PERGAMON

Vision Research 40 (2000) 1059–1067

Vision Research

www.elsevier.com/locate/visres

Apparent string shortening concomitant with letter crowding

L. Liu *, A. Arditi

Arlene R. Gordon Research Institute of Lighthouse International, 111 East 59th Street, New York, NY 10022-1202, USA

Received 17 May 1999; received in revised form 15 November 1999

Abstract

In our previous studies of the crowding effect, we have observed that human observers tend to underestimate the length of a letter string (the number of letters in the string) when the letters are close to visual acuity, and the interletter spacings are small. In this study, we asked our observers to identify letters in randomly presented four-letter and five-letter strings. We found that, when a priori knowledge of the lengths of letter strings was not available, the probability of underestimating string length increased with decreasing interletter spacing. The causes of underestimation errors appeared to be the omission of an interior letter and the merging of two neighboring letters. Since our experiments were conducted in the foveal region, neither spatial uncertainty nor split attention can explain the underestimation errors. The effect of the point spread function of the eye on closely packed letter strings is discussed. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Acuity; Crowding; Reading

1. Introduction

Closely packed small letters are much harder to read compared to the same letters presented in isolation. Various aspects of this so-called 'crowding effect' have been the focus of many recent studies. The effects of interletter spacing, letter size, letter contrast, stroke width, letter aspect ratio, presentation duration and retinal location on legibility have been evaluated (Flom, Weymouth & Kahneman, 1963; Bouma, 1970; Whittaker, Rohrkaste & Higgins, 1989; Kothe & Regan, 1990; Arditi, Cagenello & Jacobs, 1995). Lateral inhibition, masking, inaccurate eye movements and divided attention have been suggested as potential causes of the crowding effect (Stuart & Burian, 1962; Townsend, Taylor & Brown, 1971; Estes, Allmeyer & Reder, 1976; Flom, 1991; Arditi, 1994).

Most of our knowledge about the crowding effect has been obtained from letter identification experiments where the observer either knew which letter in the display was the target or knew how many letters they were supposed to report from a stimulus string. One of the advantages of this method is that it allows position-by-position comparison between stimulus and response strings. Occasionally, discrepancies between the lengths (number of letters) of the stimulus string and the response string were noticed. Estes et al. (1976) asked their observers to identify letters presented at various locations in the peripheral retina. They found, among other things, that observers sometimes failed to report an item and the position of that item was left empty. Since the occurrence of this 'omission error' increased with increasing retinal eccentricity, Estes et al. attributed it to the increasing positional uncertainty in the peripheral retina. In a recent study of lateral interaction between letters (Liu & Arditi, 1996), we asked our observers to identify small letters in five-letter stimulus strings. We noticed that observers often complained that they could not read five letters when interletter spacing was narrow. This is interesting because it was the observers who volunteered the observation that there seemed to be only four letters, even though they were informed that there were five letters in every stimulus string. In these experiments, the observers were given an unlimited viewing time and they were allowed to move their eyes freely so that their foveal vision could be used. If omission or other types of errors which result in an underestimation of stimulus string length occurs under foveal viewing, then the

---

* Corresponding author. Fax: +1-212-7519667.
E-mail address: liul@optica.lighthouse.org (L. Liu)

PII: S0042-6989(99)00247-3

positional uncertainty explanation suggested by Estes et al. (1976) may not be applicable in this case, because positional uncertainty is known to be very small in the fovea (Hirsch & Hylton, 1984).

In this study, we focused our attention on the following questions. If the a priori knowledge about the lengths of the stimulus strings was not available to the observer, how would he/she identify the letters? How well can an observer estimate the lengths of stimulus strings at different interletter spacings? What kinds of errors would an observer make if his/her estimations of the string lengths were not correct?

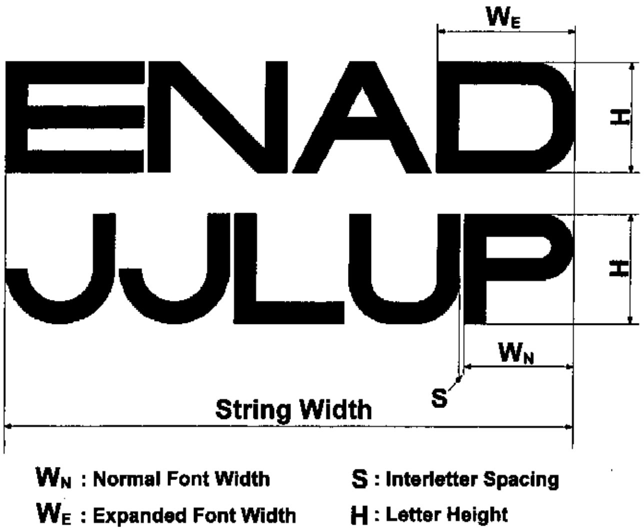

Fig. 1. Examples of four-letter and five-letter strings. The widths of the strings were equalized by expanding the letter width of the four-letter string.

Fig. 2. Examples of four-letter and five-letter strings at different interletter spacings. (a) $S = 0.04$ letter height. (b) $S = 0.24$ letter height.

2. Methods

Our approach was to randomly present four-letter and five-letter strings to observers who knew that there could be either four or five letters in each string. The observers were instructed to identify as many letters as they could from the stimulus strings.

2.1. Stimulus

We used a font that resembled (and contained) the ten Sloan letter optotypes commonly used in acuity testing. Letters were rasterized using the font design language METAFONT (Knuth, 1986), which translated geometric definitions of optotypes into pixel representations. Because every character in this font occupies the same amount of horizontal space (fixed pitch font), strings of different lengths necessarily have different physical extents. In order to eliminate the physical extent of the strings as a cue to their length while maintaining the same interletter spacings we used a horizontally expanded version of the normal optotypes to make the four-letter strings. Fig. 1 shows specifically the relationships among font and spacing parameters for the four- and five-letter strings:

$$4*W_E + 3*S = 5*W_N + 4*S$$

where W_N is the width of the normal optotypes (also equal to the letter height), W_E is the width of the expanded version of the optotypes, and S is the interletter spacing (expressed as a fraction of the letter height). If the height of the letters is H, then the width of the expanded optotypes is $W_E = (5*H + S)/4$. For example, when the interletter spacing is $0.04*H$, $W_E = 5.04*H/4 = 1.26*H$, which means that the letters in a four-letter string should be 0.26 times wider than the letters in a five-letter string. Four interletter spacings (0.04, 0.08, 0.16 and 0.24 letter height) were tested. Fig. 2a and b, respectively, illustrate stimulus strings with the narrowest (0.04 letter height, $W_E = 1.26*W_N$) and the widest (0.24 letter height, $W_E = 1.31*W_N$) spacings.

To make our data set more manageable, we restricted the letters in the interior of each string to a set of five upper case letters {A, J, L, N, U}. The first and last letters of the strings were chosen from the full set of 26 upper case letters. The interior letters were chosen because they were among the letter confusions that were observed only under narrow spacing conditions (Liu & Arditi, 1996), and because they possess exchangeable parts. However, since apparent shortening of letter strings was first reported by subjects in experiments involving all 26 uppercase letters, misjudgment of string length is certainly not confined to strings that contain only these five letters.

To ensure that the five interior letters appear for an equal number of times at every interior position, 60 five-letter strings and 20 four-letter strings were used. These are the numbers of permutations for choosing three and two letters from five letters (order is significant). Repetitions of letters in the same string were allowed. The letter strings were preconstructed and then presented in random order for each testing condition. The same stimulus strings were used for all of the spacings and all observers.

The letter height for each observer was determined in a short pilot run so that the error rate at the narrowest spacing was approximately 50% (counting all stimulus/response strings). The letter heights used for the three observers ranged between 1.0 and 1.44 cm (45–65 pixels) which subtended a visual angle of 3.44–4.96 arcmin. The letters were presented at high contrast. The luminance of the white background was 44.5 cd/m^2 and the luminance of the dark foreground was 2.44 cd/m^2. The letter strings were displayed continuously until the observer reported all the letters he/she saw.

2.2. Apparatus and procedures

The letter strings were generated using a Silicon Graphics computer and were presented on a 15 in. high-resolution (113 pixels/in.) Mitsubishi color monitor. The observer viewed the display reflected from a front-surface mirror at an optical viewing distance of 10 m. Chin and forehead rests were used to stabilize head position.

Stimulus strings were shown to each observer at a close distance before experiment so that the observer could become familiarized with the font. The widening of the letters in four-letter strings was pointed out to the observers, so as the peculiar features of the font. The facts that any of the 26 uppercase letters might be present in a letter string and that there might be repetitions of letters in a single letter string were also brought to the attention of the observers. The observers were instructed that there were either four or five letters in each stimulus string and that they should give only four or five letters as responses. The proportions of four- and five-letter strings in an experimental session were not disclosed to the observers. The subject read aloud the letters that he/she saw and the experimenter typed the responses into a text editing box on the screen. When the observer confirmed the response string, the experimenter pressed the <ENTER> key to write the string into a data file. The observer could change his/her response before the response string was entered into the data file.

2.3. Observers

Three observers participated in the experiments. The purpose of the experiment was explained to each observer and written informed consent was obtained. All observers were in their 20's and had corrected-to-normal vision. Distance corrections were worn during the experiments.

3. Results

3.1. Crowding effect

As expected, when interletter spacing decreased, fewer letters were correctly identified. However, counting correct responses was more complicated under our experiment conditions where misjudgment of stimulus string length occurred frequently. If the stimulus string and the response string had different lengths, the commonly used position-to-position comparison might greatly underestimate the correct responses. For example, an observer might read four letters of a five-letter string correctly, omitting only the third letter. If we only compared letters at the corresponding positions of the stimulus and response strings, we would conclude that there were only two correct responses (the first two letters).

One alternative way of counting correct responses was to count position-to-position correct responses only in those response strings that have the same lengths as the stimulus strings. The results of this method of scoring are shown in Fig. 3a. However, since there are more frequent mismatches between stimulus and response string lengths at narrower interletter spacings, the sample sizes would be different for different interletter spacings. Another alternative was to include all response strings but to take into consideration the effect of the difference between stimulus and response string lengths. If the stimulus and response string did not have the same length, a letter in the response string was compared not only with the letter in the corresponding position of the stimulus string but also with the letters on either side of the corresponding position. In this way, even if the string length was judged wrong by one character, correct responses could still be counted. Results obtained using this method are shown in Fig. 3b.

As both Fig. 3a and b show, the observers made the greatest errors of at least 30% at the narrowest interletter spacing (0.04 times of the letter height). However, when the spacing increased to 0.24 times of the letter height (the widest spacing), the observers correctly identified most of the letters. The deterioration of legibility at narrower spacings indicates interaction between neighboring letters, i.e. a 'crowding' effect.

The percentage correct in Fig. 3a is, on average, 10% higher than that in Fig. 3b. This is because the first method of counting correct responses excludes response strings that do not have the correct lengths. It is possible that stimulus strings whose lengths could not

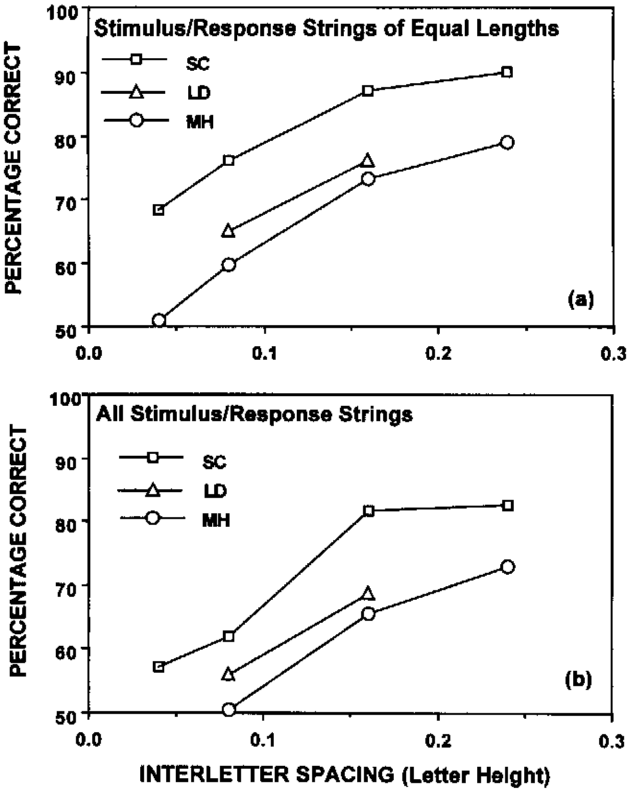

Fig. 3. Two ways to count correct responses. (a) Correct responses were counted through position-by-position comparison between the stimulus string and the response string of equal length. (b) All response strings were considered. If the stimulus and response string did not have the same length, a letter in the response string was compared not only with the letter in the corresponding position of the stimulus string but also with the letters on either side of the corresponding position. In both cases, the percentage correct responses increased with increasing interletter spacing.

be correctly judged were more difficult than those whose lengths were judged correctly.

3.2. Errors in judging string length

Reduced percentage of correct letter identification reflected only part of the effect of decreasing interletter spacing. As the interletter spacing decreased, our observers also made more mistakes in judging the number of letters in the stimulus strings. This was reflected by the fact that they gave more four-letter responses to five-letter strings at narrow spacings. We use 5→4 to refer to the error of mistaking a 5-letter string for a 4-letter string. The error of mistaking a 4-letter string for a 5-letter string is denoted by 4→5. Fig. 4 shows the percentage of errors in judging the string length.

There were only a small number of occasions where observers mistook a four-letter string for a five-letter string. The open circles in Fig. 4 represent the total 4→5 errors of all observers. Most of the time, if the number of letters was judged wrong, it was in the form of mistaking a five-letter string for a four-letter string. Such 5→4 errors increased with decreasing interletter spacing. When the spacing was wide, very few five-letter strings were mistaken for four-letter strings. When the spacing was narrow, most five-letter strings were reported as four-letter strings. One possible explanation for these 5→4 errors is that even though the observers knew that there were five letters in the stimulus string, because one of the letters was so difficult to decipher, they decided to read only the four clearer ones as their responses.

To test this possibility, we conducted a separate test in which we asked one of observers not to identify the letters but simply to estimate the length of the stimulus string, i.e. whether the string contained four or five letters. The open squares in Fig. 4 show the results of this string length estimation task for MH. It is obvious that the results of the letter identification task (solid squares) and the string length estimation task (open squares) show the same trend. This similarity suggests that the explanation proposed above is not valid. It seemed that when the interletter spacings were narrow, the observer read only four letters from a five-letter string because this string did appear to contain only four letters.

Because we used 60 five-letter strings and only 20 four-letter strings in each experiment session, there was a concern that this design might be biased toward more 5→4 errors. In the worst case, if the observer did not look at the display and randomly entered four-letter

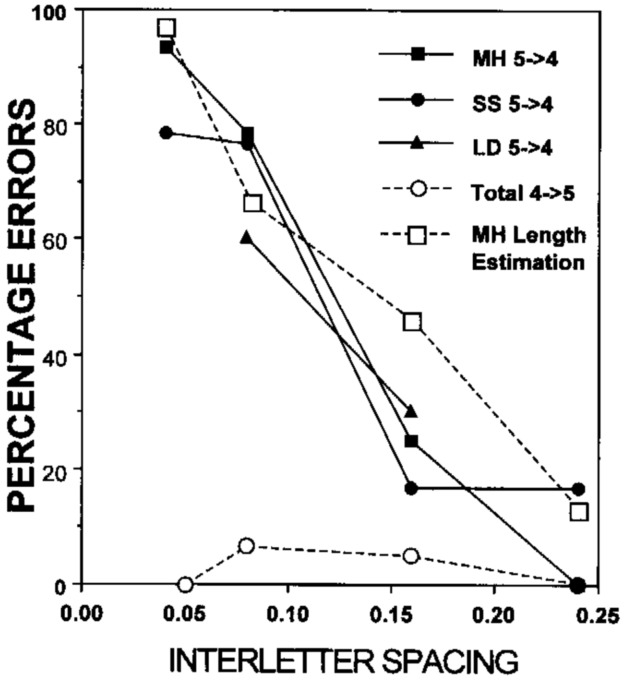

Fig. 4. Errors in judging string length. The open circles are the four greater than five errors of all of the observers. The solid symbols are the 5→4 errors committed by the three observers in the letter identification task. The open squares are the 5→4 errors committed by observer MH in the string length estimation task.

Table 1

	Wide spacing (0.24 letter height)		Narrow spacing (0.04 letter height)	
	5→4 error	4→5 error	5→4 error	4→5 error
SL	0.25	0.025	0.637	0.0375
PM	0.9	0.025	0.9625	0.0125
CP	0.28	0.09	0.7625	0.0125
CW	0.05	0.0125	0.875	0.0125

and five-letters strings, then there would be three times more 5→4 errors then 4→5 errors. The fact that there were very few 4→5 errors certainly does not support this hypothetical scenario, but the unbalanced design did raise questions about the quantitative aspects of apparent string shortening. Therefore, we repeated the 0.04 and 0.24 letter height separations with equal number of four- and five-letter strings. Each experiment session contained 20 four-letter strings and 20 five-letter strings. The rest of the experimental conditions were the same. Four observers who were not participants of the main experiments were tested. Table 1 shows the average 5→4 error rates and 4→5 error rates under the two spacing conditions. The data was based on a total presentation of 80 five-letter strings and 80 four-letter strings.

The pattern of string length error in this experiment is similar to that shown in the main experiments. There were large numbers of apparent string shortening (5→4 errors) under the narrow spacing condition (0.04 letter height), ranging from 63.7 to 96.3%. Three of the four observers showed much 5→4 errors under the wide spacing condition (0.24 letter height). Subject PM showed a high rate of 5→4 errors (90%) at this spacing, but string shortening disappeared when the spacing was increased to 1.0 letter height. There are very few 4→5 errors under both spacing conditions. Therefore, the apparent shortening of letter strings due to narrow interletter spacing is unlikely to be the outcome of a biased design.

3.3. *Three types of errors*

In looking at the recorded response strings, we found that errors that occurred under the narrow interletter spacing conditions could be celled into three categories. We present here examples of these three types of errors. It was not our intention to develop a rigorous algorithm to categorize the errors.

3.3.1. *In-place errors*

These are letters mistaken for other letters without disturbing neighboring letters. Presumably, this kind of error occurred simply because the test letters were small. Many such in-place errors are letter confusions that have also been reported in studies using single letters. These letter confusions (for example, O, C, and D; G and Q; T and Y; H and N) occurred at all interletter spacings and in both four-letter and five-letter strings. We also observed letter confusions that were likely to be caused by the inhibitory interactions between closely spaced letters. For example, in our previous study (Liu & Arditi, 1996), we showed that confusions among letters U, L and J seldom occurred when interletter spacings were wide, but they were among the most significant confusions when interletter spacings were narrow. We saw such confusions frequently in this study too. Even though these confusions were caused by the existence of neighboring letters, they can still be considered as in-place errors because they occurred when the observer correctly estimated the number of letters in the stimulus string.

3.3.2. *Omission of interior letters*

Four out of five letters of a five-letter string were correctly identified but one of the letters was missing. We observed 285 cases where four-letter strings were given as responses to five-letter stimulus strings. About 1/3 of these 5→4 errors could be categorized as pure omission of one of the interior letters from the five-letter strings. None of the letters that appeared in the interior (A, J, L, N, U) was immune to this omission. The following are examples of 5→4 errors.

MALUJ → MLUJ
MLUJA → MUJA
LNAUB → LNAB
PLJNE → PLNB
LAUNK → LAUK
WNUAJ → WUAJ

3.3.3. *Merger of neighboring letters*

Sometimes, two neighboring letters were read as one letter, which combined the strokes of the two stimulus letters. Examples of mergers of letters are:

JJLUP → JAUP
XJUAL → KANL
NNALT → WALT
QJAUC → QJNC

In many cases, however, omission or merger of neighboring letters occurred in combination with in-place errors:

MJNUP → KJNP
CUANJ → CJNJ
DLUND → DJND
OJLNM → OLUM
ZNLUG → ZNLO
EJANJ → EINJ

It is interesting that the first and the last letters in stimulus strings were usually not subject to omission. Most 'merge' errors occurred in the interior of the string. This observation agrees with previous reports that the letters at the two ends of a string are least affected by the crowding effect (Estes & Wolford, 1971; Townsend et al., 1971; Taylor & Brown, 1972; Bouma, 1973; Liu & Arditi, 1996).

4. Discussion

4.1. Point spread function of the eye and the crowding effect

Letter identification under narrow interletter spacing conditions was rather unstable, especially when there was uncertainty about the length of the string. The most frustrating experience we had in analyzing the results of this experiment was that the same letter combination did not necessarily result in the same perceptual output. It seemed that embedded in the stimulus string there was more than one possible solution. If contextual, syntactic or lexical constraints were not available and the length of the string was uncertain, as in the case of this study, the observer may choose any of these possible solutions.

Various mechanisms have been suggested to account for the difficulty that one experiences in reading closely packed small letters. The suggested mechanisms include low-level sensory interaction (lateral inhibition), inaccurate eye movements, and high-level cognitive factors such as divided attention. It is very likely that interactions between neighboring items occur at each of these levels and that they all contribute to deteriorated legibility. However, one potentially important source of 'lateral interaction' has received relatively little attention, namely, the finite point spread function of the eye. Even in the absence of any accommodative errors, the imperfections in the optical components of the eye and the diffraction at the pupil would degrade the quality of the retinal image. This optical degradation is usually quantified by the profile of the retinal image of a very small dot (point spread function, PSF). The effect of a finite PSF is to spread energy of the stimulus into neighboring retinal regions. When the stimulus is a closely packed letter string, the PSF of the eye spreads the energy across the gaps between the letters, thus the energy from neighboring letters becomes mixed. Therefore, before any sensory, motor or cognitive interactions even begin, the retinal image of a given letter within a string is already contaminated by its neighbors, due to the finite size of PSF. We used a cross-correlation technique to assess the potentially negative effects of the PSF on closely packed letter strings.

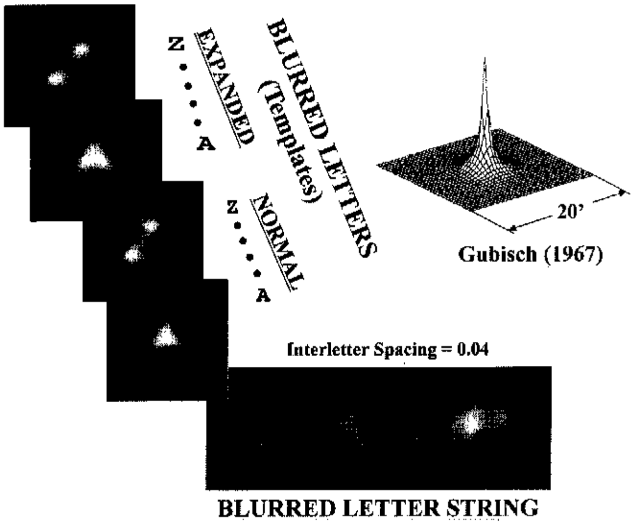

Fig. 5. Use of cross-correlation to assess the effect of the point spread function of the eye. A target letter string was blurred by the point-spread function of the human eye. Twenty-six normal letters and 26 expanded letters were equally blurred. The cross-correlation between the blurred letters (templates) and the blurred target string were calculated so that the similarity between them could be evaluated.

We used the point spread function presented by Campbell and Gubisch (1966). This PSF was derived from direct measurements of the light distribution on the retina (Campbell & Gubisch, 1966; Gubisch, 1967). It describes the overall optical quality of the optics of the eye and has been used as the basis for evaluating retinal image quality (Gubisch, 1967). The particular function we used was based on the data obtained with a 4.9 mm artificial pupil and is shown in Fig. 5. The bitmaps of the optotypes used in the experiments were used in the simulation. The letter height was 4.0 arcmin. Target letter strings of various interletter spacings were constructed from these optotypes. The bitmaps of these strings were then convolved with the PSF of the eye. The result of this convolution was a blurred version of the stimulus string, presumably resembling the retinal image of the string. The blurred image of the string 'JJLUP' is shown at the bottom of Fig. 5.

The full set of 26 normal letters and 26 horizontally expanded letters were blurred with the same PSF. The blurred letters were used as templates and the cross-correlation between these templates and blurred target letter strings were calculated. For a given template $T(i,j)$ and a piece of the image under the template $I(i,j)$, the cross-correlation between the two is

$$xc = 2\sum_i \sum_j T(i,j)I(i,j) \Big/ \left[\sum_i \sum_j T^2(i,j) + \sum_i \sum_j I^2(i,j) \right]$$

When T and I are identical, $xc = 1.0$. If they are not, $xc < 1.0$. Each blurred letter template was slid over the image of the blurred letter string, one pixel a time. At each location, a xc value was calculated. Therefore the outcome of the cross-correlation calculation is a 2-D map. We show only correlation values that exceed 0.95. Because a letter might appear in a string more than once and because strokes of neighboring letters might combine to form spurious letters, there might be more than one high cross-correlation value, or 'good' match

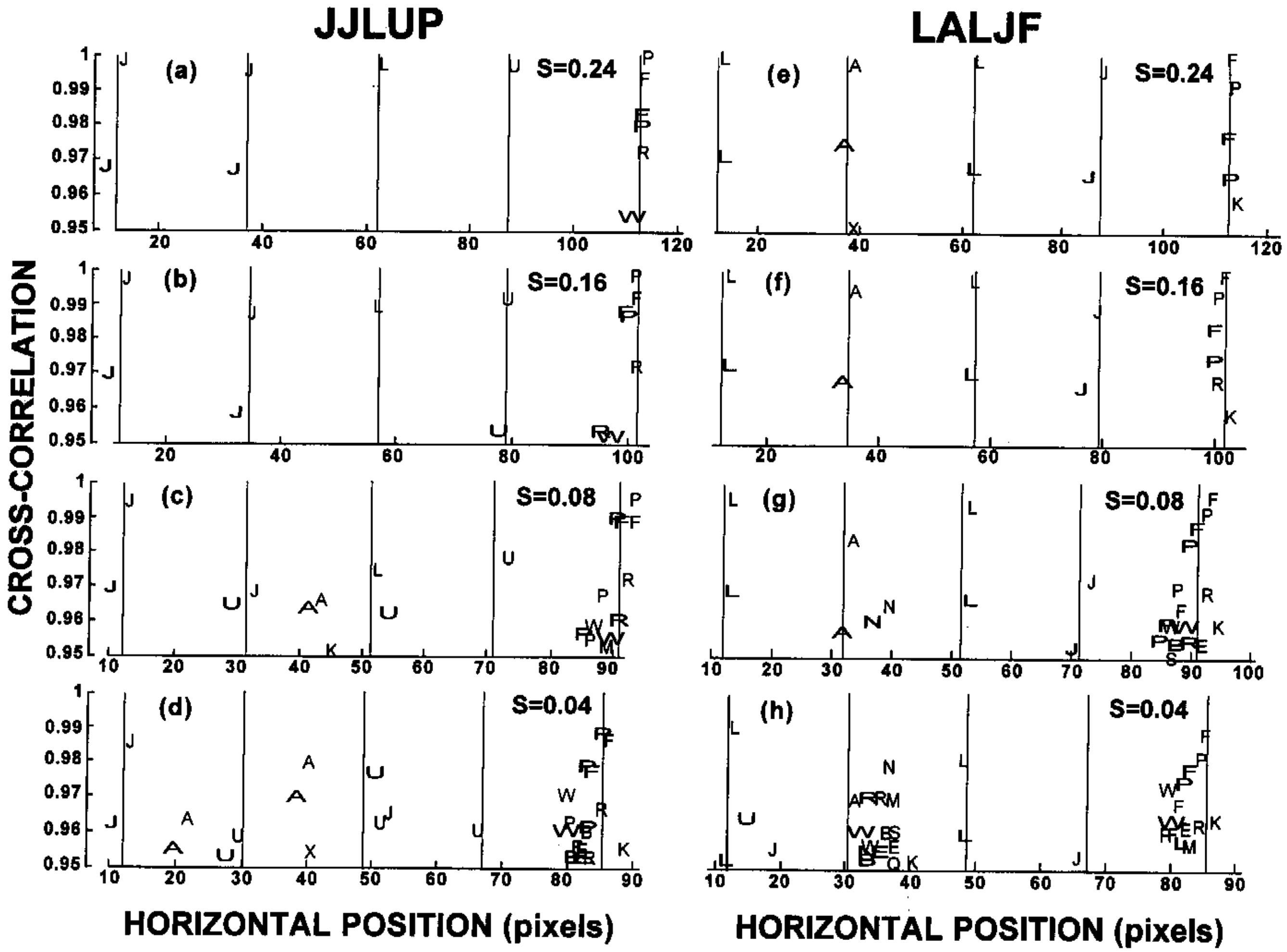

Fig. 6. Cross-correlation analysis results of two stimulus letter strings and four interletter spacings. Each individual letter in the graphs represents a peak cross-correlation value between a blurred letter string and the corresponding template. Normal upper case letters and horizontally expanded upper case letters represent results of normal letter templates and expanded letter templates, respectively. The vertical and horizontal coordinates of a letter represent the cross-correlation value and the location where this value occurs, respectively. The vertical lines are the centers of the letters in the target string. Only cross-correlation values larger than 0.95 are shown.

between a given letter template and a target string. Thus, we need to specify the cross-correlation values and the positions at which these values occur.

Although some researchers have used template matching to represent the mechanism underlying letter recognition (e.g. Loomis, 1990), we used this procedure to provide an objective evaluation of the similarity between an isolated, blurred letter and the features at various positions of a blurred letter string. No assumption about the process of letter recognition is implied.

Fig. 6 shows the results of cross-correlations between the blurred letters and two letter strings, 'JJLUP' and 'LALJF', at four interletter spacings, $S = 0.24$, 0.16, 0.08 and 0.04 letter height. The vertical lines in the graphs indicate the centers of the letters in the original strings. Each individual upper case letter represents a cross-correlation value produced by the corresponding template. Normal upper case letters represent the results of letter templates of normal templates, and horizontally stretched upper case letters represent the results of expanded letter templates. The horizontal position of a letter is the position where the peak correlation occurs. The vertical position of a letter is the magnitude of correlation. Only correlation values larger than 0.95 are shown in the graphs. While from 1.0 to 0.95 does not seem to be a large reduction of correlation value, it constitutes a large portion of the correlation variance among upper case letters. If the full set of 26 similarly blurred upper case letters correlate with each other, 50 out of 312 possible confusion pairs ($26*26/2 = 338$ possible pairs minus 26 identical pairs) have correlation values equal or larger than 0.95. The worst correlation value between any upper case letters is 0.756. Therefore, a couple of percentage points of difference in correlation values may be enough to support discrimination among uppercase letters.

When the interletter spacing was wide ($S = 0.24$ letter height, first row in Fig. 6), the 'correct' letter matchings occurred at the appropriate horizontal locations (on the vertical line) with peak correlation values close to 1.0. For example, in Fig. 6e, letters 'L', 'A', 'L', 'J' and 'F' produced the best matches on the vertical lines and at correlation values greater than 0.99. This indicates that when the letters are separated by 1/4 of letter height (a little more than one stroke width), there is very little contamination from the neighboring letters, at least with the PSF we used.

When the interletter spacing decreases, three things happen to pattern matching, which may contribute to the poor performance and high variation in reading small, closely packed letters. First, peak correlation values decrease at all locations. For example, when interletter spacing is 0.04, very few letters can produce correlation values higher than 0.99 at any location on the target string. At some locations in the string, especially in the interior, no template can score a high correlation and a notch of cross-correlation value is formed. If a human observer needs a certain correlation value to make a decision, for example, 0.96, then there will be no template that can meet this criterion around the fourth location in Fig. 6h. The observer may simply omit a letter at that location. This may help to explain the observed omission of letters under narrow spacing conditions. In fact, LALF is among the responses to stimulus LALJF.

Secondly, more and more letters produce comparable correlation values at the same location. This is shown by the clusters of letters around the vertical lines at the narrow interletter spacings. To any process that utilizes the blurred letter string, whether it is neural or cognitive, more than one candidate letter is present at these locations. Without contextual, syntactic or lexical constraints, these candidates are equally likely to be picked up as the response. This may explain why there is so much variation in the results of such experiments.

Thirdly, high correlation values occur in between letters. Blur caused by the PSF merges strokes of neighboring letters and makes a spurious letter at a location between two neighboring letters. This may explain the observed merger of letters. For example, in Fig. 6d, a high correlation with template 'A' occurs between the second and the third nominal letter position. It seems that the neighboring strokes of the letters 'J' and 'U' are combined to form an 'A'. After blurring, the letter 'L' in the third position and the left limb of the letter 'U' in the fourth position appear very much like a wider 'U'. This is shown by the expanded 'U' at the third location in Fig. 6d. To an observer, the string 'JJLUP' may look more like 'JAUP'.

Therefore, narrow separation between letters and the finite size of the PSF of the eye not only reduce the legibility but also add an uncertainty to experiment results. Models that intend to explain the results of such experiments will have to take into consideration the multiple representations of letters in the same location and the possible omissions of letters due to extremely low correlation values. The simulation shown in Fig. 6 is also consistent with a well known fact, that is, the first and last letters of a letter string are much easier to identify than the interior letters (Townsend et al., 1971; Bouma, 1973; Wolford & Hollingsworth, 1974; Estes et al., 1976). This is shown by the higher cross-correlation values at the first and the fifth locations with narrower interletter spacings.

There is evidence indicating that the crowding effect may occur at the cortical level (Flom, Heath & Takahashi, 1963). This would seem to contradict our assertion that the PSF of the eye plays an important role in the crowding effect. We believe, however, that there may be several stages of visual information processing that contribute to different aspects of the crowding effect. We have shown that the blur caused by the PSF of the eye hardly has any effect on cross-correlation values when the interletter spacings are larger than 0.24 letter height. In Flom and colleagues' experiments, the crowding effect reached its maximum at the gap width of 0.5 letter height and kept affecting visual resolution even when the gap width was equal to the letter height. This range is much wider than the spread of energy caused by the PSF. Therefore, optical degradation and cortical neural processing may work on different spatial scales.

4.2. Crowding effect at narrow interletter spacings

There is a discrepancy between the pattern of legibility deterioration with decreasing interletter spacing (Fig. 3) and the contour interaction curves obtained by Flom et al. (1963). Using a Landolt C and four flanking bars, Flom et al. (1963) demonstrated that visual acuity started to deteriorate when the Landolt C/flanking bars separation was narrower than 5.4 MAR (1.08 letter height) and reached the lowest point at a separation of 2.1 MAR (0.42 letter height). Further decrease of the separation resulted in an improvement of visual acuity. In our experiments, we found monotonic deterioration of letter legibility when interletter spacing decreased from 0.24 to 0.04 letter height (Fig. 3a and b). Although letter recognition at 0.24 letter height separation is not maximal, meaning there may be some interaction between letters, most of the legibility loss has been recovered. This range of interaction is much narrower than Flom et al. found. This discrepancy may be explained by the difference in the stimulus configurations of the two experiments. Flom et al.'s target (Landolt C) was flanked from four sides by bars while in our experiments, each letter had neighbors only on the left and/or right. Liu and Lee (1998) reported that the four flanking bars in Flom et al.'s stimulus contribute differently to contour interaction. When presented alone, the two bars that were parallel to the gap on the ring inhibited identification of the gap. Inhibition was the strongest at the closest separation (20% correct responses at 0.05 letter height) and diminished quickly when separation increased (80–90% correct responses at 0.4 letter height). Adding the other two bars alleviated inhibition at narrow separations and enhanced inhibition at wider separations. We believe that the monotonic crowding effect over the narrow interletter spacings was due to the lack of interaction from above and below the letter strings.

4.3. String length and reading

Some years ago, Arditi, Knoblauch and Grunwald (1990) compared the effect of fixed and variable character pitch on reading performance. In a fixed pitch font, every character occupies exactly the same horizontal space. In a variable (proportional) pitch font, the amount of horizontal space that a character occupies depends on the width of the character. Arditi et al. (1990) found that when the font size was near the resolution (acuity) limit, observers read fixed pitch text faster than variable pitch text. The reverse was true when the font size was larger. Our current experiment showed that the judgment of the length of a string was unreliable when the font size was small and interletter spacing was narrow. Thus, the superior reading performance with the small, fixed pitch text reported by Arditi et al. may be partially due to the fact that the fixed pitch font provided more salient information about word length. The physical extent of a word indicates the length of the word in fixed pitch text, but not in variable pitch text. However, reading is much more complex than recognizing individual letters. It is unknown how the error in estimating the lengths of words would affect reading.

5. Conclusion

When information about the length of letter strings is uncertain, observers tend to underestimate the lengths of small, closely packed letter strings. Typically, the observers tend to omit one of the interior letters or combine two neighboring letters under such conditions.

References

Arditi, A. (1994). On the relationship between letter acuity and reading acuity. In A. C. Kooijman, P. L. Looijestijn, J. A. Welling, & G. J. van der Wildt, *Low vision: research and new developments in rehabilitation* (pp. 38–45). Amsterdam, Netherlands: IOS Press.

Arditi, A., Cagenello, R., & Jacobs, B. (1995). Letter strokewidth, spacing and legibility. In *Vision science and its application. OSA technical digest series*, vol. 1 (pp. 324–327). Washington, DC: Optical Society of America.

Arditi, A., Knoblauch, K., & Grunwald, I. (1990). Reading with fixed and variable character pitch. *Journal of the Optical Society of America, A7*, 2011–2015.

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature, 226*, 177–178.

Bouma, H. (1973). Visual interference in the parafoveal recognition of initial and final letters of words. *Vision Research, 13*, 767–782.

Campbell, F. W., & Gubisch, R. W. (1966). Optical quality of the human eye. *Journal of Physiology (London), 186*, 558–578.

Estes, W. K., Allmeyer, D. H., & Reder, S. M. (1976). Serial position functions for letter identification at brief and extended exposure durations. *Perception & Psychophysics, 19*, 1–15.

Estes, W. K., & Wolford, G. L. (1971). Effects of spaces on report from tachistoscopically presented letter strings. *Psychonomic Science, 25*, 77–80.

Flom, M. C. (1991). Contour interaction and the crowding effect. In R. P. Rutstein, *Problems in optometry (amblyopia)*, vol. 3 (pp. 237–257). Philadelphia, PA: Lippincott.

Flom, M. C., Weymouth, F. W., & Kahneman, D. (1963). Visual resolution and contour interaction. *Journal of the Optical Society of America, 53*, 1026–1032.

Flom, M. C., Heath, G. G., & Takahashi, E. (1963). Contour interaction and visual resolution: contralateral effects. *Science, 142*, 979–980.

Gubisch, R. W. (1967). Optical performance of the human eye. *Journal of the Optical Society of America, 57*, 407–415.

Hirsch, J, & Hylton, R (1984). Quality of the primate photoreceptor lattice and limits of spatial vision. *Vision Research, 24*, 347–355.

Kothe, A. C., & Regan, D. (1990). Crowding depends on contrast. *Optometry and Vision Science, 67*, 283–286.

Knuth, D. E. (1986). *The METAFONT book*. Reading, MA: Addison-Wesley Publishing Company.

Liu, L., & Arditi, A. (1996). Letter confusion observed under small interletter spacings. *Investigative Ophthalmology and Vision Science (Suppl.), 37*, S167.

Liu, L., & Lee, K. (1998). Simple paradigm, complicated explanation: what does Flom's stimulus paradigm tell us about contour interaction? *Optometry and Vision Science (Suppl.), 75*, 201.

Loomis, J. M. (1990). A model of character recognition and legibility. *Journal of Experimental Psychology: Human Perception and Performance, 16*, 106–120.

Stuart, J. A., & Burian, H. A. (1962). A study of separation difficulty. *American Journal of Ophthalmology, 53*, 471–477.

Taylor, S. G., & Brown, D. R. (1972). Lateral visual masking: supraretinal effects when viewing linear arrays with unlimited viewing time. *Perception & Psychophysics, 12*, 97–99.

Townsend, J. T., Taylor, S. G., & Brown, D. R. (1971). Lateral masking for letters with unlimited viewing time. *Perception & Psychophysics, 10*, 375–378.

Whittaker, S., Rohrkaste, F., & Higgins, K. (1989). Optimal letter spacing for word recognition in central and eccentric fields. In *Noninvasive assessment of the visual system. OSA technical digest series*, vol. 7 (pp. 56–59). Washington, DC: Optical Society of America.

Wolford, G., & Hollingsworth, S. (1974). Retinal location and string position as important variables in visual information processing. *Perception & Psychophysics, 16*, 437–442.