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How Crowding Affects Letter Confusion

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ABSTRACT: *Background:* Acuity for letter recognition is known to be worse when multiple letters are presented with narrow interletter spacings than with wide spacings. How would interletter spacing affect the kind of errors made by human subjects? *Methods:* Five-letter strings that were randomly drawn from the 26 uppercase letters of the English alphabet were presented foveally to the subjects. The interletter spacings were 1.0 and 0.1 letter height. Letter confusion matrices were constructed from the data collected using these spacing conditions. *Results:* Narrow- and wide-spacing letter strings produced different letter confusion matrices. Aside from the letter confusions that were shared by both wide- and narrow-spacing strings, narrow-spacing strings produced more random confusions and a set of unique letter confusions, which was not observed under the wide-spacing condition. *Conclusion:* Increased random guessing and lateral interactions between features of neighboring letters can account for most of the acuity deterioration observed under the narrow-spacing condition. (Optom Vis Sci 2001;78:50–55)

Key Words: letter acuity, letter confusion, crowding, lateral interaction

Reduced letter legibility in the presence of other letters or features is an example of what has come to be known as "the crowding effect."[1] In most of the psychophysical studies of this phenomenon, the number of errors made in recognizing the target letters was taken as the measure of the effect of the flanking features. Although this method has been producing useful information about many aspects of the crowding effect, it does lack specificity on the origin of the errors. The type of errors made under a crowded condition may reveal the type of interactions between letters.

One way to analyze errors in a letter recognition task is to construct a letter confusion matrix (LCM). The (ι,ϕ) cell of a LCM contains the probability of the event that the ιth letter in the alphabet is named when the ϕth letter is actually presented. Entries on the main diagonal line of a LCM represent correct responses. Off-diagonal entries are errors or confusions. Although LCM has been a tool used in many studies and LCM's for uppercase English letters are readily available, these LCM's were invariably obtained using single letters and, in most cases, using tachistoscopic displays.[2–5] Therefore, the question of letter confusion under spatial crowding conditions has not been addressed. In this study, we obtained LCM's for letter strings of wide and narrow interletter spacings. Analysis of these LCM's revealed that the higher error rate observed under the narrow-spacing condition was due to an increase in random guessing and the occurrence of a set of letter confusions that was not observed under the wide-spacing condition.

METHODS

Stimuli

The stimuli used in our experiments were five-letter strings that were randomly drawn (with replacement) from the 26 uppercase letters of the English alphabet. The letters were constructed to the specifications of and contained the Sloan letters. The overall width and height of these letters were five times the width of the strokes.[6] The font design language METAFONT[7] was used to generate these letters. This set of letters is shown in Fig. 1a.

We compared letter confusions obtained at wide (1.0 letter height) and narrow (0.1 letter height) interletter spacings. Fig. 1b shows examples of letter strings with wide and narrow spacings. The angular width of a stroke is equal to the minimum angle of resolution (MAR) at visual acuity. Therefore, 1.0 letter height and 0.1 letter height are equal to 5 MAR and 0.5 MAR, respectively. One letter height separation represented an interaction-free condition. It is the interletter spacing recommended for well-designed visual acuity charts.[8, 9] On the other hand, 0.1 letter height spacing represented a strong lateral interaction condition.[10, 11] The five-letter strings were balanced so that each of the 26 letters was presented a total of 50 times for each observer at each interletter spacing. The letters were also balanced with respect to positions in the letter string so that each letter would appear 10 times at each of the five positions. This allowed us to assess positional effects quantitatively. Each interletter spacing condition was tested with a total of 260 random five-letter strings (1300 letters), which was broken into five balanced sessions.

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

(a)

XNJGH
0.1 letter height spacing

B V E W Z
1 letter height spacing

(b)

FIGURE 1.
a: The font used in our experiments. b: Examples of wide-spacing and narrow-spacing strings.

Apparatus

The letter strings were generated on a Silicon Graphics IRIS computer and were presented on a 15-inch Mitsubishi Diamond Scan color monitor at the highest contrast the monitor could deliver. The luminance of the white background was 88.3 cd/m^2, and the luminance of the dark letter strokes was 2.44 cd/m^2. The experiment was conducted in an otherwise dark room. The display was viewed through a front-surface mirror at an optical distance of 10 m. The letter height was varied so that the overall error rate under the narrow-spacing condition was roughly 50%. The letter height used in the experiments ranged from 3.44 to 4.23 arcmin. A black cardboard mask was set in front of the monitor so that only the central 1° 35′ by 35′ rectangular area was visible to the observer. Chin and head rests were used to stabilize head position.

Procedure

The observers were told that five-letter strings were to be presented on the screen, that all 26 uppercase letters might appear in the strings, and that repetitions of the same letter in a string were possible. They were given ample time to study the letter strings at a close distance before the experiment so that they could become acquainted with the letters to be identified. Observers were instructed to view the string binocularly for as long a period of time as they wanted and to respond by reading aloud exactly five letters. The experimenter typed the observer's responses into the computer. The stimulus letter string was exposed continuously until all five letters were reported. The observers were allowed to correct their responses at any time before the response string was recorded. Unrestricted stimulus duration was used to single out spatial interactions among a string of letters. In early studies of the serial position effect of letter strings, short-stimulus duration was common.[12–15] However, because letter strings occupied an extended area and because the responses to the stimulus involved recognizing and reporting several items, factors such as retinal location, memory capacity, divided attention, and reporting order had to be considered when interpreting short-display results.[16–18] When the observer was allowed to scan the letter string freely, the above factors became less important, and legibility was determined mainly by the spatial interaction among letters. Despite the ample time given to the observers, responses were usually prompt and corrections were seldom made. Stimulus and response strings were compared position by position to determine whether a letter was correctly recognized.

Subjects

Participants, aged 20 to 40 years, included one of the authors (L.L.) and three naive volunteers from the Lighthouse International volunteer pool. All subjects had normal or corrected-to-normal vision. J.A. and L.L. wore distant corrections during the experiments. The experimental protocol of this study was reviewed and approved by the Lighthouse International Human Subjects' Institutional Review Board. Informed consent was obtained from all participants.

RESULTS

Overall Error Rates

Table 1 summarizes the total correct responses of the four observers at two interletter spacings. The wide spacing produced a higher percentage of correct letter recognition than the narrow spacing. Reducing interletter spacing from 1.0 to 0.1 letter height caused a 25 to 46% reduction in correct response, showing a significant crowding effect.

Patterns of Confusion Matrices

The stimulus/response pairs obtained from the experiments were organized into confusion matrices. Fig. 2 shows the group average LCM's for wide-spacing and narrow-spacing conditions. The columns and rows in a LCM represent stimulus and response letters, respectively. The (ι,ϕ) cell of a LCM contains the probability for the event that the ιth letter is given as response when the ϕth letter is presented as stimulus. For example, in the matrix in Fig. 2b, the value 0.23 at the intersection of stimulus letter U and response letter J means that the probability of mistaking a stimulus letter U for a letter J is 0.23. In this paper, a stimulus letter U being confused with a letter J is denoted by U→J. The sum of all entries in each column is 1.0. Discrepancies from 1.0 are due to the round-off errors.

TABLE 1.
Percentage of correct letter recognition under wide and narrow interletter spacing conditions.

Observer	J.A.	K.B.	M.R.	L.L.
Letter size (arcmin)	4.23	3.71	3.71	3.44
Wide (1.0 letter height)	72%	85%	80%	86%
Narrow (0.1 letter height)	43%	60%	54%	40%

Relative Legibility

The diagonal line entries represent the relative legibility of letters. For example, under the narrow-spacing condition (Fig. 2b), the letter T was most legible (0.92); letter A came next (0.81). Letter W was least legible (0.21). Spearman's rank correlation between the diagonal lines of the two LCM's was 0.59, which indicates that relative legibilities under these conditions were correlated ($\alpha \leq 0.01$, two-tailed). Our relative legibilities correlated poorly with most published capital letter relative legibilities.[2, 19–21] The rank order correlation ranged from −0.054 to 0.42, which was not significant. The difference in relative legibility may be attributed to the difference in display methods. The experiments cited above all used tachistoscopic display. The letter sizes were usually several times larger than the subjects' visual acuity threshold. Display duration was reduced until a 25 to 50% correct rate was reached. Legibility, therefore, was likely to be determined by the processing time and by the stimulus energy that could be delivered during the brief display. In our experiments, subjects continuously viewed the display. Letter size and interletter spacing were the stimulus variables we manipulated to bring legibility to a preset level. Therefore, our relative legibilities were more likely to be determined by the optical and neural resolution of the eye and by the spatial interaction among letters. In a recent study, Reich and Bedell[22] measured single-letter relative legibility of a set of letters similar to that used in our experiments (except I). Their foveal relative legibility was very similar to ours obtained under the wide-spacing condition (Spearman's rank correlation 0.807). This is not surprising because both studies used letter sizes near visual acuity and longer stimulus duration.

(a)

RESPONSE \ STIMULUS	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
A	1.0	.00	.00	.00	.00	.00	.01	.00	.00	.00	.01	.00	.00	.00	.00	.00	.00	.01	.00	.00	.00	.00	.00	.03	.00	.00
B	.00	.57	.00	.00	.02	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.04	.00	.00	.00	.02	.00	.00	.00
C	.00	.00	.93	.02	.00	.00	.03	.00	.00	.00	.00	.00	.00	.00	.05	.00	.03	.00	.02	.00	.00	.00	.00	.00	.00	.00
D	.00	.02	.01	.93	.01	.01	.00	.00	.00	.00	.00	.00	.00	.00	.10	.00	.01	.00	.01	.00	.00	.00	.00	.00	.00	.00
E	.00	.03	.01	.00	.92	.01	.00	.00	.00	.00	.01	.00	.01	.00	.00	.00	.00	.00	.07	.00	.00	.00	.00	.00	.00	.00
F	.00	.00	.00	.00	.00	.60	.00	.00	.00	.00	.00	.00	.00	.00	.00	.13	.00	.01	.00	.00	.00	.00	.01	.00	.00	.00
G	.00	.02	.01	.01	.00	.00	.44	.00	.00	.00	.00	.00	.00	.00	.09	.00	.38	.00	.04	.00	.00	.00	.00	.00	.00	.00
H	.00	.01	.00	.00	.00	.00	.00	.90	.00	.00	.00	.00	.01	.00	.00	.00	.00	.02	.00	.00	.00	.00	.01	.00	.00	.00
I	.00	.00	.00	.00	.00	.00	.00	.00	.76	.00	.00	.00	.00	.00	.00	.00	.00	.00	.01	.00	.00	.00	.00	.01	.00	.01
J	.00	.00	.00	.00	.00	.00	.00	.00	.00	1.0	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.01	.00	.00	.01	.00	.00
K	.00	.00	.00	.00	.01	.00	.00	.01	.00	.00	.92	.00	.00	.01	.00	.00	.00	.00	.00	.00	.00	.01	.01	.08	.00	.00
L	.00	.00	.00	.00	.00	.00	.01	.00	.00	.00	.00	1.0	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
M	.00	.00	.00	.00	.00	.00	.00	.02	.00	.00	.00	.00	.77	.00	.00	.00	.00	.01	.00	.00	.00	.00	.06	.00	.00	.00
N	.00	.01	.00	.00	.00	.00	.00	.08	.00	.00	.01	.00	.03	1.0	.00	.00	.00	.02	.00	.00	.01	.00	.07	.00	.00	.00
O	.00	.03	.04	.06	.01	.00	.30	.00	.00	.00	.00	.00	.00	.00	.89	.00	.10	.00	.01	.00	.00	.00	.04	.00	.00	.00
P	.00	.00	.00	.00	.00	.40	.00	.00	.00	.00	.00	.00	.00	.00	.00	.87	.00	.03	.00	.00	.00	.00	.01	.00	.00	.00
Q	.00	.01	.01	.00	.00	.00	.06	.00	.00	.00	.00	.00	.00	.00	.07	.00	.39	.00	.03	.00	.00	.00	.04	.00	.00	.00
R	.00	.06	.00	.00	.01	.00	.01	.00	.00	.00	.04	.00	.00	.00	.00	.00	.00	.92	.02	.00	.00	.00	.13	.01	.00	.00
S	.00	.24	.00	.00	.04	.00	.17	.00	.00	.00	.01	.00	.00	.00	.01	.00	.10	.00	.79	.00	.00	.00	.07	.01	.00	.01
T	.00	.00	.00	.00	.00	.00	.01	.00	.02	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.99	.00	.01	.00	.00	.21	.00
U	.00	.01	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.02	.00	.00	.00	.01	.00	.00	.00	.99	.00	.01	.00	.00	.00
V	.00	.00	.00	.00	.01	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.72	.00	.00	.03	.00
W	.00	.02	.00	.00	.00	.00	.00	.01	.00	.00	.00	.00	.18	.00	.00	.00	.00	.01	.00	.00	.00	.00	.52	.00	.00	.00
X	.00	.01	.00	.00	.00	.00	.00	.00	.01	.00	.03	.00	.00	.00	.00	.00	.00	.00	.01	.00	.00	.01	.03	.87	.01	.00
Y	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.01	.00	.27	.00	.00	.77	.00
Z	.00	.00	.00	.00	.00	.00	.00	.00	.23	.00	.00	.00	.00	.00	.00	.01	.00	.00	.00	.00	.00	.00	.01	.01	.00	.99

(b)

RESPONSE \ STIMULUS	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
A	.81	.00	.00	.00	.01	.01	.03	.02	.01	.01	.07	.01	.03	.03	.01	.01	.01	.02	.01	.00	.03	.01	.04	.10	.00	.00
B	.00	.39	.00	.01	.13	.01	.00	.00	.00	.00	.01	.00	.00	.00	.00	.01	.01	.01	.08	.00	.01	.00	.05	.01	.00	.00
C	.01	.00	.67	.21	.01	.01	.07	.02	.01	.00	.03	.00	.01	.02	.19	.00	.04	.01	.03	.00	.01	.00	.01	.03	.01	.02
D	.00	.01	.01	.36	.02	.00	.01	.01	.03	.00	.01	.00	.00	.02	.07	.00	.01	.01	.02	.00	.01	.00	.00	.02	.00	.03
E	.00	.07	.02	.03	.49	.02	.01	.01	.03	.01	.02	.00	.01	.01	.02	.01	.02	.05	.09	.00	.00	.00	.02	.01	.00	.01
F	.00	.01	.00	.00	.02	.50	.00	.01	.00	.00	.02	.01	.01	.01	.00	.24	.01	.06	.00	.00	.00	.00	.01	.00	.00	.00
G	.00	.02	.05	.02	.01	.01	.30	.00	.01	.00	.00	.01	.00	.00	.09	.00	.22	.00	.07	.00	.00	.01	.00	.01	.00	.01
H	.01	.02	.00	.00	.01	.02	.02	.82	.00	.00	.00	.00	.02	.07	.01	.02	.00	.02	.00	.01	.01	.01	.02	.00	.02	.00
I	.02	.02	.02	.03	.02	.01	.01	.05	.39	.03	.02	.05	.04	.07	.01	.01	.02	.02	.02	.02	.03	.05	.04	.07	.04	.03
J	.03	.01	.01	.00	.00	.00	.01	.02	.01	.74	.02	.03	.02	.02	.01	.01	.01	.01	.00	.00	.23	.01	.00	.01	.01	.01
K	.01	.01	.02	.00	.05	.00	.00	.00	.00	.01	.43	.01	.01	.02	.01	.00	.00	.01	.00	.00	.00	.01	.03	.08	.01	.01
L	.02	.01	.01	.01	.01	.01	.01	.02	.02	.12	.02	.84	.01	.02	.01	.00	.01	.01	.03	.01	.25	.01	.01	.02	.00	.01
M	.00	.09	.00	.00	.03	.01	.02	.02	.00	.00	.01	.00	.81	.05	.00	.01	.04	.02	.03	.00	.01	.00	.21	.01	.00	.01
N	.04	.04	.00	.01	.03	.02	.03	.11	.01	.01	.04	.01	.06	.48	.01	.00	.02	.07	.02	.01	.02	.04	.15	.02	.02	.00
O	.01	.05	.13	.18	.02	.00	.20	.02	.00	.01	.03	.00	.03	.01	.35	.00	.09	.02	.04	.00	.01	.01	.01	.02	.00	.01
P	.01	.02	.00	.01	.01	.36	.00	.02	.00	.00	.03	.00	.00	.02	.01	.66	.01	.19	.03	.00	.00	.00	.03	.01	.02	.00
Q	.00	.08	.03	.04	.00	.00	.15	.01	.01	.00	.01	.00	.01	.01	.16	.00	.36	.01	.07	.00	.01	.00	.01	.00	.00	.02
R	.00	.04	.00	.00	.01	.02	.01	.00	.01	.00	.07	.00	.01	.02	.01	.01	.02	.36	.01	.01	.00	.00	.07	.02	.00	.00
S	.01	.11	.01	.01	.09	.00	.07	.00	.01	.01	.01	.00	.02	.01	.03	.02	.06	.02	.36	.00	.01	.02	.03	.02	.01	.01
T	.00	.01	.00	.01	.01	.02	.00	.02	.12	.01	.01	.00	.00	.01	.00	.01	.00	.03	.01	.92	.01	.01	.01	.03	.33	.01
U	.01	.00	.01	.03	.00	.00	.00	.03	.01	.05	.05	.04	.02	.03	.00	.01	.01	.01	.01	.00	.34	.01	.00	.03	.00	.00
V	.01	.00	.00	.01	.00	.00	.01	.01	.06	.02	.01	.00	.02	.02	.01	.00	.01	.01	.00	.00	.05	.56	.03	.02	.06	.01
W	.00	.01	.00	.00	.01	.00	.01	.01	.00	.00	.01	.00	.07	.02	.00	.00	.00	.00	.01	.00	.00	.00	.21	.00	.00	.00
X	.00	.01	.01	.02	.02	.00	.01	.01	.04	.01	.08	.00	.00	.01	.01	.01	.01	.01	.03	.00	.01	.03	.02	.42	.01	.00
Y	.01	.00	.01	.00	.00	.01	.02	.01	.00	.00	.01	.00	.00	.01	.00	.01	.00	.02	.00	.04	.00	.22	.02	.03	.48	.00
Z	.01	.01	.01	.01	.01	.00	.01	.01	.23	.00	.02	.00	.00	.02	.01	.00	.03	.03	.04	.00	.00	.00	.01	.03	.00	.80

STIMULUS

FIGURE 2.

Group average letter confusion matrices obtained under wide-spacing (a) and narrow-spacing (b) conditions. Each cell contains the probability of the occurrence of the corresponding confusion.

Categorizing Confusions

A large off-diagonal entry in a LCM represents a consistent confusion between two letters. It may suggest a high similarity between the two letters or, in the case of narrow spacing, a stable lateral interaction among neighboring letters. Examples of such high probability confusions in Fig. 2b are F→P (0.36), Y→T (0.33), and U→L (0.25). There are, however, many small off-diagonal entries that are likely to be the result of random guesses subjects gave when the letters became too difficult to identify. In early studies of letter legibility and confusion, misreadings that occurred less frequently than 5% of the total errors were considered scattering errors and were assigned no significance.[20, 23] We used a more vigorous statistical test to classify random confusions. We compared a probability that indicated a random selection of incorrect letters, which was $p_0 = 1/25$, with the measured relative frequency of each confusion, excluding the correct recognition. Specifically, assume that the ith letter was presented N times and it was correctly recognized C_i times. If the confusion between this letter and the jth letter occurred n_{ij} times, then the relative frequency $p_{ij} = n_{ij}/(N - C_i)$. In the case where $C_i = N$, the relative frequency p_{ij} was assigned the value 0. A z-test was used to test the hypothesis that $p_{ij} = p_0$ ($\alpha = 0.05$). This procedure was applied to every entry in an empirical LCM to identify which entries were likely to be the results of random guessing.

Consistent confusions were further categorized according to whether they occurred under both narrow- and wide-spacing conditions or only under one spacing condition. Thus, we divided observed confusions into three categories:

1. *Common confusions*: Statistically significant confusions that were common to both wide and narrow letter spacings. Examples of such confusions are F→P and Y→T.
2. *Unique confusions*: Statistically significant confusions that occurred only at one letter spacing but not the other. Examples of such confusions are U→L and J→L for the narrow letter spacings.
3. *Random confusions*: Statistically insignificant confusions that occurred because of random guessing.

Each empirical confusion matrix was parsed into three matrices according to the criteria set above. The following discussion was based on these common confusion, unique confusion, and random confusion matrices. Fig. 3 shows the relative contribution of these three categories of confusions to the total errors committed under each condition. Light gray, midgray, and dark gray bars represent the percentage contribution of common confusions, unique confusions, and random confusions, respectively. Fig. 3 reveals that different interletter spacings produced different distributions of the three categories of confusions. For each interletter spacing, however, the distribution of the three categories was rather consistent across observers. Under the narrow-spacing condition (Fig.

3a), each category contributed about one-third of the total confusions (36% ± 7%, 35% ± 8%, and 29% ± 2% for random, unique, and common confusions, respectively). Under the wide-spacing condition (Fig. 3b), 70% (±11%) of the total confusions were common to both spacing conditions. The other two categories made equal contributions (14% ± 4% and 16% ± 8% for random and unique confusions, respectively) to the total error.

The larger proportion of random confusions under the narrow-spacing condition indicated an increase in random guessing, which might reflect a general deterioration of legibility. Another source of random confusions was position exchanges. We observed that sometimes two neighboring letters were correctly identified, but their positions in the string were swapped. Because responses were scored position by position, such position exchanges resulted in random confusions.

Under the wide-spacing condition, the numbers of random confusions and unique confusions were small. On average, 35 random confusions and 41 unique confusions were made in every LCM (1300 letters presented). The majority of the consistent confusions observed in the wide-spacing LCM's could find their counterparts in the narrow-spacing LCM's (common confusions, 166 per LCM). When interletter spacing was narrow, the total number of confusions increased greatly, from 244 per LCM to 662 per LCM. However, the increase in common confusions was small, from 166 per LCM to 190 per LCM. In comparison, the increases in the numbers of random confusions and unique confusions were much larger. Random errors increased from 35 per LCM to 239 per LCM. Unique confusions increased from an average of 41 per LCM to 233 per LCM. Therefore, the increase in the error rate due to the narrowing of interletter spacing could be accounted for by a sharp increase in the number of random confusions and in the number of confusions that did not occur under the wide-condition.

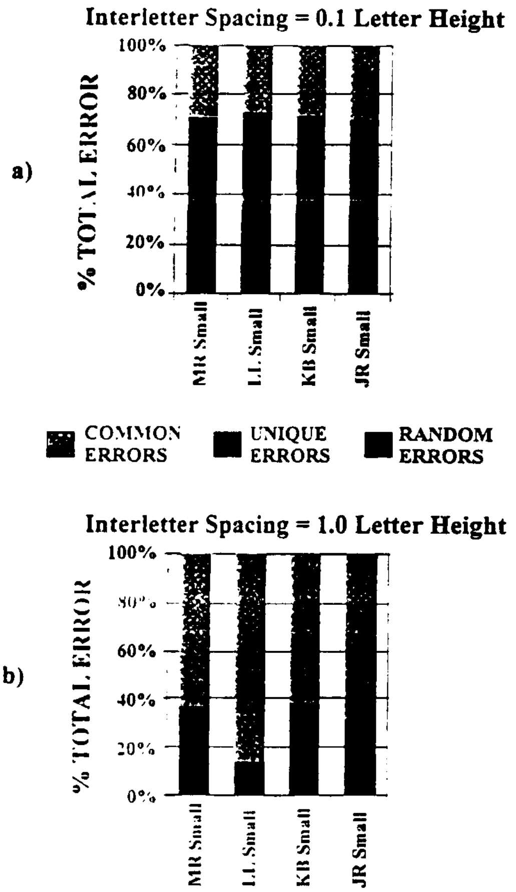

FIGURE 3.
Relative contribution of the three categories of confusions to the total error committed under wide- and narrow-spacing conditions. Light gray, mid-gray, and dark gray bars represent the percentage contribution of common errors, unique errors, and noise to the total error.

Prominent Confusions

The frequencies of the occurrences of confusions were examined. Each empirical LCM was first parsed into common confusion, unique confusion, and random confusion matrices. Then corresponding matrices from all observers were pooled together to form category matrices. Because of the parsing of confusions, some prominent confusions in the overall LCM's (Fig. 2a,b) may become less prominent in one or the other category matrices. Most confusions found in the wide-spacing LCM could also be found in the narrow-spacing LCM (common confusions). The most prominent of those were F→P (79), Q→G (76), G→O (59), V→Y (54), I→Z(44), and Y→T (41). The numbers in parenthesis are the number of times a given confusion occurred during a total of 200 presentations of the stimulus letter (pooled from four subjects). When the spacing was narrow, the most prominent common confusions were F→P (74), Y→T (70), V→Y (46), Q→G (46), G→O (40), and I→Z (40). The prominent common confusions are quite similar under the two spacing conditions. These common confusions differ from previously reported single-letter confusions. Confusions Q→G, F→P and G→O are among the top 10 confusions in Loomis' LCM.[5] Confusions Q→G and G→O make the top 20 list of Townsend's[2] LCM, but F→P does not.

The most prominent unique confusions observed under the narrow-spacing condition were U→L (52), U→J (47), D→C (43), R→P (28), J→L (26), and E→B (25). These confusions represented a set of consistent errors caused by the interactions between closely packed letters. They either did not occur or occurred only with very low probabilities (0.01 to 0.04) in Loomis'[5] and Townsend's[2] single-letter confusion matrices.

Positional Difference

Fig. 4 shows the distribution of errors at the five positions of a letter string. The hollow bars and the solid bars are percentage errors under wide and narrow interletter spacing conditions, respectively. Under the wide-spacing condition, the error rates were similar at all five positions of the letter string. Under the narrow-spacing condition, however, the error rates at the middle three positions were much higher than the error rates at the first and the last positions, indicating much more severe lateral interaction among interior letters. The inverted U-shaped serial position functions were commonly found in previous investigations of lateral masking.[2, 12–15, 24] In these studies, the letter strings were usually presented tachistoscopically on the horizontal meridian of the visual field, with one end of the strings farther away from the fovea than the other. The observed serial position functions were usually skewed because the positional effect was entangled with factors such as report sequence, attention window span, and retinal nonuniformity. In our experiments, the observers used foveal vision to discern the letter at each position, and they were given ample time to make responses; thus, the above confounding factors were eliminated. The symmetric functions in Fig. 4, therefore, represent the pure spatial positional effect.

Under the wide-spacing condition, the correlation among confusion entries (not including diagonal line entries) of the left, right, and middle three positions ranged from 0.76 to 0.90. The high correlation suggests that all positions of a widely spaced letter string have not only the same error rate but also similar letter confusions. Under the narrow-spacing condition, the correlation among the end positions and the interior positions was lower (0.54 to 0.65). This suggests that different letter confusions occur at these positions. Finally, corresponding positions of narrow-spacing strings and wide-spacing strings are also somewhat different (correlations 0.57 to 0.69). The most prominent positional specific confusions were U→L and U→J. These confusions never occurred under the wide-spacing condition regardless of position. Both confusions occurred in the interior positions of narrow-spacing strings (probability 0.29 and 0.18). Confusion U→L occurred at the first position of a narrow-spacing string (probability 0.4), but not the last position. Confusion U→J occurred at the last position (probability 0.58), but not the first position. These positional-specific letter confusions suggested that part of a letter was either suppressed by its neighbor or grouped with its neighbor.

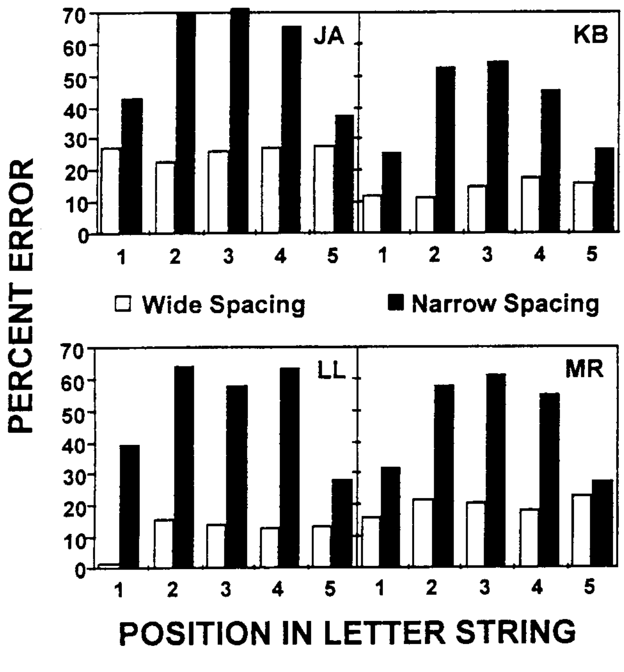

FIGURE 4.
Positional effect. The hollow bars and the solid bars represent the percentage errors committed at each of the five positions of a letter string with wide and narrow interletter spacings, respectively.

DISCUSSION

In this study, we compared letter confusion matrices obtained under wide and narrow interletter spacing conditions. Our analysis revealed that letter confusions were both quantitatively and qualitatively different under these conditions. The deterioration of legibility during the narrow-spacing condition could be attributed to an increase in random errors and to the occurrence of a set of letter confusions that was not observed under the wide-spacing condition (unique confusions).

In many of these unique confusion pairs, the response letters happen to be the stimulus letters minus some parts, the most obvious ones being U→J and U→L. Because our subjects could inspect the letters as long as they wanted, it was unlikely that the missing limbs were caused by limited processing time or limited memory capacity. Wolford and Hollingsworth[15] found that recognition of a peripherally presented test letter was impaired when it was embedded in a string of letters. Changing the two letters on the right side of the test letter to blanks improved recognition of the "right-hand" letters (B, C, E, F, G, R) more than other letters. It is possible that lateral inhibitions between neighboring letters suppressed the limbs so that they could not reach the level of decision making. It is also possible that the limbs did survive early neural interactions between neighboring features, but they were grouped with the wrong letter due to the uncertainty about the borders between neighboring letters. Our experiments were not capable of distinguishing these explanations because the combinations of 26 uppercase letters produced too many interaction patterns. An experiment that uses a small set of specially designed stimulus figures may help to pinpoint the level of feature interaction.

An important difference between previously published LCM's and our LCM's is that the triangular matrices above and below the main diagonal line are usually symmetric in previously published LCM's, but they are not in our LCM's. The asymmetry is most obvious in the matrix obtained under the narrow-spacing condition (Fig. 2b). For example, the probability of the confusion U→J is 0.23, but the probability of J→U is 0.05. This difference can be best explained by the difference in the stimuli and the difference in the purpose of the studies. Previously published LCM's were invariably single-letter confusion matrices[2–5, 22]; that is, one stimulus letter was presented and one response letter was taken. The purpose of these studies was to determine the subjective similarity among a given set of letters. Although all published empirical capital letter confusion matrices were not symmetric, there was a strong belief that they should be because the subjective similarity between a pair of letters should be the same, no matter which letter was presented as the stimulus. The common approach in handling the asymmetry of empirical LCM's was to either symmetrize a matrix by taking a simple average of each pair of entries that were symmetric to the main diagonal line[5, 22] or to parse the matrix into a symmetric similarity matrix and a set of response biases using Luce's choice model.[2, 4, 25] The purpose of our study was to demonstrate how lateral interaction among a string of letters may affect letter confusion. In a string of letters, not only the similarity between letters, but also the interaction between a letter and its neighbors determines the response. If, for example, the interaction is inhibitory in nature, then it is easy to imagine that a stimulus letter

U may appear as a J because its left limb is suppressed by its neighbor on the left. It is not obvious, however, how a stimulus letter J can appear as a U if the interaction between J and its neighbors is still inhibitory. Therefore, the basis for symmetrizing an empirical LCM simply does not exist for a letter string stimulus. Although we don't yet know the true nature of the lateral interaction among letters, we should not expect a symmetric LCM in the presence of strong lateral interaction.

In normal foveal vision, both smaller letter size and narrower interletter spacing can reduce legibility. The question is, do these two factors reduce legibility in the similar way? In other words, will smaller font size, widely separated strings produce the same confusion matrices as larger font size, narrowly separated strings? Our analysis demonstrates that our narrow-spacing letter string confusion matrix has a different structure from the structures of other published confusion matrices. The presence of the prominent unique confusions, for example, has not been observed in any other confusion matrices. This suggests that narrowing interletter spacing reduces legibility in a manner that is different from shortening stimulus duration or reducing letter size. In a pilot study,[26] we obtained LCM's using two letter sizes and two interletter spacings. It seemed that interletter spacing had a more dominant role in determining the confusion matrix. However, because we did not match the overall error rates between smaller font size, widely separated strings and larger font size, narrowly separated strings, the result was not conclusive. We are currently conducting more experiments to address this issue.

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