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Forced serial processing of words and letter strings: A reexamination

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Words and nonword strings, three and seven letters long, were displayed serially (i.e., one letter at a time) or simultaneously, with or without a backward mask following display of each letter or string. Recognition of words, and of individual letters within words, was markedly impaired in the masked serial condition relative to the unmasked serial, unmasked simultaneous, and masked simultaneous conditions. Analogous differences were smaller or nonexistent for seven-letter nonwords; however, three-letter nonwords produced relatively "wordlike" data. Implications for the issue of spatially serial vs. parallel processing in word recognition are discussed.

Travers (1973, 1974) used a technique of "forced serial processing" to demonstrate that skilled readers, when recognizing words, extract visual feature information from several letter positions at once and code the information in chunked or unitary form. Serial processing was forced by displaying words one letter at a time, with letters in normal adjacent spatial positions and in temporal order corresponding to their left-right sequence within the word. Each letter was followed immediately by a mask, in order to prevent retention of letters in iconic memory. Such display conditions produced poor recognition at brief exposure durations (e.g., 50 msec per letter), which do not allow subjects enough time to code individual letters verbally; at slower display rates (e.g., 200 msec per letter), which allow a substantial amount of verbal coding, recognition was much superior.

In both of the earlier papers, recognition under conditions of forced serial processing was contrasted with recognition under conditions intended to permit spatially parallel processing, as defined by Neisser (1967).[1] In the 1973 paper, the contrast condition was one of serial, adjacent display without masking, designed to allow retention of serially input letters in iconic memory. This condition produced uniform high levels of report accuracy (about 85% across all exposure durations from 50 to 200 msec per letter). The 1974 paper introduced a contrast condition of simultaneous display with masking. The entire word was shown for 48 msec, and performance was compared to a condition in which letters were shown successively, each for 48 msec. The simultaneous condition produced dramatically superior word recognition (84% vs. 33%). The two studies were taken to imply that simultaneous availability of information from several letters confers an advantage for word recognition in skilled readers.

To rule out the possibility that the difficulty of recognizing words under conditions of masked serial display was due to effects of the mask on letter perceptibility rather than to reduced opportunity for parallel encoding, a nonword control was run in the 1973 study. It was assumed that random letter strings permit little unitary encoding across letter clusters; therefore, differences in report accuracy for random strings displayed serially, with and without masking, were expected primarily to reflect differences in letter perceptibility. In fact, the presence or absence of the mask had almost no effect on report accuracy for random strings. Thus, the 1973 data suggested that virtually none of the difference in word recognition evoked by masked vs. unmasked serial display could be attributed to an effect of the mask on letter perceptibility (at the relatively long exposure durations employed—50 msec or more).

However, the 1974 study did not include a nonword control condition. Therefore, the contribution of letter perceptibility to the striking difference in word recognition accuracy between simultaneous and serial display conditions is unknown. Perceptibility of individual letters might have been impaired by lateral inhibition in the serial display case (since each letter appeared simultaneously with, and adjacent to, the mask for the preceding letter) or by various metacontrast and paracontrast effects which were absent in the simultaneous display case, even when the whole-word display was followed by a mask.

The present study replicated the 1973 and 1974 experiments but included the crucial nonword control for the successive-simultaneous comparison. In addition, the replication study used visual display characteristics very different from those employed in the earlier studies, and more like those of both ordinary reading and typical tachistoscopic experiments. Stimuli were black-on-white, lowercase, typewritten letters and words. (The earlier studies

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used uppercase letters formed by dot patterns, appearing in luminescent green against a dark gray background; the apparatus was a computer-controlled oscilloscope.)

Stimuli in the present study were words or unpronounceable, "unwordlike" nonwords; stimulus strings were either three or seven letters in length. Intervals between onsets of individual letters were zero (simultaneous display), 50 msec, 100 msec, or 200 msec. For half of both word and nonword stimuli, a backward mask followed each letter, concurrently with display of the next letter. (For simultaneous displays, the mask appeared 50 msec after the word or letter string.) For the other half of the displays, no mask appeared.

The design permitted comparison of the effects of forced serial processing on recognition of words and nonwords by two different methods (i.e., one in which masked serial display was contrasted to unmasked serial display, and one in which masked serial display was contrasted to masked simultaneous display). Further, it allowed some assessment of the generality of parallel processing effects across visual display conditions.

METHOD

Display Apparatus and Materials

Stimuli were displayed on a stroboscopic tachistoscope designed by Douglas Lawrence. The apparatus consists of an aluminum frame which is drawn upward past a horizontal slit at a fixed rate—in the present experiment 1/6 in., or a line of IBM type, per 50 msec. Stimuli are typed on ordinary 8½ x 11 in. sheets, which are fixed to the frame. A high-intensity strob light illuminates the sheet from behind for a period of a few microseconds, timed to coincide with the centering of a line of type in the slit. The subject views the typed stimulus from the front of the slit. Further details on the construction of the apparatus and the visual characteristics of its displays are given in Lawrence and Sasaki (1970).

By typing successive letters of a word or nonword string on successive lines of the sheet, it is possible to display letters serially. Interstimulus interval (ISI) is varied by skipping varying numbers of lines between letters. Previous research (e.g., Haber & Nathanson, 1969) suggests that serial displays using brief stimulus on times with variable ISI should be perceptually equivalent to displays in which stimulus on time is manipulated directly, as in Travers (1973).

Stimulus strings were typed in lowercase on Gray's Harbor bond paper (No. 16) using an IBM Selectric typewriter equipped with a carbon ribbon and a Courier 72 ball. Strings subtended a vertical visual angle of approximately 0°24′. Three-letter strings subtended a horizontal angle of approximately 1°10′, and seven-letter strings an angle of 2°45′. A pair of parentheses—( )—was typed 10 lines (500 msec) above the first line of each display. The parentheses served as a warning signal and bracketed the space in which the three- or seven-letter string was to appear.

The mask was a capital "X" superimposed on a capital "O" (⊗). Pilot work showed it to be highly effective. In serial displays, the mask for a given letter was typed immediately to the left of the following letter. In simultaneous displays, a row of masks, one for each letter position, appeared one line (50 msec) after the stimulus string.

Design

A repeated-measures design was used, in which eight subjects each viewed a total of 640 stimuli, 20 in each of 32 experimental conditions. The 32 conditions were defined by the intersection of the four independent variables described in the introduction: There were two stimulus classes (words and nonwords), two masking conditions (masked and unmasked), two stimulus lengths (three and seven letters), and four ISIs (0, 50, 100, and 200 msec).

The 32 experimental conditions were presented as blocks of 20 items. Presentation order of the blocks was counterbalanced as far as possible, given the constraints imposed by the number of subjects (eight). Half of the subjects saw words first, and half saw nonwords first. Within each of these two groups, half saw masked items first and half, unmasked items. Within each of the groups defined by joint orderings of stimulus types and masking conditions, half (i.e., one subject) saw three-letter items first and half, seven-letter items. Each subject saw half of the stimuli in ascending order of ISI and half in descending order; however, ISI order obviously could not be varied within the cells defined by joint orderings of stimulus type, masking condition, and length, since such cells contained only a single subject. The 20 stimuli within each block were shown in a different random order for each subject.

Stimulus Strings

Stimulus words all had frequencies in printed English greater than 10 and less than 250, according to the Kučera-Francis (1967) count. Words were selected as follows: All the three-letter words falling in the specified frequency range were listed; technical terms, contractions, and proper names were excluded (except for proper names that doubled as common words, e.g., rob, rod, sue, guy). This list was only a little longer than the 160 words required for the experiment. Seven-letter words were then picked by finding the seven-letter word closest to each three-letter word in the Kučera-Francis list. In most cases, this procedure produced exact matching of frequencies between three- and seven-letter items. Perfect matching was not possible at the upper range of frequencies, however. Matched pairs were then distributed across the eight display conditions, of the experiment (two masking crossed by four ISI conditions) so as to equalize frequency distributions as exactly as possible. This required discarding some high-frequency items which could not be matched across display conditions, or for which the three- and seven-letter matches were not sufficiently close. The procedure yielded a very close matching of frequency distributions across masking conditions, ISIs, and word lengths. Means for all 16 cells fell in the range of 60.1 to 60.8 occurrences per million.

Nonword stimuli were created from the population of letters appearing in the word stimuli by arranging the 20 words assigned to each cell of the design in columns and going down the columns, selecting each vertical sequence of three or seven letters to appear as a (horizontally displayed) nonword string under the same visual conditions. The only constraints on this process were (1) that no string appeared (intuitively) to be pronounceable or "wordlike"; and (2) that no string was used more than once in the entire experiment. Internal rearrangement of strings prevented violation of these constraints.

Subjects

The subjects were eight Stanford University undergraduates, three men and five women. All were native speakers of English. None reported uncorrected defects of vision. All were paid volunteers.

Procedure

The subjects were run in four or five sessions of approximately 2 h duration. At the beginning of the first session, the subjects were given a minimum of 32 practice trials, one or two on displays for each block of the experiment, in order to familiarize them with the apparatus and the general characteristics of the displays. The subjects were also given five additional practice trials preceding each of the 32 experimental blocks, in order to allow them to form appropriate strategies for dealing with the forthcoming display type.

The subjects were told that the purpose of the experiment was to determine the effects of various displays upon the readability of words and letters. They were instructed to identify simuli aloud as rapidly as possible. In the case of word stimuli, thv subjects were told to name the whole word if they thought they saw all of its letters, and to name individual letters otherwise. In cases where they deduced the identity of words while in the process of reporting individual letters, they were asked to supply the deduced word, but these "afterthoughts" were not scored as correct word identifications. Only words and letters reported as "actually seen" are taken into account in the analyses below.[2] Data were recorded by the experimenter while an assistant changed stimulus sheets in the tachistoscope. The subjects initiated each trial by pressing a button which caused the moving frame and strob timer to begin operation.

RESULTS

The mean percentage of letters correctly identified for each of the 32 experimental conditions is shown in Table 1. Although absolute levels of performance varied widely across subjects, the pattern of results was fairly consistent, as indicated by the outcomes of various statistical tests reported below. Table 1 also shows data averaged across subjects on words and nonwords correctly reported as wholes, i.e., with all letters reported in proper order.

Two types of statistical analysis were applied to the data: (1) A six-way analysis of variance was performed, using string type, masking condition, string length, and ISI as fixed independent variables, subjects and stimulus items as random independent variables, and proportion of letters correctly identified as the dependent variable. Data were first subjected to an arcsin transformation, as recommended by Winer (1971, pp. 399-400).[3] Significance was tested by means of quasi-F ratios, which take account of error variance due to both items and subjects (Clark, 1973; Winer, 1971, pp. 375-385). (2) Since the most instructive contrasts were buried in multiway interactions, several planned comparisons were also performed. Both the planned comparisons and selected results of the ANOVA are discussed where relevant below.

Table 1
Mean Percentage of Letters and Strings Correctly Identified as a Function of String Type, Masking Condition, String Length, and ISI

	Three-Letter				Seven-Letter			
ISI	Simul	Serial			Simul	Serial		
(msec)	0	50	100	200	0	50	100	200
Unmasked Words								
Letters	99	99	98	98	100	98	93	96
Whole Words	97	97	96	96	99	93	79	83
Masked Words								
Letters	99	85	95	99	98	71	85	94
Whole Words	97	68	88	96	93	34	51	74
Unmasked Nonwords								
Letters	96	94	93	97	78	73	69	80
Whole Strings	89	83	79	92	8	1	0	3
Masked Nonwords								
Letters	82	73	83	95	57	58	67	77
Whole Strings	53	28	41	84	0	0	0	1

Word Data

In most theoretically relevant respects, the word data replicate the findings of Travers (1973, 1974), although minor discrepancies may also be noted:

(1) Letter and word recognition are near-perfect for conditions which allow parallel processing, i.e., unmasked simultaneous displays, masked simultaneous displays, and unmasked serial displays at rapid rates (ISI = 50 msec).

(2) There is a weak tendency for unmasked serial displays to produce U-shaped accuracy functions with respect to ISI, with minima in the neighborhood of ISI = 100 msec. This tendency accords with recent observations by Haber (personal communication). Haber explains the shape of the function in terms of two opposing processes: ISIs below 100 msec facilitate retention of several letters at once in iconic memory, while ISIs above 100 msec permit increasing amounts of letter-by-letter naming. Though Travers (1973) did not find such a "bowing" of the accuracy function, it is possible that the discrepancy is due to the use of light-on-dark displays in the 1973 study. Displays with dark pre- and postexposure fields can produce visual persistence up to several seconds (Sperling, 1963). Such persistence may explain the absence of any decrement in performance at the 100-msec rate in the 1973 study.

(3) The masked serial conditions (ISI = 50, 100, and 200 msec) exert a marked detrimental effect on report of letters within words; the size of this effect diminishes as ISI increases, i.e., as the time available for coding individual letters grows. The overall impact of the mask is demonstrated by a significant main effect for masking (quasi-$F = 72.9$; $df = 1,12$; $p < .001$). There is also a significant interaction of masking and ISI (quasi-$F = 12.1$; $df = 3,49$; $p < .001$). Both of these effects obviously incorporate nonword data as well as word data; a significant String Type by Masking by ISI interaction (quasi-$F = 9.36$; $df = 3,99$; $p < .001$) shows that the patterns for words and nonwords differ, as discussed in later sections on the nonword data.

(4) The effects of the mask and of ISI are much larger for the whole-word than for the individual letter data. This might occur for either of two reasons: (a) relatively small differences in perceptibility of individual letters are compounded, by some straightforward probabalistic principle, to produce relatively large differences in recognition of the whole words in which those letters are embedded; and (b) word recognition is genuinely holistic, such that interference with normal recognition strategies produces larger effects on recognition of whole words than of letters within words. A test of the two alternatives is possible; however, the test requires an estimate of letter perceptibility which is independent of the estimate of word perceptibility. Since such independence obviously does not hold for letter-recognition data obtained with word stimuli, the test is deferred until a later section in which

nonword data are used to estimate letter perceptibility.

(5) Performance is better for three-letter words than for seven-letter words, particularly in the masked conditions. There is a significant main effect for string length (quasi-F = 73.2; df = 1,9; $p < .001$). Again, however, the is also a significant Length by String Type interaction (quasi-F = 84.0; df = 1,14; $p < .001$), indicating differing patterns between words and nonwords. Travers (1973) also obtained significant length effects, especially for masked displays, but the effects were considerably smaller than in the present study, presumably because three-letter words were not used as stimuli in the earlier work.

Nonword Data

The nonword data strengthen the conclusions of Travers (1974) but weaken somewhat the conclusions of Travers (1973):

(1) Simultaneous-successive comparison: The nonword data for masked presentation at ISIs of zero and 50 msec provide the control missing from Travers' 1974 study. These data may be compared to word data obtained under the same display conditions, in order to determine whether the large facilitating effect of simultaneous display on word recognition is due to a difference in letter perceptibility alone. (Note that at both ISI = 0 and ISI = 50 msec, the effective exposure duration fot each letter is 50 msec.) The outcome of the comparison is clear: Simultaneous display confers a greater advantage for words than for nonwords. In the case of seven-letter nonword strings, simultaneous presentation elicits somewhat *worse* performance than serial presentation. In the case of three-letter strings, performance is somewhat better in the simultaneous than in the serial case, confirming a recent finding of Arabie (1974), but the facilitation is less than that observed for words. (A t test on the difference of differences was performed, using the arcsin transformation to compensate for ceiling effects. The resulting t was 1.96; df = 7; $p < .05$.) The fact that three-letter nonwords produce relatively "wordlike" data may indicate that very short nonwords can be encoded in parallel, though not to the degree permitted by words.

(2) Masked-unmasked comparison: Unlike the serial-successive comparison, the serial-masked vs. serial-unmasked contrast of Travers (1973) becomes less clearcut when visual conditions are altered. Travers found no effect of masking on identification of nonwords of any length from four to eight letters. This somewhat counterintuitive finding was stronger than required by the parallel encoding hypothesis: The existence of some masking effect for nonwords (presumably an effect of the mask on letter perceptibility) would not in itself have contradicted the hypothesis; a greater effect of masking on words than on nonwords would have sufficed to demonstrate an additional advantage due to simultaneous availability of letters within words. The present data supply this weaker form of confirmation of the hypothesis, but only for the longer strings.

Three-letter nonwords again produce "wordlike" data; in fact, the effect of masking on three-letter nonwords is *greater* than its effect on words. This outcome may be due in part to ceiling effects for short words and in part to parallel processing of three-letter nonwords, as suggested by other aspects of the data. In any case, the three-letter data obviously do not support the hypothesis, though the discrepant results for three-letter strings do not constitute direct empirical disconfirmation of Travers' (1973) data, since such short strings were not examined in that study.

However, one data point from the present study does directly contradict an earlier finding. Seven-letter nonwords displayed without masking at 50 msec per letter were reported more accurately than seven-letter nonwords displayed with masking at the same rate. (A post hoc t test yields a significance level of .005 for the masked-unmasked comparison.) Moreover, recognition for unmasked, serially displayed nonwords was better at 50 msec per letter than at 100 msec in the present study, again confirming observations by Haber (personal communication); in the earlier study, recognition was worse at 50 msec than at 100 msec for both the masked and unmasked cases. No explanation for the latter discrepancy is immediately apparent.

The existence of a significant masking effect for seven-letter nonwords at the 50-msec display rate brings up two crucial, interrelated questions: (a) Is the effect larger for words than for nonwords, as required by the parallel encoding hypothesis? (b) Can the effect of the mask on nonwords, interpreted as an effect on letter perceptibility, explain the effect on words, even if the latter is larger?

The answer to the first question is "yes"; at both the 50- and 100-msec display rates, which are too rapid to allow letter-by-letter encoding, the mask is significantly more damaging for words than for nonwords (t for the difference of differences at 50 msec = 4.13, df = 7, $p < .005$; t at 100 msec = 5.05, df = 7, $p < .005$).

A simple probability analysis suggests that the answer to the second question is "no." The probability of identifying a letter within a seven-letter nonword without masking at ISI = 50 msec is .729; with masking, the probability drops to .584. Taking these values as estimates of probabilities of letter recognition under masked and unmasked conditions, we may calculate the probability of identifying 0, 1, 2, . . . , 7 letters by a binomial:

$$P(C) = \binom{7}{C} p^C (1 - p)^{7-C}$$

where P(C) = probability of getting exactly C letters correct, p = probability of getting any one letter correct (p = .729 or .584), and $\binom{7}{C}$ = number of possible combinations of C objects that can be drawn from a total of seven. We do not know how many letters must be identified independently in order to identify a whole word correctly. However, for all values of C, the predicted difference between whole-word accuracy levels for masked and unmasked presentations is substantially less than the actual difference. For example, if we assume that the subject can identify a word given that he has identified four or more of its constituent letters, we would predict, by summing the relevant probabilities derived from the above formula, that he should identify whole words with probability .908 in the unmasked case, which is fairly close to the observed value (.931). However, the same assumption applied to the masked case yields a whole-word probability of .679, far above the observed value of .338. Similar erroneous predictions are obtained under the assumptions that the subject needs to identify 1, 2, 3, 5, 6, or 7 letters in order to identify whole words correctly. The lesson is clear: Masking impairs word recognition substantially more than would be expected on the basis of its effects on letter perceptibility alone.

DISCUSSION

The data on balance add support to the hypothesis that visual feature information from multiple letter positions within a word is normally encoded in parallel, rather than undergoing a process of serial, letter-by-letter coding. However, the new data also suggest that earlier findings and conclusions must be qualified.

The need for qualification is particularly apparent in the case of data based on the masked-serial vs. unmasked serial comparison. The present study shows that masked serial display *can* impair report of nonword letter strings when visual conditions differ from those which led Travers (1973) to draw the opposite conclusion. One reason for the difference between present and earlier results in this regard may be that the mask used in the earlier study (a crosshatched number symbol—#) is relatively ineffective, as suggested by observations of Estes, Bjork, and Skaar (1974). More important, the greater effect of masking on words than on nonwords, a crucial datum for the parallel encoding hypothesis, holds only for strings longer than three letters. The latter fact, together with certain results of the simultaneous-serial comparison, suggests that very short nonwords, even "unwordlike" nonwords, may also be coded in parallel. (That is, verbal codes for two or three unrelated letters may be retrieved simultaneously, though presumably two or three letters cannot be rehearsed simultaneously.)

In contrast to the masked-serial vs. unmasked-serial comparison, the results of the masked-serial vs. masked-simultaneous comparison of Travers (1974) seem fairly robust across visual display conditions. Report accuracy for individual letters is essentially perfect when words are displayed as wholes for 50 msec and followed by a mask; letter report accuracy drops by 14% for three-letter words and by 27% for seven-letter words when letters within words are displayed one at a time, each for 50 msec, followed by masks. (Compare the data in Table 1 for masked words at ISI = 0 vs ISI = 50 msec.) Even more striking is the decrease in accuracy for whole-word reports as the presentation mode switches from simultaneous to serial; three-letter words show a 29% decrease and seven-letter words a 59% decrease. Part of the performance decrement associated with masked serial displays is doubtless due to general perceptual factors, as evidenced by the fact that serial display produces a 9% decrease in accuracy for three-letter *nonwords*, relative to simultaneous display of similar stimuli. However, general perceptual factors do not account entirely for the larger performance decrements obtained with words as stimuli; the decrease in accuracy due to serial display is significantly greater for words than for nonwords in both the three- and seven-letter cases—especially the latter, where simultaneous display actually *impairs* report of letters within nonwords to a slight degree.

In sum, simultaneous displays convey perceptual advantages, but the facilitating effects of simultaneous displays are especially large when the stimulus strings are words. At present, the best explanation for this pattern of results appears to lie in the utility of parallel encoding strategies for stimuli which map into unitary verbal codes. It is valuable to have a reliable technique for demonstrating parallel encoding, particularly if the technique produces relatively large effects, as the serial-simultaneous comparison does when long stimulus strings are used. Presumably it will be of interest to learn whether parallel encoding is useful for wordlike nonwords of various kinds, in order to construct a model of word recognition that takes account of subword structure. The larger the basic effect, the more likely it is that the effect will differ measurably for nonwords with relatively subtle structural differences.

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NOTES

1. For reasons of clarity, many conditions of the two earlier experiments were omitted from the present discussion.

2. The subjects usually reported words as such, rather than reporting individual letters within words, except in cases where they saw too few letters to identify the words. Often, however, they followed their whole-word reports with the information that they had only "seen" certain of the letters; in such cases, only the "seen" letters are scored in the data. The instruction to report only "seen" letters seems to have been taken seriously by at least some subjects, though it clearly cannot be claimed that the instruction eliminated guessing entirely.

3. The transformation used was $\Phi = 2 \arcsin \sqrt{X}$, where $\Phi =$ the transformed score and $X =$ the proportion of letters correct, out of three or seven, on a given trial. However, a value of .999 was substituted whenever the actual X was 1.0. The correction for ceiling effects suggested by Winer was not used, because it depends on the number of observations underlying each proportion, i.e., on the number of letters in each string. This "correction" obscures most length effects in the ANOVA.

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