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Retinal location and string position as important variables in visual information processing*

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Three experiments were conducted to isolate the effects of retinal locus and string position in tachistoscopic letter recognition. Retinal locus proved to be an important variable even when its range was restricted to less than a degree from the center of the fovea. Performance was maximal at the center of the fovea, dropping off rapidly to about 1.5 deg from the center. From that distance on, the decline in performance was quite gradual. String position was also an important factor. Retinal locus and string position interacted in such a way that the end positions were less affected by retinal locus than the middle positions. It was also found that processing order, as distinct from report order, was a significant component of the string position effect.

A number of theorists have recently formulated quantitative models of visual information processing (e.g., Gardner, 1973; Shiffrin & Geisler, 1973). Their models are based on data from detection experiments which have generally either ignored retinal acuity and string position factors or held them constant. While such a strategy may be beneficial in the understanding of some of the perceptual processes involved in visual information processing, it may lead to an incomplete or perhaps misleading view of the letter identification process.

It is a well-established fact that acuity is not constant over the entire retina. Alpern (1962) has shown that performance in a line detection experiment decreased by more than 50% within a degree of the center of the fovea. The precipitous drop in acuity is probably closely related to the corresponding drop in the density of cones (Riggs, 1965). It is unclear, however, what role retinal location plays in the letter-identification process. Several investigators have suggested that retinal locus is not a particularly important variable in the tachistoscopic recognition of letters (Bryden, 1966; Crovitz & Schiffman, 1965; Mathewson, Miller, & Crovitz, 1968). The range of the retina explored in these studies varied across 8 deg from the center of the fovea, which was more than sufficient to span the performance decrement described by Alpern (1962). These investigators have concluded that the position of a letter in the string was the primary determinant of accuracy. Other Es have suggested that retinal location may not be very important by itself, but that it can become important in interaction with string position. Estes and Wolford (1971) and White (1970) have reported that only items in the middle string positions are affected by retinal location.

A major problem in trying to determine the effects of retinal locus and string position is to isolate them from one another properly. A number of factors typically vary with the position of a letter in a string: the report order, the processing order (which may or may not be distinct from report order), the number and position of surrounding letters (the two end letters, for example, are adjacent to only a single other letter), and retinal locus. Most of the experiments cited above exercised little or no control over the report and processing orders. Ss might have begun at the left end of a string, the right end, the middle, or perhaps some mixture, depending upon the location of the fixation point and their own biases. There is also no reason why different Ss should necessarily use the same strategies for a given experiment or condition. Any such mixture of orders would make it virtually impossible to partial our retinal locus from the other variables.

Hershenson (1969) attempted to eliminate processing and report order effects by informing Ss in advance which stimulus would be presented on the next trial and asking them only to report the letters which they actually "saw." The serial position curves in his experiment appeared to be strongly affected by retinal location. It is possible, however, given the nature of the task, that Ss generally reported the letters from the fixation point outward. In this case, it would be impossible to decide whether the shape of the serial position curves was due to the report order,

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Table 1
Sample Displays from Experiment I

-12			-9			-6			-3			0			3...
D	L	N	F	H	J	T	W	R							
	D	L	N	F	H	J	T	W	R						
		D	L	N	F	H	J	T	W	R					
			D	L	N	F	H	J	T	W	R				
				D	L	N	F	H	J	T	W	R			

a drop in retinal acuity, or some combination of the two. The S's task was also somewhat different from the other experiments mentioned, and while quite interesting in its own right, may have reflected different processes from those involved in ordinary letter identification.

Our first experiment examined the effects of retinal locus and string position parametrically. The experiment was designed to unconfound the two variables completely without losing sight of their interaction.

EXPERIMENT I

The basic design of the first experiment was to instruct the Ss to process and to report the letter in a known and consistent order (while monitoring their adherence to the instructions), and to vary the retinal locus of the strings. Retinal location was operationally defined in terms of the position of the string of letters relative to the fixation point, and horizontal arrays of letters were presented at 18 different positions. Ss were instructed to process and to report the letters in a left-right order, trying to get the leftmost letter correct on every trial. A sample of the design is illustrated in Table 1. The numbers refer to typespaces, where negative numbers indicate locations in the left visual field (LVF) and zero indicates the location of the fixation point. Any observed performance variation along a *diagonal* column (the Ds, for example) could only be attributed to retinal location, since all of the items along a diagonal column had the same string position and the same number and position of surrounding letters. Since all of the items in a *vertical* column had the same retinal location, any performance variation within a vertical column would be solely attributable to differences in string position. The design was such that a separate retinal position curve could be constructed for all nine string positions, and a separate string position curve could be constructed for several retinal locations.

Method

Subjects and Apparatus. Twelve introductory psychology students from Dartmouth received course credit for their participation in the experiment. All had normal or corrected-normal vision and none wore contacts.

The stimulus materials were presented in a Scientific Prototype three-channel tachistoscope (Model GA) that was modified with 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 x 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 rectangular field described above. The luminance of the fixation and stimulus fields was set at 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 the S.

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. Thirty nine-letter character strings were generated at random without replacement from the 20 consonants (excluding Y). An entire nine-letter string subtended a visual angle of 1.89 deg. A stimulus card was constructed for each of the 30 strings at each of 18 different retinal locations, making a total of 540 stimuli. The starting position of the strings(the position of the leftmost letter) varied in 18 steps from 12 spaces to the left of the fixation point to 5 spaces to the right. Twelve spaces corresponded to a starting position of 2.63 deg in visual angle from the fixation point. The remaining letters in a string appeared in consecutive typewriter spaces. Since the starting positions were chosen so that there would be a roughly symmetrical distribution of letters in the two visual fields, the optimal place for S to focus in order to maximize overall performance on any given trial was directly on the fixation point. Each S was instructed to begin each trial by focusing on the dot and then to initiate a 200-msec exposure of the stimulus card by depressing a hand-held microswitch. Subsequent to the termination of the display, S was to report orally all of the letters that he could in a left-right order. In order to ensure a left-right processing and report order, S was urged to try to report the leftmost letter correctly on every trial. He was reminded of the instructions if he missed more than two leftmost letters in any 15-trial block. A random one-third of the stimulus cards was presented to each S, and a session lasted approximately 1 h.

Results and Discussion

The probabilities of correct responding for each string position at each retinal location are presented in Table 2. The probabilities are averaged across the 12 Ss, and there are 120 observations per point. Table 2 was constructed by transposing the matrix in Table 1. The first diagonal column from Table 1 appears as the first row in Table 2. The rows, then, running from the top down represent String Positions 1-9, and the vertical columns represent the different retinal locations. An analysis of variance was carried out on the data from the center columns of Table 2.

Table 2
Probabilities of Correct Letter Identification from Experiment I

String Position	Retinal Position																									
	-12	-11	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	13
1	73	84	84	89	90	95	95	96	96	1	99	99	94	95	97	95	89	88								
2		20	18	20	25	25	18	32	42	54	75	90	93	89	77	70	57	50	41							
3			10	09	11	09	14	11	20	31	48	75	86	79	68	54	48	39	28	29						
4				04	14	11	10	12	13	21	33	51	60	44	38	29	22	23	21	23	14					
5					05	12	14	14	16	17	25	30	39	29	14	14	10	14	17	09	14	13				
6						10	09	14	09	16	20	28	32	20	14	09	13	02	10	14	09	08	05			
7							04	05	10	16	12	25	30	14	13	04	05	08	04	08	04	09	04	04		
8								12	10	16	21	30	39	25	13	10	08	04	04	06	02	05	07	09	02	
9									28	40	50	46	49	44	30	20	12	16	15	14	14	14	17	18	19	12

The analysis was restricted to Retinal Locations -4 through +5. These are the only retinal locations represented by all string positions (i.e., the only complete unconfounding of retinal locus and string position). There were, then, 10 retinal loci crossed with 9 string positions. Both main effects were significant: retinal locus [$F(9,99) = 30.32$, $p < .01$] and string position [$F(8,88) = 72.36$, $p < .01$]. The interaction was also significant [$F(72,792) = 4.91$, $p < .01$]. From inspection of Table 2 and the F values, it seems clear that both retinal locus and string position are highly reliable and powerful variables. The strength and reliability of retinal location as a variable is somewhat surprising in that the area of the retina included by Positions -4 through +5 represents less than 1 deg on either side of the center for the fovea. Although the interaction of string position and retinal locus was significant, it was not the major factor in the data as suggested by some of the studies cited in the introduction.

The data were also analyzed breaking down retinal locus into two variables: visual field and distance from the center. This produced a three-factor design: string position (1-9), visual field (left, right), and distance (1-4). The main effect of visual field was not significant [$F(1,11) = 0.15$]. The proportion correct in LVF was 0.40 and in the RVF was 0.39. Visual field did produce a significant interaction with string position [$F(8,88) = 8.39$, $p < .01$]. Distance from the center, string position, and their interaction were all highly significant, as in the previous analysis.

To present the functional nature of the variables more clearly, some of the data from Table 2 have been illustrated in Figs. 1 and 2. Figure 1 illustrates the effect of retinal locus for some of the string positions. With the exception of the first and last position, the data appear quite orderly. All other string positions (including the ones not shown) peak at the center of the fovea and drop rapidly on either side. In addition, the effect of retinal locus at any given string position appears to somewhat level off at about 1.5 deg on either side of the center. Figure 2 illustrates the effect of string position at each of the first few retinal distances from the center. Symmetric distances in the two visual fields (e.g., +1 and -1) have been combined in constructing the figure. This combination seems justified since there was no main effect of visual field or any interaction of visual field and distance. The effect of string position also appears fairly orderly, with a sharp decrease over the first seven positions and a rise over the last two.

As mentioned earlier, there are at least three possible components of the string position effect: report order, processing order, and the number and position of surrounding letters. Wolford and Hollingsworth (1974) examined in detail the effect of varying the number and position of surrounding letters. Their basic finding was that letters tend to mask adjacent letters. Letters which had a space on only one side were subject to less interference and

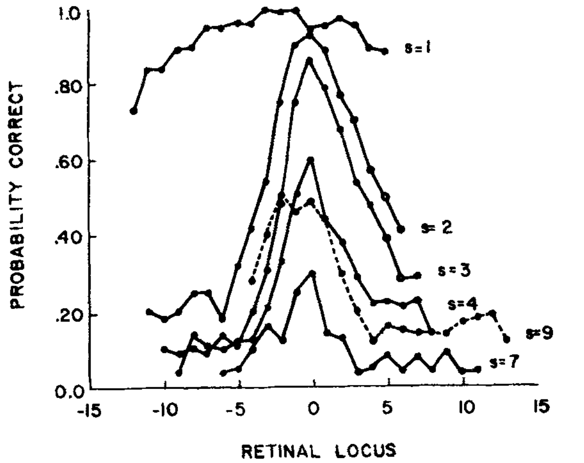

Fig. 1. Performance as a function of retinal locus at each of several string positions (s = 1, . . ., 9).

were, therefore, easier to identify, other things being equal. The lessened interference on the end letters in Experiment 1 undoubtedly contributed to the rise in performance at String Positions 1 and 9. The middle string positions, however, each had a letter on both sides, so variation in performance across the middle positions was primarily a function of report and processing order. It might be noted that if String Positions 1 and 9 are eliminated from the first analysis of variance described above, the interaction disappears, and the two main effects become essentially additive.

In Experiment I, report and processing order were intentionally perfectly correlated. Thus, there was no way of estimating the relative contributions of the two variables. It is possible that there is no such beast as processing order which operates in the absence of report order. In a model where both perceptual (i.e., feature extraction, etc.) and decisional processes occurred in parallel, one would not expect processing

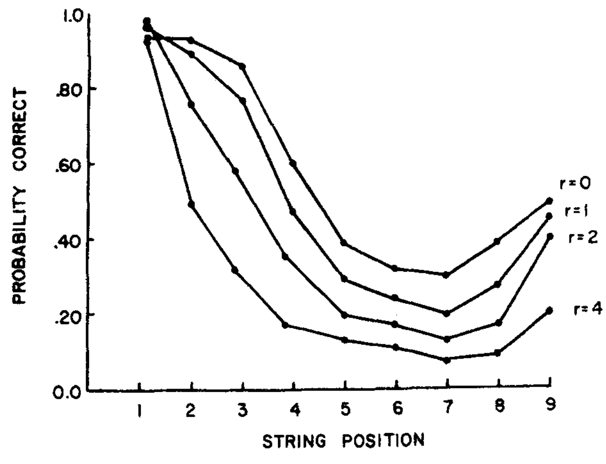

Fig. 2. Performance as a function of string position at each of several retinal loci (r = 0, . . ., 4).

order to be a variable. A model where either the perceptual process or the decision process occurred serially might well predict a processing order effect. The last two experiments were designed to address this issue by varying processing order while holding report order and retinal location constant.

EXPERIMENT II

The design of the second experiment is illustrated in Table 3. The Ss were informed at the start of each trial which direction to process the next string in. The first letter in the instructed processing order was repeated elsewhere in the string. The S's task was to report the first letter in the string and the letter subsequent to the repetition of the first letter. The correct response for all of the strings in Table 3 is ML. The distance between the two occurrences of the repeated letter was varied, and the target letter appeared at the same distance from the center of the fovea in all conditions. Thus, the report order and the retinal locus of the target letters were held constant, and only the processing order was free to vary. In addition, all target letters had at least one letter on each side to prevent the unmasking effects described earlier. With this design, it was very difficult for Ss to respond correctly unless the string was processed in the instructed order.

Table 3
Sample Display Types from Experiment II

DIST	Retinal Locus −7	−6	−5	−4	−3	−2	−1	0	1	2	3	4	5	6	7
Left-Right															
1									M	M	L	R	G	F	
2								M	G	M	L	R	F		
3							M	R	G	M	L	F			
1			M	M	L	R	G	F							
2		M	G	M	L	R	F								
3	M	G	R	M	L	F									
Right-Left															
1								F	R	G	L	M	M		
2									F	R	L	M	G	M	
3										F	L	M	R	G	M
1		F	R	G	L	M	M								
2			F	R	L	M	G	M							
3				F	L	M	R	G	M						

Method

Subjects and Apparatus. Fifteen Ss who met the same qualifications as those in Experiment I were used. The apparatus was identical to that used in the first experiment, except that E entered the verbal responses of the Ss into a portable Teletype which was connected to a time-sharing system.

Design and Procedure. Each of 144 target strings was made up of four primary letters, M, G, L, and R, plus a random filler consonant at the end of the string. The primary letter that appeared at the beginning of the string was repeated at another location in the string. The primary letter which followed the repeated letter in the instructed processing order was referred to as the target letter. Half of the strings were constructed with the target at Retinal Locus -3 (0.63 deg to the left of the fixation point) and half with the target letter at +3. In addition, half of the strings had the initial letter at the right end of the string and half at the left end. For each of the above combinations, the number of letters intervening between the two occurrences of the repeated letter varied from 0 to 2. Thus, there were 12 experimental conditions (2 visual fields, 2 processing directions, and 3 processing distances). For each of the 12 conditions, each of the 12 possible combinations of the four primary letters as repeated and target letters was used, yielding a total of 144 strings.

E began each trial by instructing S to process the forthcoming array in either an "inside-out" or an "outside-in" order. The "inside-out" instruction meant for S to begin processing at the fixation point and to work outward. Thus, S was to process in a right-left order if the string appeared in the LVF, and in a left-right order if the string appeared in the RVF. The opposite was, of course, true for the "outside-in" instruction. The advantage of these instructions over simply asking Ss to process the strings in a left-right or right-left order is that it would have been to S's advantage with the latter instructions to bias his fixation to one side or the other depending on the instructed order. With the instructions used, however, the optimal place to fixate was directly on the fixation point.

After receiving the processing order instruction, S brought the fixation point into focus and initiated a 200-msec exposure of the string by pressing a hand-held microswitch. S's task was to report both the initial letter as well as the letter following the repetition of the initial letter in the instructed processing order. S was informed that only four letters were possibly correct, and that the target letter was never the same as the initial letter. Thus, given that the initial letter was reported correctly, the probability of a correct guess was 0.33. S was given feedback regarding his performance on both letters after every 24 trials. A session lasted about 75 min.

Results and Discussion

The primary dependent measure in this experiment was the performance on the target letters. The identification of the initial letters was to insure that the Ss were processing in the instructed direction. The overall probability of correctly identifying the initial letter was 97%. Those trials on which the initial letter was not correctly identified were deleted from further analysis. The conditional probabilities of correct responding on the target letters for each of the 12 conditions are presented in Fig. 3. The main effect of processing distance was significant [$F(2,28) = 31.12$, $p < .01$]; the main effect of visual field was significant [$F(1,14) = 170.51$, $p < .01$]; and three of the interactions were also significant at the .01 level (Visual Field by Processing Distance, Processing Distance by Processing Order, and the three-way interaction).

Of primary interst is the fairly sharp drop in performance with increasing processing distance. It would appear that processing distance can be an important variable even in the absence of report order and retinal location. In this experiment, performance was clearly superior in the right visual field. A major component of the significant interactions was the flatness of the processing function for the right-left direction in the left visual field. It should be noted that Ss found this experiment quite demanding and all three points on the troublesome function are quite close to the chance value of 0.33. The flatness of the function, therefore, may be due to somewhat of a floor effect.

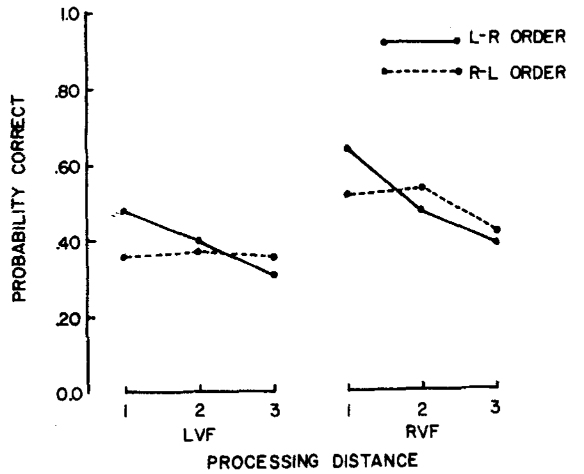

Fig. 3. Performance for each of the 12 conditions in Experiment II. Chance ≅ .33.

EXPERIMENT III

The purposes of the third experiment were to examine the effect of processing order with report order held constant in a somewhat less demanding task, and to look at the interaction between retinal locus and processing order. The design is quite similar to the one used in Experiment I. Nine-letter strings were presented at a variety of retinal locations, and Ss were instructed always to process the strings in a left-right order. A modified detection task was used in which S had to identify two target letters on each trial, and the distance between the two target letters was varied in the string. Thus, processing order and retinal locus were unconfounded as in the first experiment, and report order was held constant with the use of the detection task. Due to the difficulty in obtaining stable proportion data in a detection task with such a large number of conditions, latencies served as the primary dependent variable, and an attempt was made to keep accuracy uniformly high.

Method

Subjects and Apparatus. Six students from the introductory psychology course participated in six sessions each. The apparatus was modified by the addition of a four-button response panel at the S's station. The panel was connected to an array of lights visible only to E. A keypress lit the corresponding light and stopped a digital latency timer. A fifth key on the S's panel initiated the tachistoscopic exposure and started the latency timer.

Design and Procedure. Two hundred and forty stimulus cards were prepared. Each contained a nine-letter string of consonants. The first letter in each string was F, and the second letter (which was always the initial target letter) was D on half of the cards or R on the other half. In addition, each string contained one of two primary target letters (M or K) at one of the position, 3 through 8, inclusive. The ninth position and all remaining positions were filled with Fs. The strings were typed on the cards such that the leftmost letters varied in retinal location from -9 through 0 spaces from the fixation point. This caused the primary target letters to vary from Position -7 to Position +7, depending on the position of the primary target in the processing order. The factorial combination of the 10 retinal locations (-9 through 0), 6 processing distances (0 through 5 intervening letters between the initial target letter and the primary target letter), 2 initial target letters (D or M), and 2 primary target letters (K or M) produced the 240 stimulus conditions.

At the beginning of each trial, S was instructed to focus on the fixation point and then to initiate a 150-msec exposure of the display by pressing the start button on his panel. There was a single response key for each of the four possible combinations of initial and primary target letters, and S was instructed to depress the appropriate key as rapidly as possible while maintaining high accuracy. The S's response and reaction time (accurate to 1 msec) were typed by E into a Teletype that was linked with a time-sharing computer system. Each S participated in five sessions on consecutive days, and a new random permutation of the 240 cards was prepared prior to each session. Although S was not so informed, the data for the first session were treated as practice and were not included in the final analyses. Feedback regarding accuracy and latency was provided after every 20 trials. S was instructed to try especially to always get the initial target correct, and he was reminded of this instruction if he missed any during a 20-trial block. The emphasis on the initial target was intended to insure a left-right processing order.

Results and Discussion

In order to preserve the proper counterbalancing, the analyses have been restricted to those displays in which the target appeared in Retinal Loci -2 through +2. These were the only loci represented by all six processing orders. The mean overall probability of identifying the initial target was 0.93. Those trials on which the initial target was missed were deleted, since they may have represented failures on the part of the Ss to process in the instructed direction. The probabilities of correctly identifying the primary target, given that the initial target was correct, are shown in Tables 4 and 5. As desired, these proportions were uniformly high. An analysis of variance on the proportions (five retinal loci by six processing orders) revealed that none of the effects even approached significance. The latencies for the correct responses are also shown in Tables 4 and 5. An analysis of variance on the latencies revealed that the main effect of retinal locus was significant [$F(4,20) = 2.97$, $p < .05$], and the main effect of processing distance was also significant [$F(5,25) = 9.37$, $p < .01$]. A linear trend test on the main effect of

Table 4
Performance as a Function of Retinal Locus in Experiment III

	Retinal Locus				
Measure	−2	−1	0	1	2
Proportions	96	97	98	94	93
Latencies (msec)	893	868	850	834	843

Table 5
Performance as a Function of Processing Order in Experiment III

	Processing Order					
Measure	1	2	3	4	5	6
Proportions	96	97	95	96	96	94
Latencies (msec)	818	835	844	848	879	921

processing led to an $F(1,25) = 14.80$, $p < .01$, and accounted for 90% of the variance attributed to the processing effect. The interaction of retinal locus and processing distance was not significant [$F(20,100) = 0.86$]. There was no significant effect of days. Because latencies often violate the assumption of normality, analyses were also carried out on both the log latencies as well as on the latencies corrected for guessing (see Wolford, Wessel, & Estes, 1968). The patterns of results from these two analyses were identical to the ones reported for the raw latencies and are, therefore, not reported in detail.

As in the first experiment, then, both string position and retinal locus were important variables. Processing distance was the major component of the string position effect, since both retinal location and report order were controlled. The retinal location effect was significant, even though the area of the retina utilized by the targets from -2 through +2 represented less than 0.50 deg on either side of the center of the fovea.

An analysis of variance was also carried out with retinal location broken down into visual field and distance from the center. (Retinal Locus 0 was omitted from the anlysis). The mean latency was lower in the RVF (839 msec) than in the LVF (881 msec), but the effect was not significant [$F(1,5) = 4.76$, $p = .08$]. None of the interactions involving visual field even approached significance.

GENERAL DISCUSSION

The results from Experiments I and III indicate quite clearly that retinal locus can play a major role in visual information processing even in quite narrow ranges around the center of the fovea. String position was also a powerful variable in all three studies. The evidence concerning the components of the string position effect was quite interesting. The number and position of surrounding letters clearly influenced string position in Experiment I. When the analysis was limited to the middle positions, the interaction between retinal locus and string position disappeared. In a similar fashion, in Experiment III, where all targets had at least one letter on each side, there was no interaction between the two variables. It would appear that retinal locus is more effective when the letter in question is embedded in other letters. From the results of Experiments II and III, it seems that processing distance is an important component of the string position effect. It is not clear from the present data whether processing distance alone is sufficient to explain performance on the middle string positions in Experiment I or whether report order adds to that effect.

There were some rather interesting visual field effects in the three experiments. In Experiment I, there was no significant overall field effect. The mean probability of a correct identification for Positions -1 to -4 was 0.40, and for Positions +1 to +4 was 0.39. As is apparent in Table 2, however, the effect of visual field interacted with string position. The left visual field was superior for the end positions and the right field was superior for the middle ones. In both Experiments II and III, the right visual field was superior (although not significant in Experiment III). Thus, the possibility exists that the right visual field becomes superior when the processing demands are heavy.

Retinal locus was an important variable in the preceding experiments, unlike some earlier studies which were cited in the introduction. We believe that the primary cause of the discrepancy was the failure of the earlier studies to exercise control over processing order and spacing effects. When no control over those variables is exercised, it is not possible to accurately isolate the effect of retinal locus. Based on the present data, it would appear that models of the letter-identification process will have to include retinal locus and processing order as significant variables in order to be comprehensive.

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