Lateral masking in visual information processing*

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When unrelated letter strings are presented tachistoscopically, the end letters are reported more often than their neighbors; and when spaces are inserted into strings, performance on certain adjacent letters is superior to performance on those letters when no spaces were present. An experiment was conducted to determine the nature of those spacing effects. Letter strings were presented at a variety of retinal locations, and spaces were inserted into different positions in the instructed left-right processing order. The space effect was unrelated to processing order, but it was dependent on retinal location. To account for the various asymmetries, it was necessary to postulate that letters tend to interact with adjacent letters *and* that the interaction was not spatially symmetric. Furthermore, it was found that spaces had greater effects on "right-hand" letters than on symmetric letters. It was therefore concluded that letters interact at the feature level.

When a string of letters is presented tachistoscopically in the right visual field (RVF), the probability of identifying one of the letters as a function of serial position is usually U-shaped (see, e.g., Estes & Wolford, 1971). Variables which contribute to the correct identification of a letter include retinal location, report order, and the number and position of surrounding letters. The space following the last letter is of particular interest as none of the other three variables predict an upturn at the end of a string in the RVF. Compared to the penultimate letter, the last letter is both further from the center of the fovea and later in the instructed processing and report orders. It is possible that the last letter is aided by the absence of contour interaction on one of its sides.

There is evidence in the literature that the presence of a space in a string can have a marked effect on performance. Shaw (1969) introduced spaces into the middle of letter strings and found that a space which followed a letter in the instructed processing order (postspace) increased performance on that letter. A prespace, however, had little or no effect on the identification of that letter. A question of some importance in the understanding of visual information processing is whether that space effect is sensory in nature (due to lessened contour interaction) or cognitive (based on considerations of processing and memory). Shaw asserted that the asymmetry

implied a cognitive effect because of its relationship to the processing order. In a subsequent experiment to test this hypothesis, black rectangles were inserted into the strings instead of spaces. Shaw reasoned that the rectangles would exert as much sensory masking as letters. The rectangles, however, produced results which were very similar to those produced by spaces, so Shaw concluded that the space effect was not sensory in nature. He outlined a two-stage serial processing model to account for the asymmetry of the effect and the equality of the spaces and rectangles. The first stage of the process moved spatially at a fixed rate and found material for the second stage to identify. The presence of a space or a rectangle gave the second stage additional processing time on the preceding letters.

Townsend, Taylor, and Brown (1971) found a similar asymmetric effect using very long exposure durations (3 sec) while preventing eye movements. If the space effect were merely a matter of gaining additional time for the second stage processor, the space effect should have disappeared with the long exposure durations. Townsend et al proposed lateral masking as the explanation of the space effect. The idea was that letters tend to interact with one another at the sensory level, and the insertion of a space into the string reduces this interaction. They, however, did not deal adequately with the asymmetry of the effect.

The concept of lateral masking has recently come to play an increasingly important role in the theories of investigators working in diverse areas. The concept of lateral masking refers to the reduction in the discriminability of a stimulus due to the presence of an adjacent simultaneous stimulus. A number of tentative facts have begun to emerge about the nature of the proposed lateral masking: (1) A major part of the masking occurs beyond the retinal level (Taylor & Brown, 1972; Toch, 1956; Weisstein & Growney,

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1969). Several investigators have suggested that there may be more than one type of lateral masking: a weak form which occurs peripherally and a stronger form which occurs more centrally (Alpern & Rushton, 1965; Bjork & Estes, 1973; Estes, 1972; Turvey, 1973). (2) In order for masking to occur, the stimuli must be separated by less than 1 deg of visual angle (Collins, 1973; Collins & Eriksen, 1967). And (3) the amount of lateral masking appears to increase with increased distance from the center of the fovea (Estes & Wolford, 1971; Kolers & Rosner, 1960; Matthews, 1973).

The last finding has particular bearing on Shaw's experiments in that the retinal location of a space was confounded with its position in the processing order. A prespace was always nearer the fovea than the letter, and a postspace was further from the fovea. It is possible, therefore, that the asymmetry of the space effect was a function of the retinal location of the spaces rather than the position of the spaces in the processing order. The present experiment was designed to examine the space effect with retinal locus and processing order unconfounded. Conditions were also included to distinguish between various explanations of the asymmetry.

THE EXPERIMENT

The design of the present experiment was an extension of the design developed by Estes and Wolford (1971). Strings of letters were presented at a variety of retinal locations, and Ss were instructed to process and to report the letters in a left-right order. Spaces were introduced either before (prespace) or after (postspace) the fifth letter in the left-right order. As in Shaw's experiment, a postspace was further from the center of the fovea than a prespace when the string was presented in the RVF, but a postspace was nearer to the center of the fovea when the string appeared in the LVF. The experiment differed in at least three important respects from Estes and Wolford (1971): a more balanced design was used; new control conditions were added; and, most importantly, a wider range of the retina was examined.

Method

Subjects and Apparatus. Twenty introductory psychology students from Dartmouth College received course credit for serving as Ss. All had normal or corrected to normal vision, and none wore contacts.

The stimulus materials were presented in a Scientific Prototype three-channel tachistoscope (Model GA) that was modified by the addition of a rapid card changer on one of the channels. Character strings were presented along the horizontal median of a lighted rectangular field which subtended a visual angle of 7.82 deg in width and 1.68 deg in height. One field (the fixation field) contained a circular black fixation point measuring 0.073 deg in diam and centered with respect to the rectangle described above. The luminance of all fields was adjusted to 10.0 fL, as measured with a Macbeth illuminometer. The fixation field was visible at all times except during the presentation of the stimulus field. The total

illumination in the laboratory was provided by two 7-W bulbs that were shielded from S. The verbal responses of the Ss were typed by E into a teletypewriter that was linked with the Dartmouth time-sharing system.

Character strings were typed in Royal Bulletin typeface on white notecards. The characters were 0.29 deg of visual angle in height and 0.14 deg in width. The intercharacter space was 0.073 deg.

Design and Procedure. Twelve nine-letter consonant strings (excluding Y) were generated at random without replacement. Five different display types were used along with five different retinal locations. The display types were named with the fifth letter in the string as a referent. The control displays had all nine letters present. The prespace displays were constructed by removing the third and fourth letters (in a left-right order) from the control displays. The postspace displays were constructed by removing the sixth and seventh letters. The pre-A displays were constructed by replacing the third and fourth letters with As, and the post-A displays replaced the sixth and seventh letters with As.

The purpose of the AA displays was to control for the report order advantage of prespace displays over postspace displays. In the full-report procedure, a prespace moves the fifth letter closer to the beginning of the report order besides possibly reducing the amount of masking on the fifth letter. Such a report order advantage did not exist in Shaw's experiments as he used a detection paradigm. Since Ss were instructed not to report AAs, the pre-A condition provided the same report order advantage as a prespace without affecting the processing or lateral masking of the fifth letters as compared with the control strings.

Each of the five display types crossed with the 12 different strings appeared at five retinal locations. The fifth letters were positioned at -1.90, -0.95, 0, 0.95, or 1.90 deg from the center of the fovea, where negative number refer to positions in the LVF. The factorial combination of the 12 strings, 5 retinal loci, and 5 display types yielded a total of 300 stimulus cards.

A typewritten set of instructions was given to S when he arrived. He was instructed to fixate on the dot in the center of the fixation field. When the dot was in focus, S was to initiate a 200-msec exposure of the stimulus field by depressing a hand-held microswitch. S was to report as many of the letters as possible from each string in a left-right order. It was stressed that he should always try to get the leftmost letter correct. He was instructed to never report any double As, and he was informed that no other vowels would ever be presented. At the end of every 15 trials, S was given feedback on the number of leftmost letters correct and the percentage of correct letters overall. If S missed more than two leftmost letters, he was reminded of the instructions. Five minutes were allowed at the start of each session for dark adaptation, and a session lasted approximately 60 min.

The 300 stimulus cards were randomly permuted. The first 150 cards were shown to the first S and the remaining 150 to the second. The following Ss saw the same permutation in reverse order. The cards were then randomly permuted again for the next series of four Ss.

Results and Discussion

The mean probabilities that the fifth letter was reported correctly in each of the 25 experimental conditions (5 display types by 5 retinal loci) are shown in Fig. 1. The results are averaged across the 20 Ss, and each point is based on 120 observations. Letters did not have to be reported in the correct order to be scored as correct. The fifth letters are of particular interest because they represent the only completely balanced unconfounding of report order and retinal location. The main effect of display type was significant [$F(4,76) = 14.47$, $p < .01$], as was the main effect of retinal locus [$F(4,76) = 9.64$, $p < .01$]. The interaction between these variables was not significant.

The average probabilities of correct responding for all nine string positions are presented in Table 1. The pattern of results in this table was consistent with the pattern found in the fifth-letter data. An analysis similar to one presented by Estes and Wolford (1971, Table 2) was carried out on the full data set to test the relative importance of processing order vs retinal location in determining the effect of the spaces. The results of the analysis are presented in Table 2. The first row of the table represents all of the letters which were followed by a space in the processing order averaged across all string positions, retinal loci, and space conditions. The second row represents all of the letters which were preceded by a space in the processing order. The third row contains those letter

Given the dependence of the space effect on the retinal location of the spaces, it seems reasonable to argue that the effect was the result of sensory processes. The various asymmetries in the data, however, require a rather complicated sensory explanation. There were 10 different space conditions, pre- and postspaces at each of five retinal locations. Only four of those improved performance with respect to the appropriate controls. One common feature of those displays was that the space appeared on the peripheral side of the fifth letter. In both space conditions for the displays at 0 deg, however, the space was on the peripheral side of the fifth letter and

[illegible]

Table 2
Relative Dominance of Retinal Locus Versus Read-Out
Order in Determining the Space Effect

	Position	Per- centage Correct	Difference from Control	Difference/ Maximum Difference
Read-Out Order	Before Space	67.1	12.6	.27
	After Space	39.5	15.2	.20
Retinal Location	Central	60.1	20.0	.33
	Peripheral	46.4	10.8	.17

neither condition led to improved performance. The first ingredient in the sensory explanation, then, is that spaces are more effective in the periphery. Alpern (1953) postulated that there was increased contour interaction in the periphery. A space in the periphery, then, might remove some letters which would otherwise interact with the fifth letter and reduce its discriminability. There are several potential physiological mechanisms for the increased interaction, as receptive fields become larger as you move into the periphery and the amount of neural interaction between retinal receptors also increases.

The hypothesis of increased interaction in the periphery, however, is not sufficient to characterize all of the space effect. Two of the space conditions which were ineffective were actually further into the periphery than two of the effective space conditions. Namely, the postspace at -1.90 deg was less effective than the prespace at -0.95 deg and the prespace at 1.90 deg was less effective than the postspace at 0.95 deg. The retinal ordering of the spaces, then, does not predict their effect. For a space to improve performance on a given letter, the space must be *both* in the periphery *and* on the peripheral side of the letter. One explanation which is consistent with the latter half of the requirement is that the interaction between letters is not symmetric, but that a particular letter receives more masking from letters on its peripheral side. The removal of those letters, therefore, is more beneficial than the removal of the letters on the foveal side. Bouma (1973) postulated a similar asymmetric interaction to account for the identification of end letters in words and nonwords presented at a variety of retinal locations. A possible physiological mechanism for the asymmetric interaction might be increasingly eccentric receptive fields as you move into the periphery.

In review, our proposed explanation of the various space effects observed in our data and elsewhere in the literature is that letters interact with one another and the amount of that interaction is greater in the periphery than in the fovea. Furthermore, the interaction is assumed to be asymmetric. When a space is introduced into a string and that space is both in the periphery and on the peripheral side of a letter, contours are removed which would have interacted with that letter and performance on that letter is

improved compared to performance on a similar letter in a spaceless string.

A possible artifact which was brought to our attention is that Ss might have processed the displays in the LVF in a right-left order and then tried to output them in the instructed left-right order. If this were in fact true, then our data would not contradict Shaw's conclusion that the space effect depends on the processing order. This potential artifact can be rejected on several grounds: (1) The artifact is contrary to subjective reports, and there are several studies in the literature which claim that Ss have a strong bias for processing in a left-right order (Bryden, 1966; Scheerer, 1972; Sperling, 1967). (2) There is no reason why Ss in our study should both disobey direct instructions and also process in an order contrary to their natural bias. (3) There is evidence in our data which argues against the potential artifact. If Ss were trying to process in one direction and output in the other, they would be more likely to make transposition errors than if the processing and report orders coincided. (A transposition error is defined as the output of two or more letters from a string in an incorrect order.) The probability of a transposition error was .26, .34, .37, .27, and .23, respectively, for string positions from -1.90 to 1.90 deg. The effect was significant [$F(94,76) = 9.15$, $p < .01$], but the shape of the function is not consistent with the postulated artifact. To support the artifact, one would predict a monotonically decreasing function rather than the inverted U-shaped function that was obtained.

Some theorists have argued that the processing of letter arrays is not linear, but begins at both ends and moves toward the center of the strings (Merikle, Coltheart, & Lowe, 1971). This view of processing is also inconsistent with the asymmetries found in our results. The spaces in the present experiment were in the middle of the strings, so every string actually had four ends rather than two. The processing model of Merikle et al offered no explanation of why some of the ends but not others would lead to superior performance. Henderson and Park (1973) have also rejected the processing view of Merikle et al for other considerations.

In several of our discussions, we have referred to report order and processing order as two separate entities. There is no question that a describable serial report order exists. Our Ss were quite good at reporting the letters one at a time. It is not at all clear that a processing order exists which is distinct from the report order. In fact, most of the recent models of visual processing have postulated parallel processing. We are considering the possibility of distinct report and processing orders here only to demonstrate that none of the existing processing models appears consistent with the space effects which have been obtained.

Going back to the beginning of the introduction, it seems likely that the upturn of the serial position curve at the end of an unbroken string of letters is closely related to the space effect. Specifically, when a string is presented in the RVF, performance on the last letter is superior to the performance on the penultimate letter even though it is further from the center of the fovea. This upturn is quite consistent with the fact that the last letter has no letters on its periphery and therefore receives less masking than the next to the last letter.

LETTER-TYPE ANALYSIS

Although the preceding explanation does an adequate job of describing the various asymmetries that characterize the space effect (post hoc), it does not offer any explanation of the similarity of spaces and rectangles in their effect on performance. Why isn't a solid black rectangle as masking as a letter? One possible explanation is in terms of a feature detection model. Several investigators have claimed that the initial stage in letter identification is one of feature extraction (e.g., Rumelhart, 1970). These features are presumably extracted by feature detectors similar to the ones studied by Hubel and Wiesel (1965) in their research with cats. One property of these detectors is that for every type of feature detector there is an optimally shaped stimulus which will maximally inhibit that detector. For instance, with a line detector, the optimal inhibitor would probably be an adjacent parallel line or a thin, elongated annulus. In general, large fields of uniform brightness have relatively little effect. At the level of feature detectors, then, black rectangles may produce less inhibition than adjacent letters. Using an analogy from direct masking studies, a black postexposure field would be a much less effective mask than a postexposure field filled with letter pieces.

We, therefore, analyzed this experiment and a related experiment for some evidence that the masking which we are postulating operates at the feature level. To do this, we examined the space effect as a function of the types of letters involved. If we split the letters in half, bilaterally, we can ask the question as to which half of the letter is sufficient for the identification of that letter. For some of the letters, only the right half is sufficient (B, C, E, F, G, and R). For instance, if only the left half were available, F, P, and R would be identical. For another set of letters, either half is sufficient (H, M, Q, T, V, and W). For the remaining letters, the location of the critical features is somewhat ambiguous. We want to determine whether spaces have a different effect on "right-hand" letters vs symmetric letters. The letter classification provided here is based on the type font used in constructing the displays. The classification may not be valid for other type fonts.

We have hypothesized that masking is asymmetric. It also seems reasonable to hypothesize that the amount of interaction produced by a letter diminishes as a function of the distance from that letter. This latter hypothesis is supported by the data in Table 1. Namely, the letters not adjacent to spaces are not aided by the presence of spaces. Given these two assumptions, we would predict that if the masking operates at the subletter (or feature) level, then the space effect might be more pronounced on "right-hand" letters.

The data from the present experiment are not optimal for examining the space effect as a function of letter type, as only 12 different strings were used and letter type was not considered in the construction of the strings. To verify the reliability of any letter type difference, we examined the data from a previous experiment (Wolford & Hollingsworth, 1974), which was run to study confusion errors in the full-report procedure. The basic design of that experiment was to present 320 five-letter strings to a number of Ss. All of the strings were presented in the RVF, beginning at the center of the fovea. Ss were instructed to process and respond in a left-right order. The font and apparatus were identical to those of the present experiment. The superiority of that experiment is that 160 random strings were used and all 20 consonants appeared roughly equally often at each of the five serial positions. The serial position curves, as a function of letter type, are depicted in Fig. 2. As predicted, the space effect was more pronounced for the "right-hand" letters. The upswing (the probability correct at Serial Position 5 minus the probability correct at Position 4) was significantly greater for the "right-hand" letters [$t(4) = 8.78, p < .01$]. We ran a similar test on the individual letters and obtained a $t(10) = 5.08, p < .01$. The latter test has no inferential significance but does indicate that the

Fig. 2. Serial position curves as a function of letter type.

letter-type effect was not confined to a small set of aberrant letters. While these data do not directly resolve the rectangle problem, they are clearly consistent with the idea that lateral masking operates at the feature level.

The letter-type difference found above was then examined in the present experiment to provide semi-independent verification of the asymmetric interaction that was described earlier. Because of the small set of strings, the end positions were more balanced with respect to usable letter types than were the fifth letters. The final upswings (the probability correct on the ninth letter minus the eight) for the strings located at -1.90 and 0.95 deg were examined, because the end letters of these strings were roughly equidistant from the fovea. We predicted that there would be more of an upswing for the right-hand letters, as in the previous analysis, and we also predicted less of an upswing for both types in the LVF because of the assumption of asymmetric masking. Both predictions were borne out. The upswing for the "right-hand" letters went from .14 in the LVF to .25 in the RVF. The upswing for symmetric letters went from $-.03$ to $.01$. Both main effects were significant: letter type, $F(1,19) = 28.06$, $p < .01$; and retinal location, $F(1,19) = 7.61$, $p < .05$. The interaction was not significant. It should be noted that one might expect some upswing in the LVF simply because the ninth letter is closer to the fovea than the eighth letter.

The results of both the space location analysis and letter-type analysis are consistent with a lateral masking interpretation. The magnitude of the space effect was clearly dependent on the relative retinal location of the space and not on the position of the space in the processing order. While Shaw's model makes no explicit prediction about the effect of a space on different letter types, it seems that the assumption of increased processing time would aid both letter types. We find it quite interesting that we were forced to postulate asymmetric masking to account for the various effects and would like to amass more data on the issue. The operation of the space effect at a feature level is quite consistent with most current views of letter identification as a feature extraction process.

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