Recognition of Jagged (Pixelated) Letters in the Periphery

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Running head: Recognition of jagged vs. smooth letters

Abstract

Previous studies found that for a group of mixed low vision observers, letter counting with smooth (anti-aliased) letters was better than with jagged (pixelated) letters on a CRT display.[1] However using a tachistoscopic presentation, Geiger and Lettvin[2] found that for normally sighted observers, recognition of jagged letters was more accurate than that of smooth letters in the periphery. In this paper, we further investigated this effect using a high-resolution CRT display. Our results indicate that for normally sighted observers, recognition of jagged letters is not different from that of smooth letters in the periphery. This suggests that letter smoothing on a CRT display might not benefit reading for low vision patients with central field loss.

Key words: Letter recognition, reading, low vision, central field loss, CRT displays

Introduction

With computers and internet communications now intricately intertwined into our daily lives, we are forced to read from CRT displays more frequently than ever. Several studies have found that normally sighted observers read more slowly from CRT displays than from printed hard copies due to the jagged appearance of the letters on a regular CRT monitor.[3-5] Reading speed decreases even more when the resolution of the CRT display is reduced and the jaggedness of the displayed text is elevated.[6] To minimize the influence of jagged letters on reading, several researchers tried an anti-aliasing procedure on a high-resolution CRT display to smooth character fonts so that the letters resembled those printed on paper. They found that reading speed was improved and could be equivalent to that on paper. Thus, the researchers concluded that the image quality of the displayed text (smooth vs. jagged) determined the difference in reading performance between CRT displays and paper.[7, 8]

Given that more and more low vision patients benefit from using a CRT monitor to present enlarged text for reading, it is important to know whether using smooth letters on a CRT display could improve letter recognition in low vision patients. Bailey and his colleagues[1] investigated this using a letter counting task in which patients were asked to count the number of prespecified letters on a display containing several rows and columns of letters. The number of occurrences of the test letter on a display varied from 5 to 25, and the background letters were selected randomly from the rest of the alphabet. To successfully perform the task, patients needed to recognize the test letter among a group of the background letters. Two versions of 24-point Times Roman font were used to generate the letter display. The smooth version had 24 pixels per font height and the jagged version had half the resolution (12 pixels per font height). Bailey et al. found that for working distances where the letters subtended a visual angle of at least twice each individual subject's resolution limit, smooth letters allowed for faster and more accurate performance for low vision subjects than jagged letters. At distances where the letters subtended a visual angle near the threshold of each subject, smoothing the letters helped improve only the accuracy of performance. Bailey et al. proposed that letter smoothing on CRT displays could help low vision patients to recognize letters better. As a consequence, designers of computer displays for low vision reading might take this into consideration.

Interestingly, Geiger and Lettvin[2] tachistoscopically presented pairs of smooth or jagged letters to normally sighted subjects using a slide projector and found that the jagged letters could be recognized at a higher accuracy than the smooth letters in the periphery. The smooth letters they used resembled letters printed on paper and the jagged letters simulated letters displayed on a low-resolution CRT monitor. In each briefly presented letter pair (<7 ms), one letter was in the center while the other was in the periphery along the horizontal axis. The subject's task was to fixate on the center and to identify both the center letter and the peripheral letter. The eccentricity of the letters in the periphery ranged from 2.5º to 12.5º from the center letter. Geiger and Lettvin reported that at eccentricities larger than 7.5º (on both left and right sides), the percent recognition for the jagged letters was higher than that for the smooth letters. This was true despite the fact that the jagged and smooth letters were of the same font, size, stroke width and contrast.

If Geiger and Lettvin's findings are valid and can be replicated on a CRT display, this might suggest that low vision patients with central field loss could benefit from a pixelated display for reading in the periphery. On the other hand, Bailey et al.'s findings that low vision patients performed better on the letter counting task with smooth rather than jagged letters suggest the opposite. To clarify this issue, we further investigated whether jagged letters can facilitate letter recognition in periphery on a high-resolution CRT monitor. Furthermore, letter smoothing often demands a lot of extra computing power. Whether this extra power is needed for letter smoothing for text presented away from the fovea was also addressed in this study. In the first experiment, we presented one letter in the center and one letter in the periphery at various eccentricities and compared percent recognition between smooth and jagged letters. In the second and third experiments, we used the same procedure except that a three-letter nonword (trigram) instead of a single letter was presented in the periphery. For all three experiments, we did not find any significant difference in the recognition of jagged and smooth letters at all eccentricities tested. Because jagged and smooth letters do not make any difference in the periphery, our results suggest that applying the anti-aliasing procedure to smooth letters on a CRT display might not benefit reading of low vision patients with central field loss. This will result in faster, more economical computer displays for low vision patients who have lost central vision.

Experiment 1: Single Letter Recognition

The purpose of this experiment was to find whether anti-aliasing letters on a CRT display impacted letter recognition in the periphery. In Geiger and Lettvin's study[2], they used slide projectors to tachistoscopically present smooth and jagged letter pairs. By manipulating the anti-aliasing procedure on a high-resolution CRT display, we generated similar smooth and jagged letters to those in Geiger and Lettvin[2]. Therefore, we expected to replicate their findings on a CRT monitor.

Methods

Participants. Seven naïve subjects (18-35 yo) with normal or corrected-to-normal vision were paid to participate in the experiment. All subjects were graduate students or staff members at Schepens Eye Research Institute and were native English speakers.

Stimuli. The stimuli were generated in the same way as in Geiger et al.[2, 9] A group of ten Helvetica letters was used. The letters were composed of three sub-groups: one with straight strokes (E, H, T, I), one with straight and diagonal strokes (N, V, M), and another with curved strokes (O, C, S). The angular height of the letters subtended 36 minutes of visual arc. Letter pairs (central and peripheral; Figure 1) were constructed by selecting two letters from different sub-groups of the10 letters to reduce the lateral interaction between letters from the same sub-group.[10] In each letter pair, a letter was presented in the center at the fixation point and the other on the left or right side along the horizontal meridian (Figure 1). Five eccentricities (2.5º, 5º, 7.5º, 10º, & 12.5º) were tested on each side (left or right). At each eccentricity and on each side, 10 letter pairs were used; none of the letter pairs were repeated. Each letter was presented once at each eccentricity on both sides and matched with a different letter at the center for each presentation. Letters were black and presented on a white background (luminance = 75 cd/m^2) on a Nanao Eizo monitor (1024 x 600 pixels) at 122 Hz using a VisionWorks system (Durham, NH).

Testing conditions. There were two testing conditions in the experiment. In the *Smooth Letter* condition, letter pairs were composed of anti-aliased letters that were drawn in a matrix of 16 x 17 pixels in Adobe Photoshop using 9 point Helvetica. In the *Jagged Letter* condition, letter pairs were composed of jagged letters that were generated from smooth letters by thresholding the gray pixels through a Matlab routine. The routine examined each of the smooth letters on a 0-255 grayscale, where 0 was black and 255 was white. For each pixel, if the value was 127 or less, the routine changed the value to 0. Otherwise, the routine changed the value to 255. The result was a jagged letter (Figure 1). The smooth and jagged letters visually matched those used in Geiger and Lettvin[2].

Insert Figure 1 about here

Procedure. We used the same testing procedure as in Geiger and Lettvin[2]. All subjects participated in both jagged and smooth letter conditions in a counterbalanced order. Trials were randomized and blocked by eccentricity and letter condition. At the beginning of each trial, a black fixation point was displayed. After a verbal warning, the fixation point was replaced by a "flash" of a letter pair, followed by a blank white screen appearing for 2.5 s (Figure 2). Then the fixation point reappeared. The subject was asked to report the letters in the letter pair (center letter first followed by the peripheral letter). The subject was required to guess if the subject could not recognize the peripheral letter presented. Trials were repeated whenever subjects misreported the central letter.

Insert Figure 2 about here

In Geiger and Lettvin's study[2], the presentation time of the stimuli was set for each subject to ensure that s/he could recognize smooth letters with at least 90% and just about 100% accuracy at 2.5°. Because the longest presentation time used in their study was less than 7 ms, while our fastest presentation time was about 8.2 ms (1 frame), we kept presentation time constant and lowered the contrast level of the stimuli for each subject to achieve the desired performance criterion used by Geiger and Lettvin[2]. As a result, the contrast level of the stimuli used in the experiment ranged from 50% to 70%. The contrast level was defined by the Michelson contrast formula $(L_{max} - L_{min})/(L_{max} + L_{min})$, where L_{max} is the luminance of the white background and L_{min} is the luminance of the letter pairs.

Results

Figure 3 shows the recognition accuracy of smooth vs. jagged letters at different eccentricities. We corrected the percent accuracy data for guessing and then used an arcsine transformation to convert the proportional data to normally distributed data.[11] We then subjected the converted data to a 2 (testing condition) x 5 (eccentricity) x 2 (testing side) repeated-measures ANOVA. Only the main effect of eccentricity was significant ($F(4,24)=111.14$, $MSe=.18$, $p<.0001$). As the eccentricity became farther away from the center, the recognition accuracy for both the smooth and jagged letters decreased. Post hoc tests (Newman-Keul's test) showed that recognition of the jagged letters was not different from that of the smooth letters at any of the eccentricities; this was true for both left and right sides.

Insert Figure 3 about here

Discussion

Contrary to Geiger and Lettvin's findings[2], we did not find that jagged letters were easier to recognize than smooth letters at any eccentricity tested. In accordance with previous studies on peripheral letter recognition, we found that performance fell off with eccentricity due to the decreased visual acuity to perceive the letters as they get further away from the fovea.[9, 12-15]

Our failure to replicate Geiger and Lettvin[2] could be due to stimulus duration. In their study, the stimulus duration was 5 ms on the average while in our study, the stimulus presentation time was approximately 8.2 ms. Although we decreased the contrast level of the letters for each subject to increase the difficulty level of the task, we still observed a higher overall recognition accuracy than in their study. For example, Geiger and Lettvin found that the percent accuracy at 12.5° eccentricity was 13% and 22% for the smooth and the jagged letters respectively while we found that subjects recognized both types of letters at 33%. This indicates that the contrast reduction did not impact the peripheral performance in the same way as the temporal reduction.

To further examine the recognition equality of jagged and smooth letters in the periphery, in the next experiment, we replaced the single letter in the periphery with a three- letter nonword (trigram). Trigrams (e.g. SMT) are more complex than single letters and have been found to be harder to recognize than single letters in the periphery.[16, 17] Furthermore, trigrams have the advantage of being more like words, so the results would have more direct implications on reading. If the jagged letter effect existed, we would observe a higher percent recognition of jagged trigrams than that of the smooth ones at eccentricities larger than 7.5°.

Experiment 2: Trigram Recognition

Method

Participants. Fourteen subjects (18-35 yo) with normal or corrected-to-normal vision were paid to participate in the experiment. Of them, seven had participated in Experiment 1. All subjects were graduate students or staff members at Schepens Eye Research Institute and were native English speakers.

Stimuli. The same group of ten letters from Experiment 1 was used. For each stimulus, the letter presented at the fixation point was unchanged while the letter presented in the periphery was replaced with a trigram. The trigram was constructed by selecting one letter from each of the three different letter sub-groups. None of the three letters were the same as the letter in the center. For convenience, we described the letter positions in the trigram as the innermost (closest to the center letter), the middle, and the outermost (furthest to the center) (Figure 4). The distance between the letters was set to about 0.7º. Only 5º and 10º eccentricities (defined as the visual angle from the center letter to the middle letter in the trigram) were tested on the left and right side in this experiment. At each eccentricity on each side, 35 stimuli were used and none of them were repeated.

Insert Figure 4 about here

Testing conditions. The same testing conditions (smooth vs. jagged) as in Experiment 1 were used.

Procedure. The same procedure as in Experiment 1 was used except that the presentation time of the stimulus was increased to114.8 ms (14 frames), and the subject's task was to report the center letter first followed by the three peripheral letters in the trigram from left to right. The114.8 ms stimulus duration was determined in a pilot experiment to be the time at which all subjects could recognize the trigrams at 5º eccentricity more than 80% of the time. The contrast level of the stimuli used in the experiment ranged from 50% to 100%.

Results

As in Experiment 1, the percent accuracy data were corrected for guessing[1] and then were transformed into normally distributed data. We subjected the transformed data to a 2 (testing condition) x 5 (eccentricity) x 2 (testing side) x 3 (letter position) repeated-measures ANOVA. The main effects of eccentricity, testing side, and letter position were significant, with $F(1,13)=145.77$, $MSe=.22$, $p<.0001$, $F(1,13)=24.08$, $MSe=.19$, $p<.001$, and $F(2,26)=110.53$, $MSe=.24$, $p<.0001$ respectively. The interaction between eccentricity and letter position was also significant ($F(2,26)=14.17$, $MSe=.11$, $p<.0001$), as was the interaction between testing side and letter position ($F(2,26)=18.75$, $MSe=.10$, $p<.0001$).

Post hoc tests (Newman-Keul's) found that none of the letters in the jagged trigrams were recognized differently from the corresponding letters in the smooth trigrams. This was true at both eccentricities (5º and 10º) on both left and right sides (Figure 5c). The power of the *t*-test on the smooth vs. jagged condition was 0.85. For both jagged and smooth trigrams, recognition accuracy for the three letters in the trigram

[1] Because subjects were not informed that the letters in the trigrams were all different, letter guessing in a trigram is assumed to be independent of each other and the probability is 0.1.

decreased with eccentricity (Figure 5a). However, the outermost letter in the trigram was recognized at a higher percent accuracy than the innermost and the middle letters at both eccentricities on both sides, and the innermost letter was recognized better than the middle letter at 10º eccentricity on both sides (Figure 5b). Finally, a right field advantage was found for the recognition of the middle and the innermost letters at both 5º and 10º eccentricities while a left field advantage was found for the recognition of the outermost letter at 10º eccentricity.

Insert Figure 5 about here

Discussion

As in Experiment 1, we did not find that recognition accuracy of jagged letters was higher than that of smooth letters. Different from Experiment 1, we found a right field advantage for the peripheral letter recognition of the middle and the innermost letters in the 3-letter trigram. This was consistent with previous findings that there is a right field advantage for recognition of complex letter strings but not of single letters.[12, 14-16, 18-20] The explanation that Bouma et al. provided was that native English speakers read from left to right, so they had developed a scanning habit of looking ahead and perceiving more word-like properties on the right. If this were true, a left field advantage would be expected for languages that read from right to left, such as for Hebrew. However, several studies tested native Hebrew speakers and found that the right field advantage disappeared but a left field advantage was not found.[19, 21, 22] Thus, the explanation that the right field advantage is language specific and caused by reading habits might not be supported. Bouma[18] reported that the right field advantage was stronger for the inward letters than for the outward letters. The left-field advantage for the outermost letter at 10º eccentricity found in this experiment is puzzling and we have yet to find an answer for it.

The results indicate that recognition of the outermost letter was the best, followed by the innermost letter and then the middle letter. This effect has also been reported in previous studies and been explained by directional asymmetry of letter interactions in a letter string.[13, 16, 18] That is, the outermost letter has a masking (suppressing) effect on the inward letters that is stronger than in the reverse direction. As a consequence, the outermost letter is often recognized with the highest accuracy. Because the middle letter is suppressed by letters on both sides, it is recognized the worst.

From the findings of Experiments 1 and 2, we wanted to propose that recognition of jagged letters is not different from that of smooth letters in the periphery. However, we observed that in the ten letters used to generate stimuli, the group of four letters with straight strokes (E, H, T, and I) would appear smooth even in the jagged letter condition. This was true in both Geiger and Lettvin's study and ours[2].   As a result, each jagged trigram used in Experiment 2 contained a smooth component. To remove this confounding factor, we replaced (E, H, T, I) with (A, Q, U, X) to make sure that all letters in the jagged condition were jagged in Experiment 3. Again, if the jagged letters are easier to recognize than smooth letters in the periphery, the recognition accuracy for the jagged letters should be higher than that for the smooth letters.

Experiment 3: Trigram Recognition with Complete Jagged Components

Method

Participants. Eight subjects (18-35 yo) with normal or corrected-to-normal vision were paid to participate in the experiment. Among them, six participated in the previous experiments. All subjects were graduate students or staff members at Schepens Eye Research Institute and were native English speakers.

Stimuli. The same stimuli and eccentricities from Experiment 2 were used except that E, H, T and I were replaced by A, Q, U and X, respectively.

Testing conditions and procedure. The same testing conditions (smooth vs. jagged) and procedure as in Experiment 2 were used. The contrast level of the stimuli used in the experiment ranged from 60% to 80%.

Results

The same pattern of results as in Experiment 2 was found. The main effects of eccentricity, testing side, and letter position were significant, with $F(1,7)=53.32$, $MSe=.30$, $p<.001$, $F(1,7)=17.25$, $MSe=.18$, $p<.01$, and $F(2,14)=201.01$, $MSe=.06$, $p<.0001$ respectively. The interaction between eccentricity and letter position was significant ($F(2,14)=4.68$, $MSe=.08$, $p<.05$), as was the interaction between testing side and letter position ($F(2,14)=41.42$, $MSe=.10$, $p<.0001$).

Figure 6a plots the recognition accuracy of the outermost, the middle and the innermost letter in the smooth trigrams, and Figure 6b plots the recognition accuracy difference between the smooth and the jagged conditions. As in Experiment 2, post hoc tests (Newman-Keul's) found that recognition of the jagged letters was no different from that of the smooth letters (Figure 6b). This was true for all three letter positions in the trigram at both eccentricities on both sides. The power of the *t*-test on the smooth vs. jagged letter condition was 0.78. Different from Experiment 2, the recognition of the outermost letter outperformed that of the innermost and the middle letters at both 5º and 10º eccentricities on the left side but only at 5º eccentricity on the right side. At 10º eccentricity, the recognition of the outermost letter was not statistically different from that of the innermost letter but was better than that of the middle letter. Surprisingly, we found that the recognition of the middle letter was better than the innermost letter at 5º eccentricity on the left side, but this may be a spurious effect. The same right field advantage was found for the recognition of the middle and the innermost letters, yet the recognition of the outmost letter turned out to be better in the left field than in the right field at all eccentricities in this experiment.

Insert Figure 6 about here

Discussion

The introduction of more jagged components in the entire trigram does not change our previous findings that the recognition of the jagged letters in the periphery was comparable to that of the smooth letters. Clearly, the increased salience of jaggedness in the jagged letter condition did not have much influence on subjects' performance.

We replicated left field advantage for the recognition of the outermost letter. Since subjects were instructed to always report the letters from left to right, the left field advantage of the outmost letter might be due to the processing distance effect.[23] That is, assuming that there is a "pure" serial position effect determined only by letter eccentricity and retinal locus and is thus symmetric on the left and right side, the processing distance effect would increase the recognition accuracy of the letters being reported the first, in our case, the outermost letter in the left field and the innermost letter in the right field. We propose that the interaction between the processing distance effect and the right field advantage effect found by Bouma et al.[12] explains the smaller recognition accuracy difference between the outermost and the innermost letters in the right side than in the left side as shown in Figure 6a and Figure 5b.

General Discussion

To summarize the results, in Experiment 1, we used the same stimuli and similar experimental procedure as in Geiger and Lettvin[2] but did not find that recognition of jagged letters was better than that of smooth letters. In Experiment 2, we presented a 3-letter trigram instead of a single letter in the periphery. Still, recognition of jagged letters was comparable to that of the smooth letters. In Experiment 3, we removed the letters containing straight strokes to ensure that all letters in the jagged condition had jagged components. Still, this did not alter the finding that jagged letters were not recognized more accurately than the smooth letters in the periphery.

Our results seem to be in conflict with previous findings that subjects read faster with smooth letters than with jagged letters.[3-5] However, it should be noted that our task was not a reading task that involved recognition of words, but rather a letter recognition task that involves recognition of certain selected letters in the periphery. During reading, people usually move their eyes from word to word, fixate on the word of interest for a while and then move again. It rarely happens that they will try to recognize a letter in the periphery while fixating on another one in the center. Thus, our findings might not apply to normal reading behavior. However, for reading in low vision patients with central field loss, it often happens that they have to use their peripheral vision to recognize letters in the periphery. This is why our findings have implications on text display designing for low vision reading.

The results from the current study are also inconsistent with Bailey et al.'s findings[1] that a group of mixed low vision patients performed better on a letter counting task with smooth letters than with jagged letters. Unlike our study, the smooth letters they used were of a standard 24 point Times Roman font displayed on a Macintosh screen, and the jagged letters were generated by reducing the resolution of the smooth letters by half. Our jagged letters were of the same resolution as our smooth letters, and the only difference between them was that the gray scale of the pixels contained in the smooth letters was binarized into black and white in the jagged letters. Because the two studies used different methods to generate the experimental stimuli, we do not think that our results directly speak to theirs. Furthermore, in Bailey et al.'s study, few of their mixed low vision patients had central field loss, so there is not enough evidence to support the claim that patients with central field loss would benefit from an smooth letter display for reading in the periphery.

The question remains why we could not replicate Geiger and Lettvin's[2] jagged letter effect on a high-resolution CRT display. Although we replicated the eccentricity effect that recognition of the letters fell off with distance from the fixation, we did not find that recognition of jagged letters was better than that of smooth letters at any eccentricity tested in three experiments. One might assume that Geiger and Lettvin printed the smooth letters on a slide so their smooth letters might appear smoother than our smooth letters displayed on a CRT monitor. However, five subjects were asked to compare the smooth letters from the two different studies, and they all reported that the smooth letters used in the two studies looked alike. Another possibility is that Geiger and Lettvin[2] used a tachistoscopic presentation for the stimuli and varied the stimulus duration to achieve the desired recognition accuracy at a certain eccentricity while we used a computer presentation and varied the stimulus contrast level. The temporal reduction and the contrast reduction might have affected the subjects' performance in a different way. However, the similar shape of the percent accuracy curves found in the two studies does not support this hypothesis. We remain uncertain why they found better recognition of jagged letters in the periphery.

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References

1. Bailey, I. L., Boyd, L. H., Boyd, W. L., & Clark, M. Readability of computer display print enlarged for low vision. *American Journal of Optometry and Physiological Optics* 1987; 64: 678-685.

2. Geiger, G., & Lettvin, J. Y. Jagged letters are more easily recognized than smooth ones in the peripheral visual field. *Perception* 1998; 27 (suppl.): 15.

3. Creed, A., Dennis, I., & Newstead, S. Proof-reading on VDUs. *Behavior and Information Technology* 1987; 6: 3-13.

4. Gould, J. D., Lizette, A., Barnes, V., Finn, R., Grischkowsky, N., & Minuto, A. Reading is slower from CRT display than from paper: Attempts to isolate a single-variable explanation. *Human Factors* 1987; 29: 269-299.

5. Wilkinson, R. T., & Robinshaw, H. M. Proof-reading: VDU and paper text compared for speed, accuracy and fatigue. *Behavior and Information Technology* 1987; 6: 125-133.

6. Sommerhalder, J., Bagnoud, M., Safran, A. B., & Pelizzone, M. Reading of 4-letter words in a stabilized area of the visual field: Effects of pixelization and eccentricity. *Investigative Ophthalmology & Visual Science* 2000; 41: S437.

7. Gould, J. D., Lizette, A., Finn, R., Haupt, B., & Minuto, A. Reading from CRT display can be as fast as reading from paper. *Human Factors* 1987; 29: 497-517.

8. Jorna, G., & Snyder, H. Image quality determines differences in reading performance and perceived image quality with CRT and hard copy displays. *Human Factors* 1991; 33: 459-469.

9. Geiger, G., Lettvin, J. Y., & Fahle, M. Dyslexic children learn a new visual strategy for reading: a controlled experiment. *Vision Research* 1994; 9: 1223-1233.

10. Geiger, G., & Lettvin, J. Y. Enhancing the perception of form in peripheral vision. *Perception* 1986; 15: 119-130.

11. Winer, B. J. *Statistical Principles in Experimental Design*. McGraw Hill, NY, 1962; 221.

12. Bouma, H. Visual recognition of isolated lower-case letter. *Vision Research* 1971; 11: 459-474.

13. Geiger, G., Lettvin, J. Y., & Zegarra-Moran. Task-determined strategies of visual process. *Cognitive Brain Research* 1992; 1: 39-52.

14. Heron, W. Perception as a function of retinal locus and attention. *American Journal of Psychology* 1957; 70: 38-48.

15. Hirata, K, & Osaka, R. Tachistoscopic recognition of Japanese letter materials in left and right visual fields. *Psychologia* 1967; 10:7-18.

16. Bouma, H. Interaction effects in parafoveal letter recognition. *Nature* 1970; 226: 177-178.

17. Woodworth, R. S., & Schlosberg, H. *Experimental Psychology*. Methuen, London, 1954.

18. Bouma, H. Visual interference in the parafoveal recognition of initial and final letters of words. *Vision Research* 1973; 13: 767-782.

19. Mishkin, M., & Forgays, D. G. Word recognition as a function of retinal locus. *Journal of Experimental Psychology* 1952; 43: 43-48.

20. White, M. J. Laterality differences in perception: a review. *Psychological Bulletin* 1969; 72: 387-405.

21. Orbach, J. Retinal locus as a factor in the recognition of visually perceived words. *American Journal of Psychology* 1952; 65: 555-562.

22. Orbach, J. Differential recognition of Hebrew and English words in right and left visual fields as a function of cerebral dominance and reading habits. *Neuropsychologia* 1967; 5:127-134.

23. Wolford & Hollingsworth. Retinal location and string position as important variables in visual information processing. *Perception & Psychophysics* 1994, 16, 437-442.

Figure Captions

Figure1. Examples of smooth and jagged letters used in the experiments magnified by about 25 times. Note the gray scale of pixels contained in the smooth letters is binarized into black and white in the jagged letters.

Figure 2. A schematic drawing of the presentation procedure for one stimulus.

Figure 3. Recognition accuracy (%) as a function of eccentricity (deg) for the smooth vs. jagged letters in Experiment 1.

Figure 4. Examples of the stimuli used in Experiment 2.

Figure 5. Recognition accuracy (%) as a function of eccentricity (deg). (a) Recognition accuracy of the middle letter as a function of eccentricity for both smooth and jagged letter conditions; (b) Recognition accuracy of the inward, the middle and the outward letter for smooth letters; and (c) recognition accuracy difference between smooth and jagged letter conditions.

Figure 6. Recognition accuracy (%) as a function of eccentricity (deg). (a) Recognition accuracy of the inward, the middle and the outward letter for smooth letters, and (b) recognition accuracy difference between smooth and jagged letter conditions.

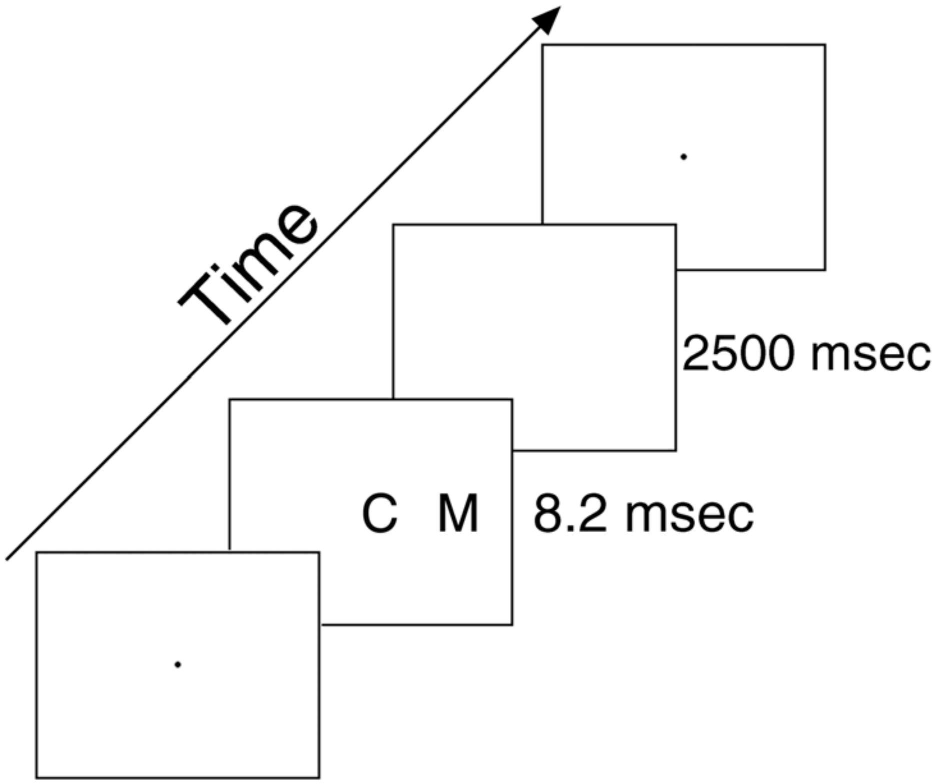
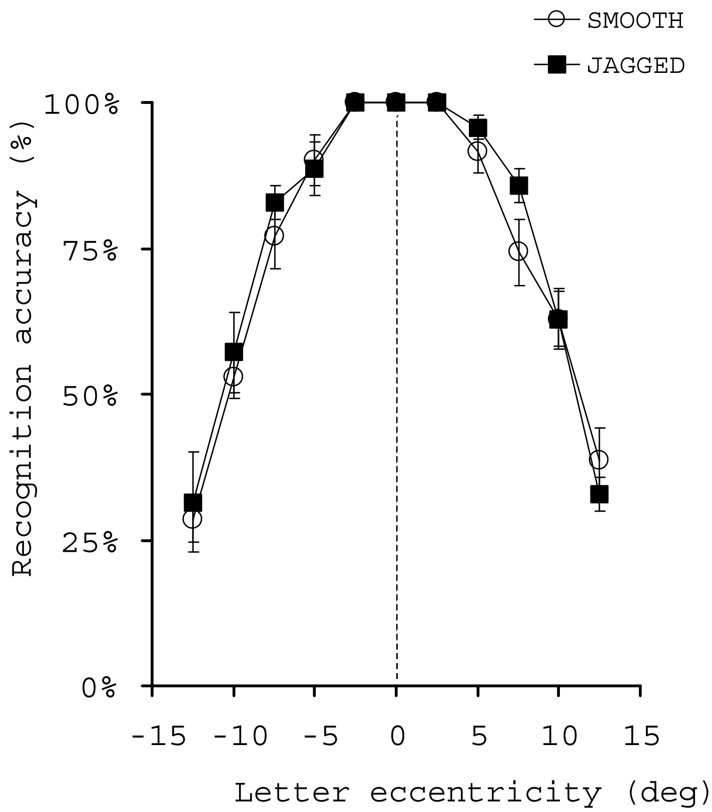


Figure 2



SMOOTH
JAGGED
Recognition accuracy (%)
100%
75%
50%
25%
0%
-15
-10
-5
0
5
10
15
Letter eccentricity (deg)

Figure 3

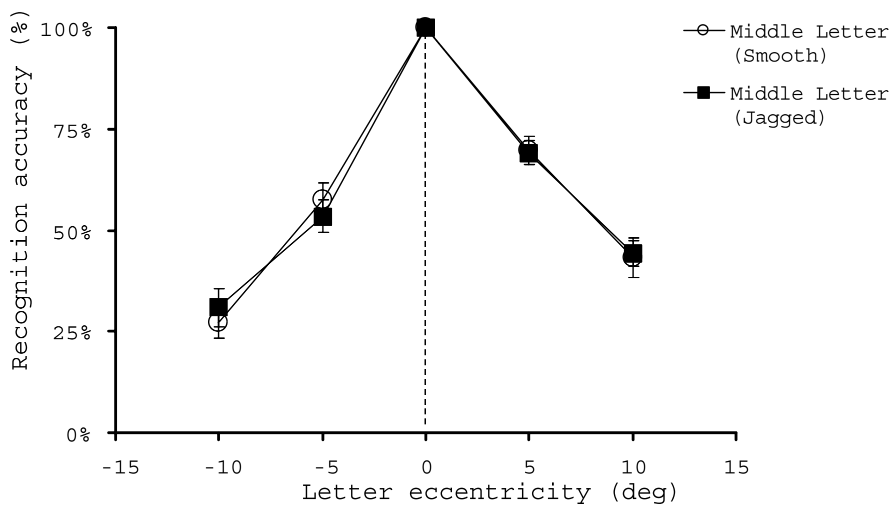


Figure 5a

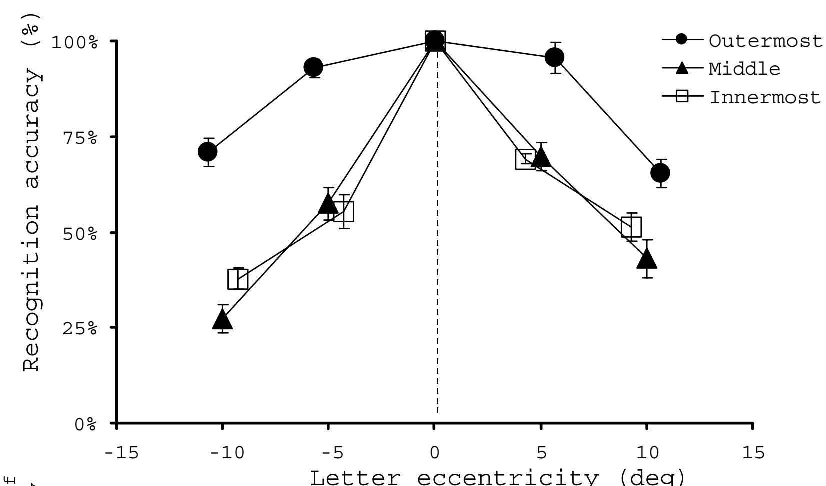


Figure 5b

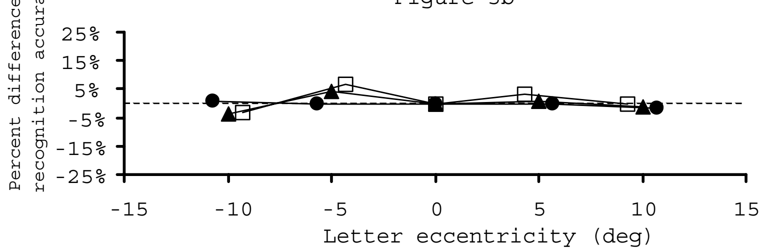


Figure 5c

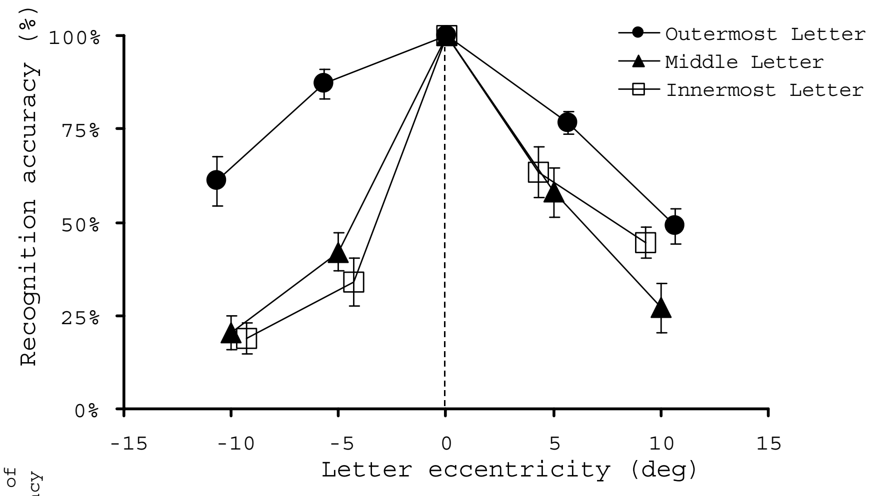


Figure 6a

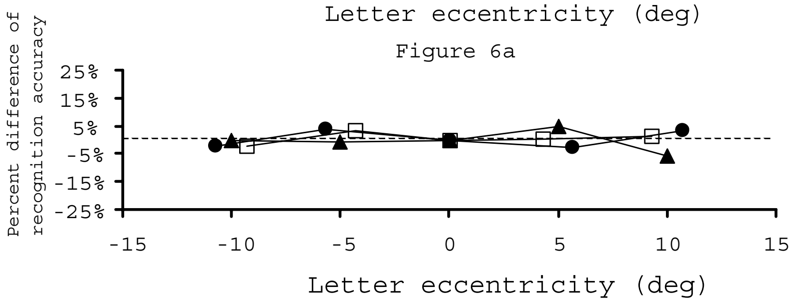


Figure 6b