predictions, howecer, we shall stick with the non-accumulative assumption, even though it appears to be violated in experience. Blackwell (1963) employed a similar assumption in considering a central scanning model where each scan erased the effects of previous scans.

Variability in the moment was not included for simplicity. Shallice (1967) has demonstrated that inclusion of variability greatly expands the range of possible moment models, and also makes it more difficult to falsify the test between theories of a triggered and of an untriggered moment.

A more serious problem comes in externalizing the effect of $p(d)$. Rather than assume a hypothetical relation between $p(d)$ and performance, we shall compare the performance achieved at a given inferred proportion of registered dots with that achieved with a given proportion of plotted dots, P(D). At rapid rates of plotting, it is assumed that all of the dots are registered in a single moment. We then test whether the relation between $p(d)$ and performance mirrors that between P(D) and performance. That is, based upon inferences from the perceptual model, we shall infer that a certain fraction of the dots is registered within a single perceptual moment. That performance will be compared to performance obtained when a known fraction of the dots is plotted.

4.4. Comparison of model with results from randomly-ordered sequences

The comparison between the inferred proportion of dots registered within a single moment, $p(d)$, with the actual fraction of dots plotted, P(D), is provided in fig. 6 for a single letter and in the second panel of fig. 4 for five-letter words. The filled points represent performance scores obtained under P(D) variation; the open points are inferred $p(d)$ levels. The latter points were derived from the left panel of fig. 4 for five-letter words, and from the open points of fig. 7 for single letters. An independent discrete moment of 120 msec is assumed for single letters in fig. 6; an independent discrete moment of 150 msec is assumed for five-letter words in the second panel of fig. 4.

There is a systematic discrepancy between the obtained points and the inferred levels based upon the independent moment for single letters in fig. 6. We can shift the inferred curve in either direction by assuming a different duration for the underlying moment, m. The lower portions of the curves more nearly overlap with m approaching 240 msec; the upper portions of the curves more nearly overlap with m approaching 60 msec. However, an ever poorer fit is achieved via the triggered moment. Assuming moments of 60, 120 or 240 msec, the right-most 5, 8, or 12 open points would, respectively, all be assigned a

$p(d)$ level of 1.0 by the triggered model. This would result in an even larger discrepancy between the inferred $p(d)$ and obtained P(D) relations.

The correspondence between $p(d)$ and P(D) is considered to be very good for five-letter words of the second panel of fig. 4. Since the correspondence between $p(d)$ and P(D) was not very good for single letters, the discrepancy between the two estimates of the duration of the perceptual moment, 120 vs 150 msec, is not considered to be serious.

4.5. Comparison of model with results from two-burst sequences

The independent discrete moment model leads to the predictions of the lower right box of fig. 9 in terms of $p(d)$, the inferred proportion of registered dots. The model suggests a break in the two-burst performance curve at an inter-burst delay equal to the moment duration. Such a break is evident in fig. 5 for single letters at 120 msec, the same duration employed in examining the deletion results of fig. 6. There also is an apparent break in the third panel of fig. 4, but at 320 msec, which is over twice the duration of the moment assumed in examining the deletion results of the second panel of fig. 4.

Moreover, the correspondence between the obtained (solid points) and predicted (open points) functions is poor for inter-burst durations less than the duration of the assumed hypothetical moment. For five-letter words represented in the third panel of fig. 4, two predicted functions are drawn: one based on a moment related to the locus of the sharp change in performance (320 msec), and one based upon a moment related to the deletion results (150 msec). In both cases, the prediction of the independent discrete moment suffers. It is noted, however, that the results would have departed even more markedly from that predicted from the triggered discrete moment, represented in the lower left panel of fig. 9.

4.6. Comparison of model with results from multi-dot frames with and without overlap

The analysis described in the Appendix is applicable to single dots interspersed by IDI, as illustrated in the top half of fig. 1. With more than one dot plotted within each frame, but without overlap, the same analysis might be expected to prevail in terms of the average $p(d)$, although quantal changes will be introduced for a given onset phase, due to the grouping of the dots. The results of the left panel of fig. 4 show little change with grouping of the plotted dots. With plotting overlap, as illustrated in the lower half of fig. 1, there is also no change in the inferred $p(d)$ except those related to the initial grouping of dots. The results of the right panel of fig. 4, however, show large changes with overlap. How the model should best be modified to reflect the overlap tests remains unclear.

4.7. Extension of model to individual letters

The previous analyses for single letters pertained only to the average performance over the set of 26 alphabetic characters, in which it was assumed that all letters consisted of the same number of dots. A set of secondary predictions also can be made from a theory of the perceptual moment. For a fixed IDI, letters with a small number of dots are associated with a smaller display duration than letters with a large number of dots, and hence are more likely to be received in the same moment. Therefore, higher performance scores should be obtained with letters with a smaller number of dots, as was noted in table 3. It is noted that, while the number of dots per letter could have been held constant, dot density may then have provided a cue for character recognition.

The high correlations among three plotting procedures in table 4 may have resulted from systematic response bias. But, since the same response bias could also have operated under stroke plotting (IV), the insignificant correlations with IV argue against an explanation in terms of response bias. More likely, the correlation among the three scrambled plotting procedures is mediated by the number of dots per letter.

Even the number of dots per letter may not be the crucial variable. Letters with a smaller number of dots upon a fixed grid typically consist of horizontal and vertical strokes; letters with a larger number of dots upon a fixed grid are typically curved. If the relevant variable is more nearly related to letter features, such as straight lines and curves, rather than to the number of dots, per se, subsets of letters with common stroke properties should remove the correlation with the number of dots. As shown in the lower half of table 4, such correlations remain high, at least for the three related experimental procedures for three subsets of letters, although their individual significance cannot be tested because of the small number of letters within each subset. The correlation between procedures within subsets is again of the same magnitude as the correlation with the number of dots per letter.

Table 3
Rank-order analysis for individual letters.

Letter	# dots	I. Random plotting		II. Random deletion		III. Two-burst		IV. 'Stroke' plotting	
		a	e	b	e	c	e	d	e
A	16	0.533	13	1.74	7	1.35	10	1.83	22
B	20	0.800	24	2.19	23	1.65	19	1.35	10
C	13	0.405	8	1.65	4	1.37	13	1.33	8
D	18	0.467	9	2.28	25	1.56	15	1.62	19
E	18	0.616	16	1.87	11	1.37	11	1.56	18
F	14	0.682	20	1.76	9	1.22	6	1.83	21
G	17	0.782	23	2.18	22	1.82	24	1.35	9
H	17	0.664	19	1.93	18	1.75	22	1.55	17
I	11	0.150	1	1.51	2	1.16	3	1.86	23
J	12	0.352	4	1.66	5	1.19	4	1.89	25
K	14	0.392	6	1.89	13	1.27	7	1.26	6
L	11	0.229	2	1.39	1	1.03	1	1.23	5
M	17	0.529	12	1.93	16	1.59	17	1.87	24
N	17	0.471	10	2.20	24	1.78	23	1.81	20
O	16	0.696	21	1.91	15	1.57	16	2.34	26
P	15	0.354	5	1.93	17	1.38	14	1.46	14
Q	18	0.867	26	2.10	21	1.91	26	1.42	12
R	18	0.665	18	1.95	19	1.33	8	1.19	2
S	15	0.850	25	2.39	26	1.87	25	1.10	1
T	11	0.250	3	1.57	3	1.21	5	1.22	4
U	15	0.394	7	1.87	12	1.37	12	1.28	7
V	13	0.519	11	1.76	10	1.62	18	1.44	13
W	17	0.717	22	1.75	8	1.71	21	1.47	15
X	13	0.617	17	1.89	14	1.34	9	1.22	3
Y	12	0.574	15	1.70	6	1.10	2	1.54	16
Z	16	0.542	14	1.97	20	1.66	20	1.39	11

a. ratio of sum of ranks over sum of possible ranks summed over 16 IDI's.
b. average number of presentations, averaged over 14 deletion levels.
c. average number of presentations, averaged over 12 IBI's.
d. average number of presentations, averaged over 13 IDI's.
e. rank within column.

Table 4
Summary of Rank-Order Correlations

a. Entire Alphabet

		I	II	III	IV
#.	Number of Dots	0.625	0.741	0.657	0.116
I.	Random Plotting		0.564	–0.631	–0.078
II.	Random Deletion			0.757	–0.130
III.	Two-Burst Plotting				–0.030
IV.	Stroke Plotting				

0.557 $p < 0.01$ level (25 *df*)
0.137 $p > 0.50$ level (25 *df*)

b. Subsets

	I vs II	I vs III	II vs III	I vs #	II vs #	III vs #	IV vs #
Straight[a]	0.77	0.77	1.00	0.71	0.89	0.89	0.26
Curved[b]	0.70	1.00	0.70	0.70	0.30	0.70	0.60
Mixed[c]	0.77	0.60	0.77	0.97	0.89	0.74	–0.51
Angular[d]	–0.37	–0.03	0.53	–0.08	0.43	0.74	0.52

a ≡ E F H I L T.
b ≡ C G O Q S.
c ≡ B D J P R U.
d ≡ A K M N V W X Y Z.

5. Summary

Based upon average performance over the entire set of 26 alphabetic characters, three sets of independent measures may be related, with varying degrees of success, in terms of a model of a non-triggered, independent discrete perceptual moment of about 120 msec. The model also predicts the relative performance of the individual letters although the predicted correlations among the separate measures may have been simply mediated by features correlated with the number of dots per letter.

Appendix I: Calculation of the effective proportion of dots

This section considers the calculation of the effective proportion of presented dots captured within a single perceptual-moment frame, $p(d)$. We shall assume that if a sequence spills over into more than one 'frame', only the frame with the largest number of dots will be selected. Except for the determination of that moment with the largest number of presented dots, there is assumed to be no information contributed by successive moments. For simplicity, the analysis will ignore the following considerations: (1) there are large differences in the accuracy of recognition for individual letters and for individual subjects; (2) the number of dots per letter, and hence their actual duration, is not constant; and (3) the relation between performance and fraction of painted dots is non-linear, even when averaged over all characters (fig. 8) so that averages across variables may be not entirely representative of the relations between individual values of the variables.

There are three special cases to consider: Case (a) where the total display duration, D, is smaller than the duration of a single perceptual moment, m; Case (c) where the display duration is longer than two perceptual moments; and Case (b) for intermediate conditions.

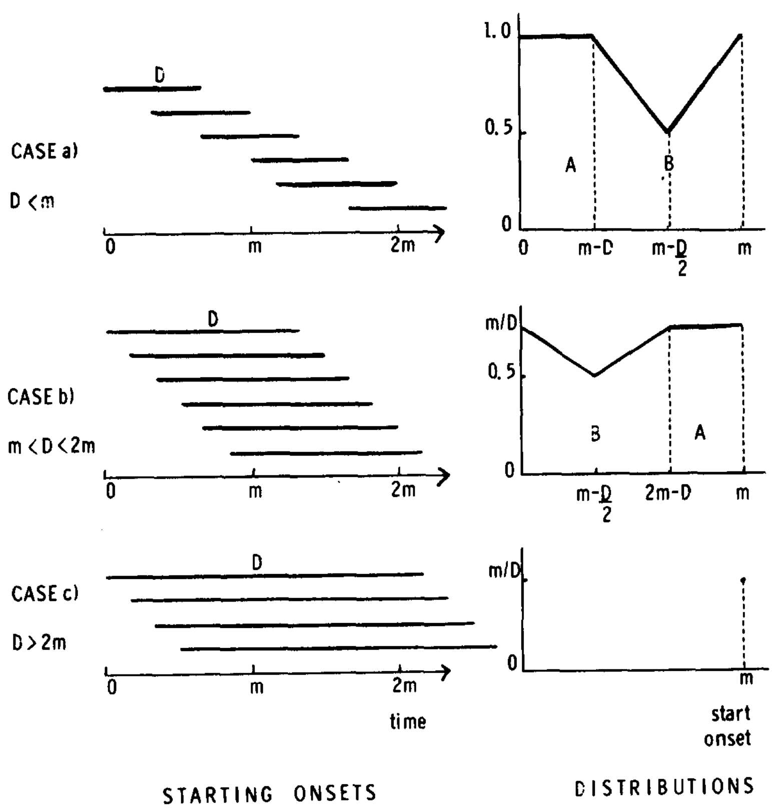

Fig. 10. Illustration of placement of a display of duration (D), relative to an underlying train of hypothetical moments (left); and, the distribution of effective display durations, relative to the starting onset of the display (right).

We shall assume there is an underlying stream of perceptual moments of period m, whose boundaries are unsynchronized with respect to the onset of the display sequence. Thus, relative to the boundaries of successive moments, the onset of the display is represented by a uniform distribution over the duration of a moment.

The three cases are schematically illustrated in fig. 10. Within each case, the left side illustrates a uniform distribution of starting onsets of the display from 0 to m with respect to a hypothetical underlying train of discrete perceptual moments, 0, m, $2m$, ... Within each case, the right side illustrates the distribution of the effective proportion of presented dots.

Case (a): D < m

For Case (a), two regions of starting onsets of the display are distinguished. In region A, stimulus duration D is entirely encompassed within a single moment m with starting positions from 0 to $(m-\mathrm{D})$. In region B, with starting onsets from $(m-\mathrm{D})$ to m, the display straddles two successive moments. The display exactly straddles two moments for a display onset at $(m-\mathrm{D}/2)$ with a uniform distribution on each side of that onset. Therefore:

$$\begin{aligned} p(d) &= \mathrm{P_A}p(d)_\mathrm{A} + \mathrm{P_B}p(d)_\mathrm{B} \\ &= \frac{(m-\mathrm{D})}{m}. 1.0 + \frac{\mathrm{D}}{m}\frac{(1.0+0.5)}{2} \\ &= 1 - \frac{\mathrm{D}}{4m} \quad \text{or} \quad 1 - \frac{r}{4} \end{aligned}$$

where r is the ratio of the total display duration to the duration of the perceptual moment.

Case (c): D > 2m

When the display duration is greater than twice the moment duration, the display will always encompass an entire single moment, irrespective of its onset. Therefore, $p(d) = m/\mathrm{D} = 1/r$

Case (b): m < D < 2m

For Case (b), two regions of starting onsets can be distinguished. In region A, with onsets from $2m - \mathrm{D}$ to m, the next moment will be encompassed entirely and the proportion of cases is given by Case (c). In region B, the display straddles two moments, being equally divided at an onset of $m - \mathrm{D}/2$, with a uniform distribution on each side of that onset. Therefore:

$$\begin{aligned} p(d) &= \frac{(\mathrm{D}-m)}{m}\cdot\frac{m}{\mathrm{D}} + \frac{(2m-\mathrm{D})}{m}\frac{(m/\mathrm{D}+0.5)}{2} \\ &= 1 - \frac{\mathrm{D}}{4m} \quad \text{or} \quad 1 - \frac{r}{4} \end{aligned}$$

which is identical to Case (a).

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