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ORIGINAL ARTICLE

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Single-letter recognition as a function of exposure duration

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Abstract The time course of visual letter recognition was investigated in a single-stimulus identification experiment. On each trial, a randomly chosen stimulus letter was presented at 1 of 12 equiprobable positions that were equally spaced around the circumference of an imaginary circle centered on fixation. Exposure duration was varied from 10 to 200 ms, and the letter was followed by a pattern mask. The subject's task was to report the identity of the stimulus letter but refrain from guessing. For the briefest exposures, correct reports never occurred. For longer exposures, the function relating the probability p of recognizing the letter to the duration t of the stimulus exposure was well approximated by an exponential distribution function: $p(t) = 1 - \exp[-v \cdot (t - t_0)]$, where v is the rate of processing and t_0 is the minimum effective exposure duration. The generality of this finding may be limited to cases in which stimuli are highly discriminable and response criteria are conservative. Extensions to Poisson counter or random walk models are considered for cases in which stimuli are confusable.

Introduction

The time course of visual recognition has been investigated in many whole-report experiments (e.g., Allport, 1968; Busey & Loftus, 1994; Loftus, Duncan, & Gehrig, 1992; Shibuya & Bundesen, 1988; Sperling, 1963, 1967; Townsend, 1981; van der Heijden, 1981). In a typical whole-report experiment, the subject has to report as many items as possible from a briefly exposed array of unrelated items (e.g., randomly selected alphanumeric characters), which is followed by a mask. The number of correctly reported items (the score) depends on the stimulus-onset asynchrony (SOA) between the stimulus array and the mask. Corrected for guessing, the score appears to be zero when the SOA is smaller than some threshold t_0. As the SOA exceeds t_0, the mean score initially increases at a high rate and then levels off as it approaches either a value of about four items or the number of items in the stimulus, whichever is smaller.

Representative performance curves (whole-report mean score functions) for arrays of two, four, and six items are illustrated in Fig. 1. The mean scores are group data for the two subjects tested by Shibuya and Bundesen (1988). The performance curves have been fitted by theoretical functions predicted by the fixed-capacity independent race model (FIRM) of Shibuya and Bundesen and the general theory of visual attention (TVA) proposed by Bundesen (1990, 1998a, 1998b). The theoretical fit implies that for arrays of four or six items, performance was affected by limitations in short-term memory capacity, but for arrays of only two items, memory limitations had no effect. The theoretical function fitted to the mean scores for the two-item arrays equals $2 \times p(t)$, where $p(t)$ is the probability that an individual item in a two-item array is correctly reported at exposure duration t. Probability $p(t)$ was given by Equation 1:

$$p(t) = \begin{cases} 0 & \text{for } t < t_0 \\ 1 - \exp[-v \cdot (t - t_0)] & \text{for } t \geq t_0 \end{cases} \qquad (1)$$

where parameter v is the processing rate for each item and t_0 is the minimum effective exposure duration. The fit shown in Fig. 1 was found with v at a value of 26 items per second and t_0 at 19 ms.

In the FIRM and the TVA, an item can be reported from a stimulus display if the item is stored in visual short-term memory (VSTM). When only one or two items are presented, effects of memory limitations are negligible (cf. Luck & Vogel, 1997). In this case, an item can be reported if the encoding process for the item is

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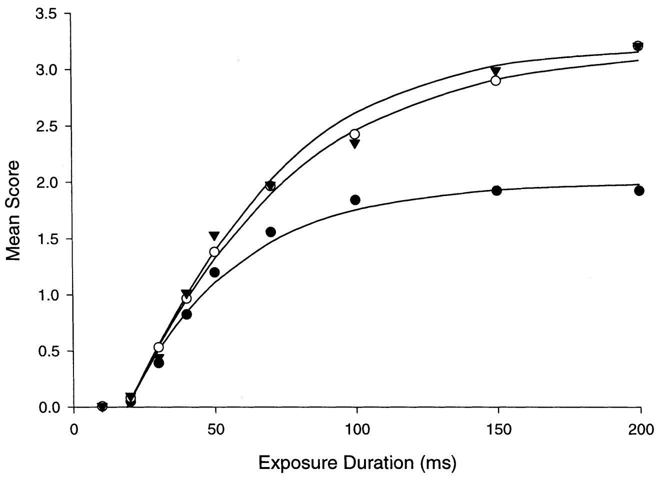

Fig. 1 Mean score (number of items correct in whole report) as a function of exposure duration with display size N as the parameter in the experiment of Shibuya and Bundesen (1988): group data for 2 subjects. N was 2 (*solid circles*), 4 (*open circles*), or 6 (*triangles*). A theoretical fit is indicated by smooth curves. The observed data are replotted from Fig. 1 of Shibuya & Bundesen, 1988

completed before the processing is interrupted by the mask.

In the TVA, an item is encoded into VSTM by encoding a perceptual categorization of the item. When memory limitations can be neglected, an element x of category i can be reported if the perceptual categorization "element x belongs to category i" is completed before processing is interrupted by the mask. Equation 1 follows from the assumptions that (a) the time taken to encode a perceptual categorization is exponentially distributed, and (b) the time available for encoding equals the stimulus duration in excess of the minimum effective exposure duration t_0.

The experiment reported in the present paper is a follow-up on the study by Shibuya and Bundesen (1988). The experiment tested the validity of Equation 1 by measurements of single-stimulus identification performance as a function of exposure duration. After the presentation of the experiment, the generality of the findings are discussed, and extensions of TVA-based accounts to Poisson counter and random walk models are considered.

Method

Subjects. Three students at the University of Copenhagen served as subjects. Their vision was normal or corrected to normal.

Displays

Stimulus. Each stimulus display showed a single letter, which was chosen at random from a set of 18 upper-case consonants (B, C, D, F, H, J, K, L, M, N, P, R, S, T, V, W, X, and Z). The spatial position of the letter was chosen at random from a set of 12 possible positions (1 o'clock, 2 o'clock,...,12 o'clock) at the periphery of an imaginary circle centered on the fixation cross. Under the experimental viewing conditions, the letter subtended a visual angle of about 0.4° vertically and 0.3° horizontally. The angular distance from the center of the letter to the fixation point was 1.84°.

Mask. Each stimulus display was followed by a mask. The masking display showed four identical patterns: one masking pattern at the position where the stimulus letter had appeared and three masking patterns at other possible stimulus positions (chosen at random from the 11 remaining positions). A masking pattern was equal in size to a stimulus letter; it consisted of a rectangle equal in height and width to an H, an O inscribed in the rectangle, an X that formed the diagonals of the rectangle, and a cross that divided the rectangle into four identical rectangles. The mask conformed to Eriksen's (1980) minimal test: When mask and stimulus were physically superimposed, the stimulus could not be seen at all.

Apparatus and procedure. The subject was seated in front of a computer-driven cathode ray screen (Tektronix 604 Monitor equipped with P-31 fast-decay phosphor) at a viewing distance of 1.2 m in a semi-darkened room. A stimulus letter covered about 0.8 × 0.6 cm on the screen. The letter was displayed by periodic intensifications at a rate of 100 Hz, each with a luminous directional energy of approximately 1 cdμs/cm (cf. Sperling, 1971). The background luminance of the screen was about 0.3 cd/m^2.

At the beginning of a trial, the fixation cross was presented at the center of the screen. When the cross was adequately fixated, the subject pressed a key to produce an immediate exposure of the stimulus display. The stimulus exposure comprised 1, 2, 3,..., or 20 intensifications at the rate of 100 Hz, which corresponded to exposure durations of 10, 20, 30,..., and 200 ms. When stimulus exposure terminated, the mask was exposed for a period of 500 ms (50 intensifications at the rate of 100 Hz).

The subject's task was to report the identity of the stimulus letter but refrain from guessing. If the subject was "fairly certain" that the letter was correctly identified, he or she should type the letter on a keyboard and then press a return key. Otherwise, the subject should press only the return key. When the return key was pressed, the reported letter, if any, was shown at the bottom of the screen, and the subject either confirmed the report by pressing one key or corrected the report for typing errors by pressing another key and typing the corrected report.

Design. Each subject participated in 200 trials for each exposure duration, which yielded a total of 4000 trials per subject. The 4000 trials were presented in 200 blocks of 20 trials, 1 with each of the 20 exposure durations.

Results

Correct reports

Table 1 shows the observed proportion of correct reports as a function of the exposure duration of the stimulus letter for each of the three subjects. The same data are illustrated in Fig. 2. The observed proportions were fitted by theoretical proportions $p(t)$ found by Equation 1. As can be seen from Table 1 and Fig. 2, the least squares fits by Equation 1 were close.

The least squares fit to the results of Subject EA was obtained with $v = 77$ letters/s and t_0 at 19 ms. For Subject MK, the corresponding estimates were $v = 60$ letters/s and $t_0 = 36$ ms. For subject AO, the estimates were $v = 119$ letters/s and $t_0 = 16$ ms.

Table 1 Observed (*Obs.*) and theoretical (*Th.*) proportions of correct reports

Exposure duration	Subject					
	EA		MK		AO	
	Obs.	Th.	Obs.	Th.	Obs.	Th.
10	0.000	0.000	0.000	0.000	0.000	0.000
20	0.100	0.084	0.000	0.000	0.345	0.347
30	0.515	0.577	0.040	0.000	0.815	0.802
40	0.855	0.804	0.225	0.219	0.925	0.940
50	0.930	0.910	0.550	0.571	0.970	0.982
60	0.960	0.958	0.780	0.764	0.990	0.994
70	0.985	0.981	0.865	0.871	0.995	0.998
80	0.995	0.991	0.945	0.929	0.960	0.999
90	0.995	0.996	0.980	0.961	0.995	1.000
100	1.000	0.998	0.960	0.979	0.990	1.000
110	1.000	0.999	0.985	0.988	0.995	1.000
120	1.000	1.000	0.985	0.994	0.985	1.000
130	0.995	1.000	0.965	0.996	1.000	1.000
140	0.995	1.000	0.995	0.998	0.995	1.000
150	1.000	1.000	0.985	0.999	1.000	1.000
160	1.000	1.000	0.995	0.999	1.000	1.000
170	0.995	1.000	0.995	1.000	0.995	1.000
180	1.000	1.000	0.995	1.000	1.000	1.000
190	1.000	1.000	0.990	1.000	1.000	1.000
200	1.000	1.000	0.990	1.000	1.000	1.000

Errors

Errors of commission (intrusion errors) were rare. The total number of commission errors across the 4000 experimental trials was 74 for Subject EA, 0 for Subject MK, and 33 for Subject AO. The percentage of errors among the reported letters was 2% for Subject EA, 0% for Subject MK, and 1% for Subject AO.

Discussion

The reported experiment aimed at testing the validity of Equation 1 by measurements of single-stimulus identification performance as a function of exposure duration. The results showed that Equation 1 provided good approximations to the data. By a simple analysis in terms of the TVA, the results lend support to the assumptions that (a) the time taken to encode a perceptual categorization of the form "element x belongs to letter type i" into the VSTM is exponentially distributed, and (b) the time available for encoding equals the stimulus duration in excess of a minimum effective exposure duration t_0.

Our simple analysis in terms of the TVA presupposes that a letter x of type i was reported if, and only if, the correct perceptual categorization, "x belongs to i," was encoded into the VSTM. The analysis was based on the simplifying assumptions that (a) perceptual confusions among letter types (i.e., incorrect perceptual categorizations with respect to letter type) could be neglected, and (b) guessing could be neglected. Neglecting perceptual confusions seemed reasonable because the stimulus letters were low in visual similarity; they were constructed to be highly dissimilar to each other. Neglecting

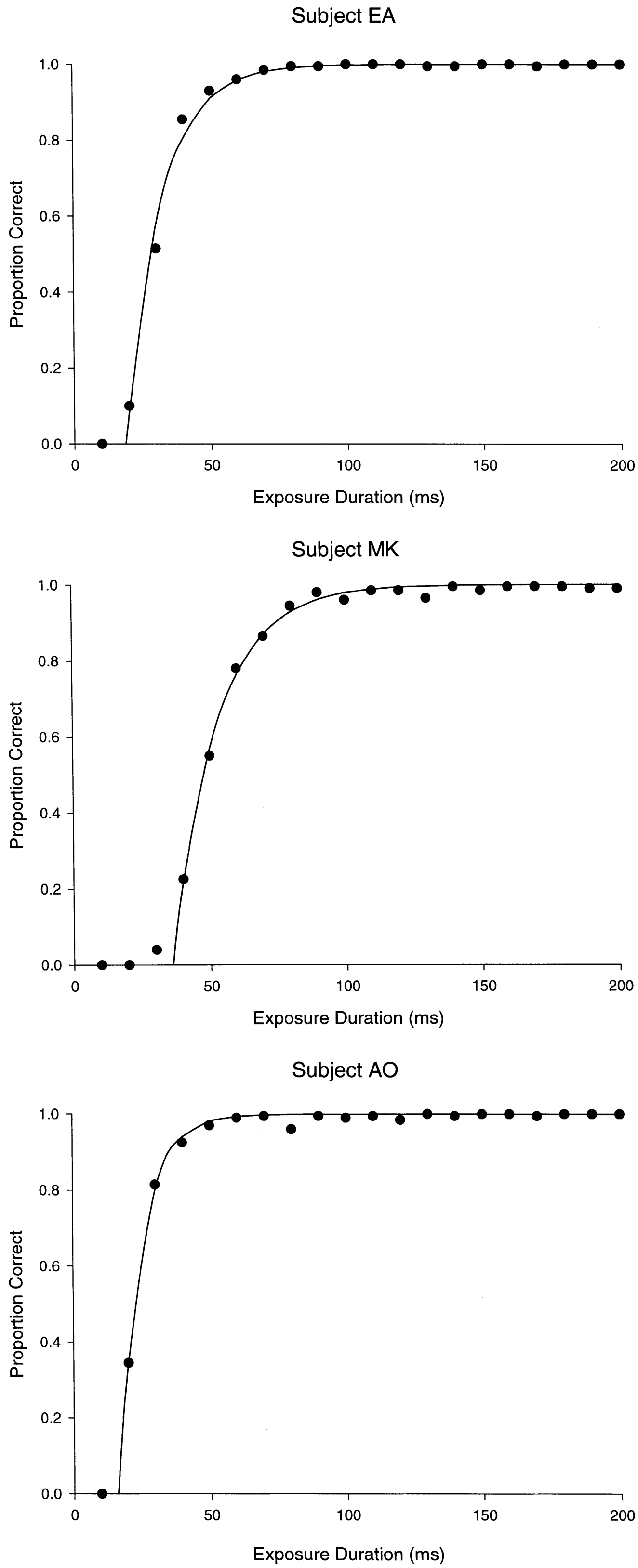

Fig. 2 Proportion of correct reports of the identity of a single, postmasked stimulus letter as a function of the exposure duration of the letter: individual data for 3 subjects: Subjects EA (*top panel*), MK (*middle panel*), and AO (*bottom panel*). Theoretical fits are indicated by *smooth curves*

guessing seemed reasonable because subjects were instructed to refrain from guessing; a letter should be reported if, and only if, the subject was "fairly certain" that it was correctly identified. The results supported our simplifying assumptions: Errors of commission were rare.

Limitations and extensions

The generality of our experimental findings may be limited to cases in which performance is based on the subject's first full identification of the stimulus (in the present case, the first-completing perceptual categorization with respect to the precise identity of the stimulus letter). Such cases may be found when stimulus discriminability is high and response criteria are conservative.

Suppose response criteria were lowered, so that subjects were encouraged to respond not only when a full identification of the stimulus had been made but also when only a *partial identification* (a coarse categorization) of the stimulus had been made. In this case, sophisticated guessing on the basis of partial identifications would be expected. For example, a subject who knows that every stimulus x is a letter and perceives that "x is round" might guess that "x is an O" or that "x is a Q;" if the subject perceives that "x has a vertical bar," he might guess among characters with a vertical bar. Relative to performance based on only full stimulus identifications, performance based on a mixture of full and partial identifications should lead to fewer errors of omission (missing responses) but more errors of commission (false responses). The shape of the function relating the probability of correct report to the exposure duration of the stimulus should depend on the particulars of the sophisticated-guessing strategy used by the subject.

Counter and random walk models

When stimulus discriminability is high, the subject can respond on the basis of the first perceptual categorization she or he makes (the *immediate* perception of the stimulus) without making many errors of commission. However, when stimulus discriminability is low, false perceptual categorizations should be frequent. When discriminability is low, the fact that a certain perceptual categorization has been made (encoded at least once into the VSTM) constitutes only weak evidence concerning the true identity of the stimulus. Accordingly, responding on the basis of the immediate perception of the stimulus should yield relatively few errors of omission but many errors of commission. To keep a low rate of commission errors, the response rule must be changed.

Suppose that once a perceptual categorization has been represented in the VSTM, the same categorization may be confirmed by being made anew. If so, then the subject may base the response on the categorization that first reaches a criterion of having been made r times, where $r > 1$. In this case, the subject should behave in accordance with a so-called *Poisson counter* or *accumulator* model (for reviews, see Luce, 1986; Townsend & Ashby, 1983, Chap. 9). Baseline performance based on immediate perception is found when $r = 1$. As the criterion r is raised, the rate of commission errors is reduced at the expense of an increase in the rate of omissions.

A related possibility is to base the response on the categorization that first reaches a criterion of having been made d times more than any alternative categorization. This possibility leads to so-called *random walk* models with exponential interstep times (for reviews, see Luce, 1986; Townsend & Ashby, 1983, Chap. 10; see also Bundesen, 1982; Logan, 1996; Nosofsky & Palmeri, 1997; Ratcliff & McKoon, 1997). Baseline performance reflecting immediate perception is found when $d = 1$. As the criterion d is raised, the rate of commission errors decreases and the rate of omissions increases.

Responding on the basis of the categorization that first reaches a given criterion is a plausible strategy, but the strategy is less efficient when subjects aim for accuracy and not for speed. When only accuracy is emphasized, the stimulus analysis may be continued throughout the period of stimulus exposure, and the subject may determine the most frequent categorization (i.e., the categorization that is made the greatest number of times). By analogy with the counter models described above, the subject may give the most frequent categorization as the response if the categorization has been made at least r times. If no categorization has been made r times or more, the subject may withhold the response. As before, raising the criterion r reduces the rate of commission errors at the expense of an increase in the rate of omissions.

Similarly, by analogy with the random walk models described above, the subject may give the most frequent categorization as the response if the categorization has been made at least d times more than any alternative categorization. If no categorization has been made at least d times more than any alternative categorization, the subject may withhold responding. Again, as the criterion d is increased, the rate of commission errors decreases and the rate of omissions increases.

In summary, when stimulus discriminability is low, the rate of commission errors can be reduced by using a strategy by which the identity of the stimulus must be confirmed a certain number of times – or a certain number of times more than any alternative categorization – before a response is made. Depending on the particular response rule used by the subject, he or she may behave in accordance with a Poisson counter or accumulator model, a random walk model with exponential interstep times, or modifications of such models in which stimulus analysis is prolonged throughout the period of stimulus exposure. When the response criterion is raised, the rate of commission errors is reduced, but the rate of omissions increases. Concomitantly, the function relating the probability of correct report to the exposure duration of the stimulus should change in shape.

Concluding Remarks

In the reported experiment, the relationship between stimulus recognition and exposure duration (i.e., the function relating the probability of correctly reporting the stimulus letter to the duration of the stimulus exposure) was well approximated by the exponential distribution function given by Equation 1. The generality of this finding may be limited to the case in which performance is based on the subject's immediate perception of the identity of the stimulus (the subject's first full identification of the stimulus). We have treated this case as a baseline and described ways of changing the response criterion relative to the baseline: The subject may lower the response criterion and make sophisticated guesses on the basis of partial stimulus identifications, or the subject may raise the response criterion and require that the identity of a stimulus be confirmed a certain number of times (or a certain number of times more than any alternative categorization) before responding. In either case, the functional relationship between stimulus recognition and exposure duration may be quite different from the relationship seen in the present experiment.

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