

Effects of ocular transverse chromatic aberration on peripheral word identification

Shun-nan Yang, Yu-chi Tai, Hannu Laukkanen and James Sheedy  
Vision Performance Institute, Pacific University, Oregon, USA

Running title: TCA effect on peripheral word identification

Corresponding author:  
Shun-nan Yang, Ph.D  
College of Optometry, Pacific University  
2043 College Way, Forest Grove, OR 97116  
Email: [shunnan.yang@pacificu.edu](mailto:shunnan.yang@pacificu.edu)  
Phone: 1.503.352.2852

Abstract

Transverse chromatic aberration (TCA) smears the retinal image of peripheral stimuli. We previously found that TCA significantly reduces the ability to recognize letters presented in the near fovea by degrading image quality and by exacerbating crowding effect from adjacent letters. The present study examined whether TCA has a significant effect on nearfoveal and peripheral word identification, and whether within-word orthographic facilitation interacts with TCA effect to affect word identification. Subjects were briefly presented a 6- to 7-letter word of high or low frequency in each trial. Target words were generated with weak or strong horizontal color fringe to differentially attenuate the TCA in the right periphery and exacerbate it in the left. The center of the target word was 1, 2, 4, and 6 degrees to the left or right of a fixation point. Subject's eye position was monitored with an eye-tracker to ensure proper fixation before target presentation. They were required to report the identity of the target word as soon and accurately as possible. Results show significant effect of color fringe on the latency and accuracy of recognizing low- but not high-frequency words. The effect was more salient in the right periphery. Individuals' subjective preference of color-fringed text was correlated to the effect of color fringe on word identification in the near periphery. Our results suggest that TCA significantly affects word identification, especially in the right periphery and when within-word facilitation is weak. TCA likely plays an important role in limiting reading efficacy, and proper text rendering may reduce TCA and subsequent facilitate reading.

## Introduction

Human ability in discerning a visual stimulus, or visual acuity, decreases with greater image eccentricity from the fovea (Berkley, Kitterle, & Watkins, 1975; Dakin & Hess, 1997; Low, 1951). Several cognitive-neurophysiological factors have been identified to influence visual acuity at different retinal eccentricities, including retinal neural density (Croner & Kaplan, 1995; Hirsch & Curcio, 1989), cortical magnification (Cowey and Rolls, 1974), and attention allocation (Morrison, 1984; Reichle et al., 2004). However, achromatic and chromatic optical aberration has also been shown to affect visual acuity across the retina as well (Anderson, Mullen, & Hess, 1991; Banks, Geisler & Bennett, 1987; Campbell & Gubisch, 1966; French, Snyder & Stavenga, 1977; Ogboso & Bedell, 1987; Williams, 1985).

Transverse chromatic aberration (TCA) results from chromatic dispersion and causes a wavelength-dependent displacement in the retinal image (Howarth, 1984; Marcos, Burns, Moreno-Barriusop, & Nararro, 1999; Rynders, Lidkea, Chisholm, & Thibos, 1995; Thibos, Bradley, Still, Zhang, & Howarth, 1990). Figure 1A shows how chief rays from two light sources, away from the achromatic axis, are refracted at the principle plane of the lens in a reduced-eye model (Thibos et al., 1990). The short wavelength (blue) is refracted more than the long wavelength (red) light. As a result, for a stimulus in the left periphery, TCA could cause a bluish fringe on the medial edge of the retinal image that would be seen as a bluish band on the right edge of the perceived image, and a reddish band on the left. When the stimulus is in the right periphery the opposite effect is expected. The amount of TCA at different peripheral eccentricities

can be predicted from the refractive properties of the ends of the visible spectrum (434nm vs. 687nm), resulting in .6 minutes of arc at 1° eccentricity and 2.5 minutes of arc at 10° eccentricity (Howarth, 1984; Marcos, Burns, Prieto, Navarro, 1999; Rynders et al., 1995; Ogboso and Bedell, 1987; Simonet and Campbell, 1990; Thibos, 1987; Thibos et al., 1990).

--- Figure 1 ---

The effect of TCA on the performance of complex visual tasks, such as reading, has received little scrutiny. In reading, the human visual system extracts detailed visual information from a limited visual span that is generally within 4° of eccentricity in the right periphery, and within 2° in the left (McConkie and Rayner, 1975, 1976). Conversely, a letter placed at 2.8° eccentricity would only generate chromatic aberration of 0.9 min of arc, and 2.7 min of arc for 8° eccentricity. Figure 1B shows examples of the expected TCA at different eccentricities for an example word, without considering the lateral difference in eccentricity for the letters in the word. The predicted TCA effect within the visual span for reading thus appears quite small, suggesting that the smearing of letter image associated with the TCA might not be significant enough to affect letter identification and subsequent high level linguistic processing. In line with this, several studies investigating TCA effect on visual acuity showed that the effect size of TCA on visual acuity increased with image eccentricity, but the effect is small and highly variable within 5° of eccentricity (Rynders et al., 1995; Williams, 1985).

In a recent study, we examined the effect of TCA on letter identification in the near fovea (1° horizontal eccentricity) while manipulating the orientation of artificial

horizontal color fringe, the amount of inter-letter spacing, and the similarity of adjacent letters (Yang et al., 2009). A target letter was placed in the middle of a five-letter string and displayed for 120ms. The whole letter string was either colored fringed in red-blue orientation (reddish fringe at the left edge of the letter and bluish fringe at the right), in blue-red orientation, or not color-fringed. Subjects were asked to identify the target letter as accurately as possible without a time limit. Any difference in the accuracy of identifying color-fringed letters, compared to non-fringed ones, was attributed to the attenuation or exacerbation of the TCA due to the artificial color fringe.

Results of the previous study showed that when the target letter was in the right near fovea and with artificial color fringe opposite to the direction of TCA, significant improvement in the accuracy of letter identification was observed. This effect was present only when the inter-letter space was small (the default spacing for 11-point font) but not when the space was doubled. A similar effect was found when the target letters were placed in the left near fovea and with opposite color fringe. These findings suggest that TCA significantly reduced the ability to recognize letters in the near fovea by impeding identification of individual letters, and by exacerbating lateral interference among letters. Subsequently, attenuating the TCA with artificial fringe improved letter identification.

That TCA has an effect on letter identification in the near fovea does not necessarily suggest a significant TCA effect on reading performance. In normal reading the text is composed of real words for which adjacent letters possess various amounts of orthographic frequency (e.g., “*th*” is of higher orthographic frequency than “*xe*”).

Frequently paired adjacent letters in a word allow it to be identified more readily even when individual letters were degraded (Johnson and McClelland, 1980; McClelland and Rumelhart, 1981). In contrast, in the earlier study that showed TCA effect on letter identification, random letters strings were used that exacerbated lateral interference but provided no orthographic facilitation. In processing real words, TCA may have much small or nonexistent effect on determining its accuracy and speed, as orthographic facilitation is able to help achieve word identification despite of TCA.

In addition, the observed significant TCA effect on letter identification at 1° eccentricities cannot be readily applied to peripheral word identification in reading, where visual information can be extracted from as far as 4° to the right. TCA at greater eccentricities may not be large enough to substantially affect the accuracy and latency of word identification.

In the present study, to determine whether TCA significantly affects word identification and whether its effect is affected by word eccentricity and familiarity, skilled readers were briefly presented with a six- to seven-letter word of high and low frequency. The center of the target word was 1, 2, 4, and 6 degrees to the left or right of a fixation point. Subject's eye position was monitored with an eye-tracker to ensure proper fixation. The target word was displayed for 120ms and then removed to prevent saccadic foveation. Subjects were asked to verbally report the identity of the target word as quickly and accurately as possible.

To measure TCA effect, the target words were generated with horizontal red fringe at the left edge and blue fringe at the right edge. The fringe was rendered with

ClearType (CT) technology and was set at the maximum (100%) and moderate (50%) levels based on a Gaussian filter. Figure 1C shows the different levels of color fringe and their expected effects on visual stimulation at different eccentricities. In our previous study with a letter identification task, the CT-generated color fringe attenuated TCA when its color fringe was opposite to the expected TCA, and exacerbated TCA when it was in the same direction as the TCA (Yang et al., 2009). For the present study we anticipated that the artificial color fringe should reduce or increase the TCA at different eccentricities, dependent upon whether it is placed in the left (increase) or right periphery (decrease), thus changing the accuracy and speed of word identification. The maximum color fringe should result in greater changes in word identification ability at the same eccentricity, as it was more easily perceived by the subject.

We previously found that individuals were different in their preference to color-fringed text (Yang et al., 2009). Their preference could reflect how color fringing helps improve text appearance and facilitate visual processing. To investigate the relationship between subjective preference to color fringe and the effect of color fringe on word identification, subjects were also asked to rate their preference to text rendered with the same levels of color fringe and their preference to the corresponding color-fringe level was correlated to the effect of color fringe on word identification at different eccentricities.

To determine the influence of orthographic facilitation on the TCA effect, the target word was of either low- or high-frequency. It was expected that TCA effect would

be smaller with higher frequency words because word identification is less dependant upon the identification of individual letters but more on orthographic facilitation.

## **Methods**

### **Subjects**

Thirty-four native English speakers (34% male, average age: 23.7 yrs), with normal or corrected binocular visual acuity of 20/20 or better, were recruited from the Pacific University community for either monetary compensation or for course credit. Before participating in the experiment, each subject read and signed a consent form approved by the Pacific University Institutional Review Board for Human Subjects.

### **Materials**

Nine hundred and sixty target words of six- to seven-letter length were selected from the Francis-Kucera corpus (Kucera and Francis, 1967). Half of the chosen words were selected from the lower frequency end, and half from the higher end of frequency count. Eleven-point Consolas font (each letter extending 7 pixels or 18.7 min of arc horizontally from a viewing distance of 50 cm) was chosen to render the target words.

Color-fringed text was generated using a special program "CTRAS" developed by Microsoft to generate ClearType (CT) word images, with red fringing on the left edge and blue fringing on the right. CT smoothes text appearance on liquid crystal display (LCD) horizontally by manipulating the light intensity of the three sub-pixels (left to right: red, green and blue), but in so doing creates a horizontal color fringe. Here CT text was rendered in the RGB order (red fringe in the left and blue in the right), that is opposite to the expected TCA in the right periphery (blue fringe in the left and red fringe in the

right). The perceived color fringe is the result of different light intensities of red, green, and blue subpixels. A stronger light from the red subpixel compared to the blue subpixel would lead to a more reddish appearance. The Gaussian filter level was set at 100% for strong CT, 50% for weak CT, and 0% for B&W. A higher percentage of Gaussian filtering reflects a greater amount of difference in light intensity for the three subpixels. The effect of color fringe on attenuating and exacerbating TCA was determined by computing the difference in the accuracy and response time between identifying B&W and color-fringed words. Figure 1C shows an example target word rendered in B&W, weak CT, and strong CT. Note that the only difference among these three conditions is that the various intensities of color fringes that led to the image being more reddish (100%) or not at all (0%). The graded pixel luminance level at the left and right edges of letters in all three conditions was the result of anti-aliasing rendering, i.e., the smoothing of text appearance with a gradual drop off of pixel luminance.

During the experiment, the images were loaded into video memory before each trial for stimulus presentation. The presentation of word images was achieved by aligning the center of the word to the selected position (1, 2, 4, or 6 degrees) to the left or right of the fixation point.

### **Apparatus**

A Pentium 1.8 GHz Dell personal computer was used to conduct the experiment and generate the stimuli. Experiment Builder software (SR Research Inc.) was used to script the experiment and control the progress of trials. A 19" LCD monitor with RGB sub-pixel order (1024 by 768 pixel screen resolution) with a 60Hz vertical refresh rate

was used to display the image. A chin-forehead rest was used to stabilize the subject's head and to maintain the viewing distance (50cm) and angle (perpendicular to the screen surface).

Eye movements were monitored using the SR Research Eyelink eyetracker. It uses head-mounted infrared light cameras to acquire the pupil image and corneal reflection at a 500Hz sampling rate. The spatial resolution is  $.005^\circ$  and its accuracy is  $.5^\circ$ . Its tracking range is  $60^\circ$  of visual angle, and the tracking was conducted binocularly.

Verbal responses to target presentation were registered by a voice key (SV-1 Smart Voice Key, Cedrus Inc.) and the response time in relation to target onset was encoded for post-processing. The verbal response was also recorded with a digital recorder (iHP-140, SRS Lab, Inc.) and the accuracy of the response was verified after the experiment.

Subjective preference to B&W and color-fringed text was measured using an analog scale. Subjects were shown two paragraphs displayed on the LCD screen and asked which one they "see more clearly." The paragraphs were rendered in the same levels of color fringe and in B&W and in 11-point Consolas font. Subjects indicated their preference by marking an analog scale displayed on a computer screen using a mouse.

### **Procedure**

The experiment lasted for about 90 minutes. Each subject underwent five blocks of trials with brief breaks arranged between blocks. The subjective questionnaire for font preference was conducted during the break periods. Figure 2 shows the testing sequence for a trial. Each trial began when the subject pressed the space bar to initiate

a calibration procedure. A fixation point was displayed on the center of the screen and the subject was asked to carefully look at the fixation point and to press the space bar to correct any drift error in eye position from the previous trial. A fixation point was then displayed on the screen center until the subject fixated on it continuously for 500ms. The fixation point was removed and a target word was then displayed 1, 2, 4, or 6 degrees to the left or right of the fixation point. The target word was displayed for 120ms and then removed to prevent saccadic foveation. The subject was asked to verbally report the target word, but to remain silent if s/he was not able to identify it. The trial ended when a verbal response was detected, or at 3000ms after the offset of the target word if no response was detected. The next trial began 500ms later. The verbal response was recorded and analyzed afterwards, and the response time was recorded with the voice key device. These were repeated until a block of 192 trials was completed and a break followed. At the end of the experiment, the subject was debriefed about the purpose of the study.

--- Figure 2 ---

### **Data analysis**

Percentage of correct responses and the resultant response times was calculated relative to word frequency, word location, and rendering type. Outliers for response time were excluded with a criterion of 4 standard deviations. Missing values were replaced by group means. Repeated measures ANOVAs were used to evaluate effects. Mauchly's test of sphericity was conducted to determine if the variance of response accuracy in each condition was equal and a significant violation of such assumption was

treated with Greenhouse-Geisser correction (Vonesh and Chinchilli, 1997). Logit analysis was conducted to reduce the measured subjective preference for paired text into a one-dimensional scale, with a value of zero indicating equal preference and values of 1 and -1 indicating the certain preference for each of the paired text.

## Results

### Response Accuracy

Response accuracy was computed in relation to font rendering, word position, and word frequency. Results of 3-way repeated measures ANOVAs show that there was significant effect of font rendering ( $F(2, 32) = 41.045, p < .0001$ ), target position ( $F(7, 27) = 34.649, p < .0001$ ) and word frequency ( $F(1, 33) = 228.222, p < .0001$ ). There was interaction between word frequency and target position ( $F(7, 27) = 13.074, p < .0001$ ), between font rendering and word frequency ( $F(2, 32) = 4.700, p = .016$ ), but not between font rendering and word frequency ( $F(7, 37) = .948, p = .468$ ). There was interaction among font rendering, target position, and word frequency ( $F(14, 20) = 3.369, p = .007$ ).

Figure 3 shows the percentages of correct response relative to font rendering, target position, and word frequency. In Figures 3A and 3B, as expected, the correct percentage was generally higher for targets appearing in the right periphery than in the left periphery. In Figure 3A, for high-frequency words, in the right periphery the color-fringed words consistently led to significantly higher response accuracy than B&W words except for 6° eccentricity. Figure 3B shows a similar effect of target position on response accuracy for low-frequency words, but no significant difference in response

accuracy between B&W and color-fringed words. Comparing Figures 3A and 3B revealed significantly higher response accuracy for high-frequency words.

--- Figure 3 ---

To evaluate the effect of orthographic facilitation on word identification in relation to font rendering, the differences in the correct percentage of recognizing high- and low-frequency words were normalized against the accuracy for low-frequency words ( $(P_{\text{high}} - P_{\text{low}}) / P_{\text{low}}$ ). Figure 4 shows the amount of orthographic facilitation at different eccentricities for the three font rendering conditions. A positive value on the Y axis indicates a facilitation effect of word frequency. Figure 4 reveals that orthographic facilitation was reduced by the color fringe at 2° and 4° eccentricities in the left periphery, and was increased at 4° and 6° eccentricities in the right periphery.

--- Figure 4 ---

Results of 3-way repeated measures ANOVAs for response time show that there were significant effects for target position ( $F(7, 27) = 10.739, p < .0001$ ) and word frequency ( $F(1, 33) = 25.114, p < .0001$ ), but not font rendering ( $F(2, 32) = 1.153, p = .328$ ). There were also interactions between font rendering and word frequency ( $F(2, 32) = 3.421, p = .045$ ), target position and word frequency ( $F(7, 27) = 3.493, p = .009$ ), and between font rendering and target position ( $F(14, 20) = 4.087, p = .034$ ), and among the three variables ( $F(14, 20) = 1.764, p = .120$ ).

Figure 5 shows the response times for trials with correct responses. Figure 5A reveals that with higher frequency words, there was clear effect of target position, but little difference in response time across all target positions for the three font rendering

conditions. Conversely, as shown in Figure 5B, with low frequency words there was significant reduction in response time for target positions in the right periphery for both low and high CT conditions, compared to the B&W condition.

--- Figure 5 ---

Figure 6 shows the amount of orthographic facilitation in response time for the three font rendering conditions. This was derived from normalizing the difference in response times between high- and low-frequency words against the response time for low-frequency words ( $(RT_{high} - RT_{low}) / RT_{low}$ ). A negative value on the Y-axis indicates orthographic facilitation. Figure 6 reveals that compared to the B&W condition, the low CT condition resulted in significant orthographic facilitation in response time for targets presented in the right periphery. For the high CT condition, this rightward facilitation was weaker. There was no consistent facilitation effect in the left periphery for both conditions.

--- Figure 6 ---

To determine whether individual preference of font rendering predicts the ability to process the text at higher efficiency at certain eccentricities, the amount of change in response accuracy for 100% and 50% CT words relative to B&W words for different eccentricities was correlated to the level of preference for text with the same pairs of text conditions. Figure 7 shows scatter plots for the 8 eccentricities. Each data point indicates the corresponding color fringe preference and amount of change in response time. The X axis represents the preference of text rendering (right: color-fringed > B&W; left: B&W > color-fringed); the Y axis represents the change in response time (right:

reduced latency; left: increased latency). Data points placed in the up-right quadrant indicate a preference for color-fringed text to B&W text was accompanied by a reduction in response time. Data points placed in the lower-left quadrant indicates a preference for B&W text to color-fringed text was accompanied by an increase in response time. Therefore, data points in these two quadrants would be consistent with the predicted relationship between text preference and response latency.

In Figure 7, most of data points are located in the right, indicating that most subjects preferred color-fringed text regardless if it was moderately (magenta symbols) or strongly fringed (blue symbols). The panels for left 2°, right 1°, and right 2° eccentricities show a clear positive correlation between CT preference and CT effect on response accuracy, with subjects having greater CT preference also showing a greater improvement in response time for words with higher color fringe.

--- Figure 7---

#### Discussion

To measure the effect of transverse chromatic aberration (TCA) on peripheral word identification, the present study utilized color-fringed word stimuli to attenuate TCA in the right periphery and exacerbate it in the left periphery. The influence of orthographic facilitation on TCA effect was evaluated by manipulating the familiarity of word stimuli. Results show that the accuracy and speed of word identification was significantly improved in the near part of the right periphery tested, confirming that TCA plays a role in determining our ability to process words with peripheral vision. However, no clear change in response accuracy and increase of time and accuracy were observed

for words displayed in the left periphery, where exacerbated TCA is expected. Subjects preferred color-fringed text over B&W text and such preference was accompanied by the improvement in response accuracy in the near fovea, where text information can be effectively extracted.

TCA also interacted with orthographic facilitation in determining the efficacy of word identification. The facilitation was greater for color-fringed words displayed in the right periphery than for B&W words. In contrast, the facilitation effect was slightly lower for color-fringed words than for B&W words in the left periphery.

### ***TCA Effect and Word identification***

The actual effect of TCA on vision depends on the spatial resolution of retinal image processing at various eccentricities. If the magnitude of TCA is smaller than the resolution of retinal encoding, the processing of visual stimuli would not be consistently affected by it. We previously observed significant TCA effect on recognizing letters placed at 1 ° retinal eccentricity (Yang et al., 2009). However, since both TCA and the inter-neuron distance on retina increase with eccentricity, it is unclear whether human vision is also significantly affected by TCA at farther eccentricities.

The present results showed that TCA effect was present not only in the near right periphery at 1 degree, but also at 2- and 4-degree eccentricities, affecting the accuracy and/or the latency of word identification. In the left periphery, TCA effect was either absent or it slightly decreased response accuracy and response time. Previous studies have reported that in normal reading, the effective visual span from which visual information can be extracted is about 12 letters to the right and 5 letters to the left.

With the present viewing distance and letter size, the target positions amount to distances of 3.2, 6.4, 9.6, and 13.2 letters from the fovea. Therefore, TCA appears to significantly affect one's ability to extract word identity within the previously identified visual span in reading.

Note that stronger color fringe in text rendering did not consistently exert larger or smaller effect on word identification compared to moderate color fringe. The lack of difference in their effect suggests that the different intensities of sub-pixel displays at the fringe of text image do not affect their efficacy in heightening or reducing TCA. It is likely that other factors, such as the amount of spatial offset created by the rendering, determines the change in accuracy and latency of word identification instead.

One interesting question is whether the size of visual span is actually altered by the level of TCA. Since attenuating TCA significantly improves the accuracy of word identification in the right periphery, it is reasonable to assume that eliminating the TCA would further extend the useful visual span in reading. Further research is needed to determine TCA effect on the size of visual span in the context of normal reading, when multiple words are present and sentential context plays a role in word identification.

### ***The Asymmetric Effect of Color fringe***

The present results consistently display a larger TCA effect in the rightward periphery in word identification, when word stimuli were rendered with red fringe on the left edge and blue fringe on the right edge of their images. This is in line with our earlier finding that letter identification at 1° eccentricity was improved more in the right near fovea than was impeded in the left with the same pattern of color fringe. This

asymmetry cannot be explained by the location of eye fixation, as the eye position was monitored to maintain proper fixation in the center of the screen before target onset. Although it cannot be ruled out that the actual eye fixation was slightly to the right of the fixation point and within the measurement error of the eyetracker, such a bias would have predicted a lateral shift of symmetric curves for response accuracy and latency; instead, there was simply a skew toward the right for these curves, indicating a greater rightward influence of TCA in word identification.

An alternative explanation of the asymmetry is a rightward shift of covert visual attention that is independent of eye fixation (Posner, 1984; Morrison, 1984; Reichle, Rayner, & Pollatsek, 1999, 2004). The heightened attentional effect in the right periphery could magnify the TCA effect by improving the spatial resolution of visual processing in the visual cortex. This explanation is supported by the better response accuracy and shorter response time with B&W word stimuli. Since the subjects we recruited were native English speaker, they likely acquire the rightward tendency in attentional allocation through extensive reading activity, leading to an advantage in signal processing in the right periphery. Further research is needed to determine whether directing visual attention away from the right periphery affects TCA effect on visual processing.

### ***TCA Effect and Contextual Facilitation***

The identification of a visually presented word is mostly affected by two factors: sentential context and orthographic familiarity (Rayner, 1998; Reichle et al., 2004). Previous studies have reliably demonstrated that higher-frequency words can be

identified faster and more accurately in the fovea and in periphery (e.g., Rayner and Raney, 1996). According to the prominent model of word identification, the identification of a word is based on both bottom-up analysis of visual features for individual letters and top-down orthographic knowledge of adjacent letters within a word (Johnson and McClelland, 1980; McClelland and Rumelhart, 1981). As such, a word can be correctly identified even when it is miss-spelled slightly or when the visual features of individual letters are degraded. At times, a word can be mistaken as a visually-similar word without any visual impedance. TCA likely affects word identification by degrading the visual feature of individual letters. However, the degradation may not be significant enough to impede the ability to identify a word if sufficient top-down information is provided (McClelland and Rumelhart, 1981).

The present results confirm the effect of orthographic facilitation on word identification, with high frequency words resulting in much higher response accuracy and shorter response time. There was also an interaction between orthographic facilitation and the TCA effect on word identification, showing that the orthographic effect was greater in the right periphery where TCA was significantly reduced by the color fringe, and was smaller in the left periphery when TCA was slightly exacerbated by color fringe. The decrease of orthographic facilitation with color fringe in the left periphery might have resulted from the degradation of text appearance that severely disrupted the visual encoding of any orthographic information.

To conclude, the present findings show that TCA significantly affects text processing in reading. It is possible to increase the visual span in which text processing

takes place, and to enhance the efficiency and accuracy of text processing within the traditionally defined effective visual span, by reducing the amount of TCA in the right periphery with color fringed characters. Proper font rendering methods might be able to aid reading performance in the right periphery where previewing process takes place while exerting little hindrance in text processing in the left periphery.

**Acknowledgment**

This study was supported by a grant to James Sheedy from the Advance Reading Group at Microsoft Corporation.

References

- Anderson, S., Mullen, K., & Hess, R. (1991). Human peripheral spatial resolution for achromatic and chromatic stimuli: Limits imposed by optical and retinal factors. *The Journal of Physiology*, 442(1), 47-64.
- Bahcall, D. O., & Kowler, E. (1999). Attentional interference at small spatial separations. *Vision Research*, 39(1), 71-86.
- Banks, M. S., Geisler, W. S., & Bennett, P. J. (1987). The physical limits of grating visibility. *Vision Research*, 27(11), 1915-1924.
- Berkley, M. A., Kitterle, F., & Watkins, D. W. (1975). Grating visibility as a function of orientation and retinal eccentricity. *Vision Research*, 15(2), 239-244.
- Campbell, F., & Gubisch, R. (1966). Optical quality of the human eye. *The Journal of Physiology*, 186(3), 558-578.
- Cowey, A., & Rolls, E. (1974). Human cortical magnification factor and its relation to visual acuity. *Experimental Brain Research*, 21(5), 447-454.
- Croner, L. J., & Kaplan, E. (1995). Receptive fields of P and M ganglion cells across the primate retina. *Vision Research*, 35(1), 7-24.
- Dakin, S. C., & Hess, R. F. (1997). The spatial mechanisms mediating symmetry perception. *Vision Research*, 37(20), 2915-2930.
- French, A., Snyder, A., & Stavenga, D. (1977). Image degradation by an irregular retinal mosaic. *Biological Cybernetics*, 27(4), 229-233.
- Hirsch, J., & Curcio, C. A. (1989). The spatial resolution capacity of human foveal retina. *Vision Research*, 29(9), 1095-1101.

- Howarth, P. A. (1984). THE LATERAL CHROMATIC ABERRATION OF THE EYE. *Ophthalmic and Physiological Optics*, 4(3), 223-226.
- Johnston, J., & McClelland, J. L. (1980). Experimental tests of a hierarchical model of word identification. *Journal of Verbal Learning and Verbal Behavior*, 19(5), 503-524.
- Kucera, H. and Francis, W. N. (1967). *Computational Analysis of Present Day American English*. Brown University Press, Providence.
- Low, F. N. (1951). Peripheral visual acuity. *A.M.A. Archives of Ophthalmology*, 45(1), 80-99.
- Marcos, S., Burns, S. A., Moreno-Barriusop, E., & Navarro, R. (1999). A new approach to the study of ocular chromatic aberrations. *Vision Research*, 39(26), 4309-4323.
- Marcos, S., Barbero, S., & Jimenez-Alfaro, I. (2005). Optical quality and depth-of-field of eyes implanted with spherical and aspheric intraocular lenses. *Journal of Refractive Surgery (Thorofare, N.J.: 1995)*, 21(3), 223-235.
- McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: Part 1. an account of basic findings. *Psychological Review*, 88(5), 375-407.
- McConkie, G. W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics*, 17(6), Jun 1975, 578-586.
- McConkie, G. W., & Rayner, K. (1976). Asymmetry of the perceptual span in reading. *Bulletin of the Psychonomic Society*, 8(5), Nov 1976, 365-368.

- Morrison, R. E. (1984). Manipulation of stimulus onset delay in reading: Evidence for parallel programming of saccades. *Journal of Experimental Psychology: Human Perception & Performance*, 10(5), Oct 1984, 667-682.
- Ogboso, Y. U., & Bedell, H. E. (1987). Magnitude of lateral chromatic aberration across the retina of the human eye. *J.Opt.Soc.Am.A*, 4, 1666-1672.
- Posner, M. I., and Cohen, Y. (1984). Components of performance. In X, ed. H. Bouma, D. Bowhuis, *Attention and Performance* (pp. 531-56). Hillsdale, NJ: Erlbaum.
- Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, 124, 372-422.
- Rayner, K., and Raney, G. E. (1996). Eye movement control in reading and visual search: effects of word frequency. *Psychonomic Bulletin & Review* 3 (1996), pp. 238–244.
- Rayner, K. (1975). Parafoveal identification during a fixation in reading. *Acta Psychologica*, 39(4), Aug 1975, 271-281.
- Reichle, E. D., Rayner, K., & Pollatsek, A. (2004). The EZ reader model of eye-movement control in reading: Comparisons to other models. *Behavioral and Brain Sciences*, 26(04), 445-476.
- Reichle, E. D., Rayner, K., & Pollatsek, A. (1999). Eye movement control in reading: Accounting for initial fixation locations and refixations within the E-Z reader model. *Vision Research*, 39(26), Oct 1999, 4403-4411.
- Rynders, M., Lidkea, B., Chisholm, W., & Thibos, L. N. (1995). 'Statistical distribution of foveal transverse chromatic aberration, pupil centration, and angle in a population of young adult eyes. *J.Opt.Soc.Am.A*, 12, 2348–2357.

- Simonet, P., & Campbell, M. C. W. (1990). Effect of illuminance on the directions of chromostereopsis and transverse chromatic aberration observed with natural pupils. *Ophthalmic and Physiological Optics*, 10(3), 271-279.
- Tai, Yu-Chi, Sheedy, James E., & Hayes, John R.. (2006). Effect of letter spacing on legibility, eye movements, and reading speed. *Journal of Vision*, 6(6), 994a.
- Thibos, L. (1987). Calculation of the influence of lateral chromatic aberration on image quality across the visual field. *J.Opt.Soc.Am.A*, 4, 1673-1680.
- Thibos, L., Bradley, A., Still, D., Zhang, X., & Howarth, P. (1990). Theory and measurement of ocular chromatic aberration. *Vision Research(Oxford)*, 30(1), 33-49.
- Vonesh, E. F., and Chinchilli, V. G. (1997). *Linear and nonlinear models for the analysis of repeated measurements*. London, UK: Chapman and Hall.
- Williams, D. R. (1985). Visibility of interference fringes near the resolution limit. *J.Opt.Soc.Am.A*, 2(7), 1087-1093.
- Williams, D. R. (1986). Seeing through the photoreceptor mosaic. *Trends Neurosci*, 9, 193–198.
- Yang, S.-N., Tai, Y.-C., Laukkanen, H., & Sheedy, J. (2009). Effects of ocular transverse chromatic aberration on near foveal letter identification. *Vision Research*, 49(23), 2881-2890.

## Figures

Figure 1. Illustration of transverse chromatic aberration (TCA), example of TCA effect on word images at 2° and 8° eccentricities, and examples of color-fringed word stimuli. A) TCA on the retinal image of peripheral stimuli. B) Expected TCA effect on an example word at different eccentricities. C) Examples of testing stimuli with high (100%) ClearType(CT)-induced color fringe, moderate (50%) color fringe, and non-fringed B&W.

Figure 2. Experimental paradigm. In each trial, a target word was displayed at the left or right of fixation point, with the center of the letter string 1°, 2°, 4°, or 6° away from the fixation point. Word frequency and target eccentricity were randomly determined from trial to trial. Subjects orally reported the identity of target word. A voice key was used to measure response time; a trial was terminated 3000ms after the offset of the target if no oral response was registered by the voice key.

Figure 3. Mean response accuracy for identifying words presented at different eccentricities. The lack of overlap for any two data points indicates a statistically significant difference of  $\alpha < .05$  for the corresponding conditions. A) Response accuracy for high-frequency words rendered in high color fringe (100% Gaussian), moderate high fringe (50% Gaussian), and no fringe (B&W). B) Response accuracy for low-frequency words.

Figure 4. Normalized frequency effect on response accuracy in relation to target eccentricity. The value on the Y axis was derived from the difference between

the percentages of correct response for the two text conditions, divided by that for the B&W condition. The lack of overlap for any two data points indicates a statistically significant difference of  $\alpha < .05$  for the corresponding conditions in response accuracy.

Figure 5. Mean response time for identifying words presented at different eccentricities.

The lack of overlap for any two data points indicates a statistically significant difference of  $\alpha < .05$  for the corresponding conditions. A) Response time for high-frequency words rendered in high color fringe (100% Gaussian), moderate high cringe (50% Gaussian), and no fringe (B&W). B) Response time for low-frequency words.

Figure 6. Normalized effect of word frequency on response time in relation to target eccentricity. The value on the Y axis was derived from the difference in response times between high- and low-frequency words against the response time for low-frequency words. The lack of overlap for any two data points indicates a statistically significant difference of  $\alpha < .05$  for the corresponding conditions.

Figure 7. Effects of color fringe on the change in response time in relation to individual preference to text condition. Each panel shows the results for one horizontal eccentricity. The X axis represents the preference of text rendering (right: color-fringed > B&W; left: B&W > color-fringed); the Y axis represents the change in response time (right: reduced latency; left: increased latency).

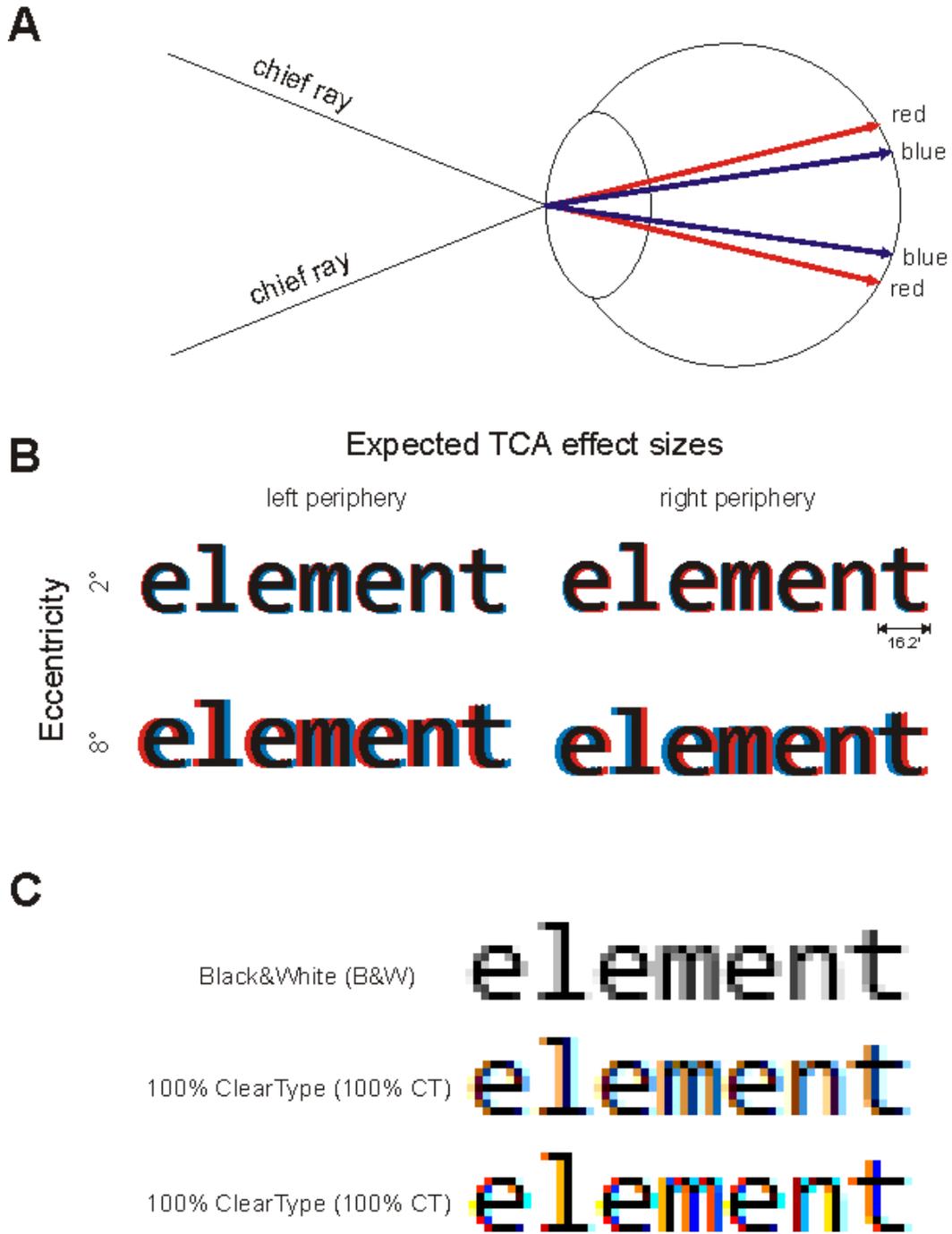


Figure 1

TCA effect on peripheral word identification

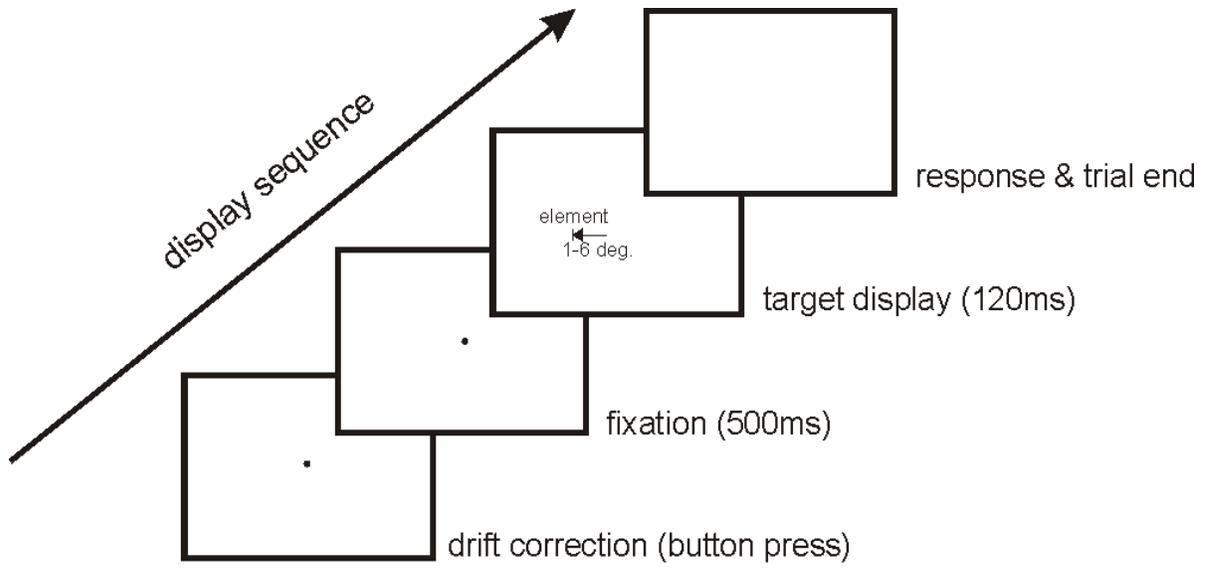


Figure 2

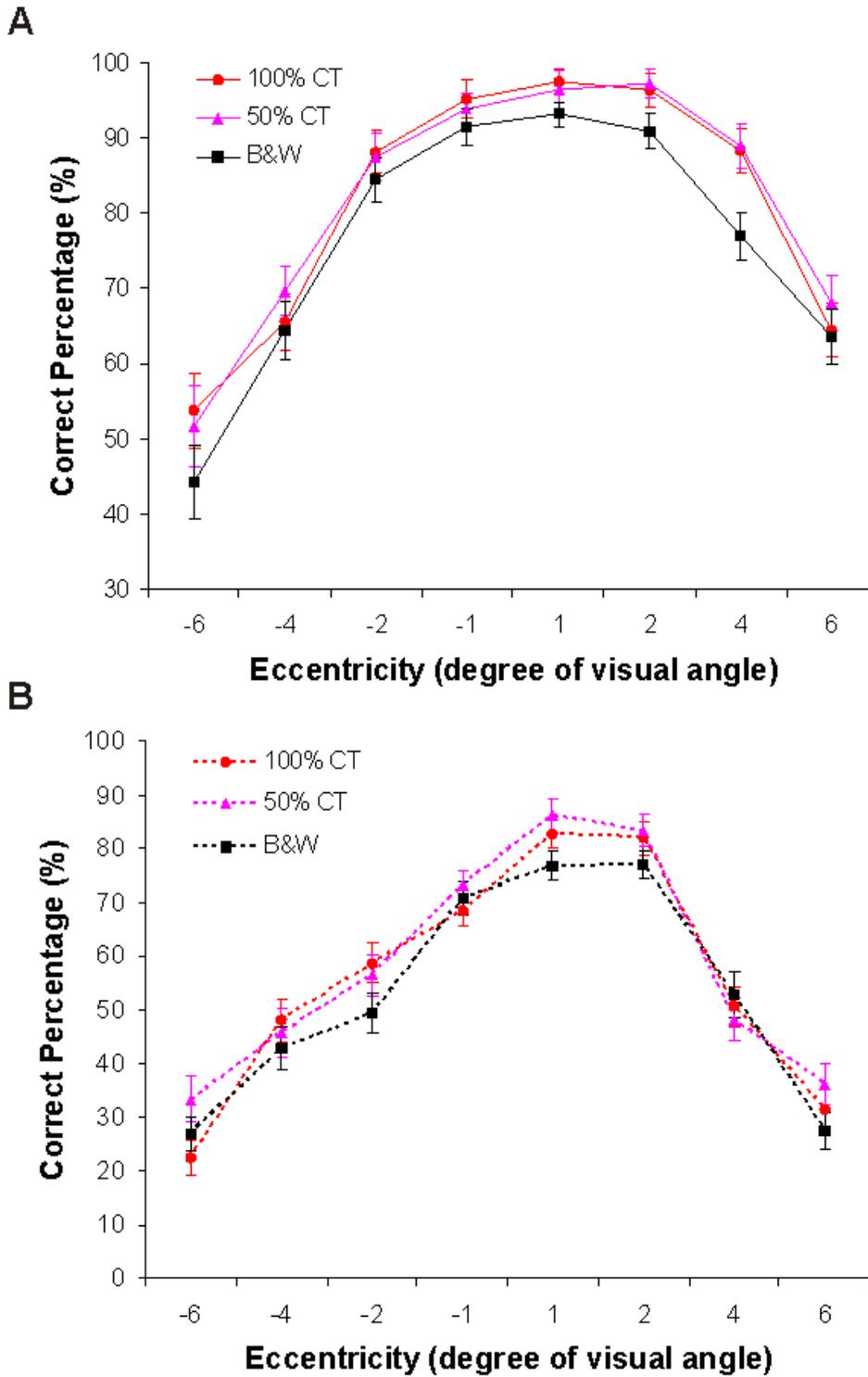


Figure 3

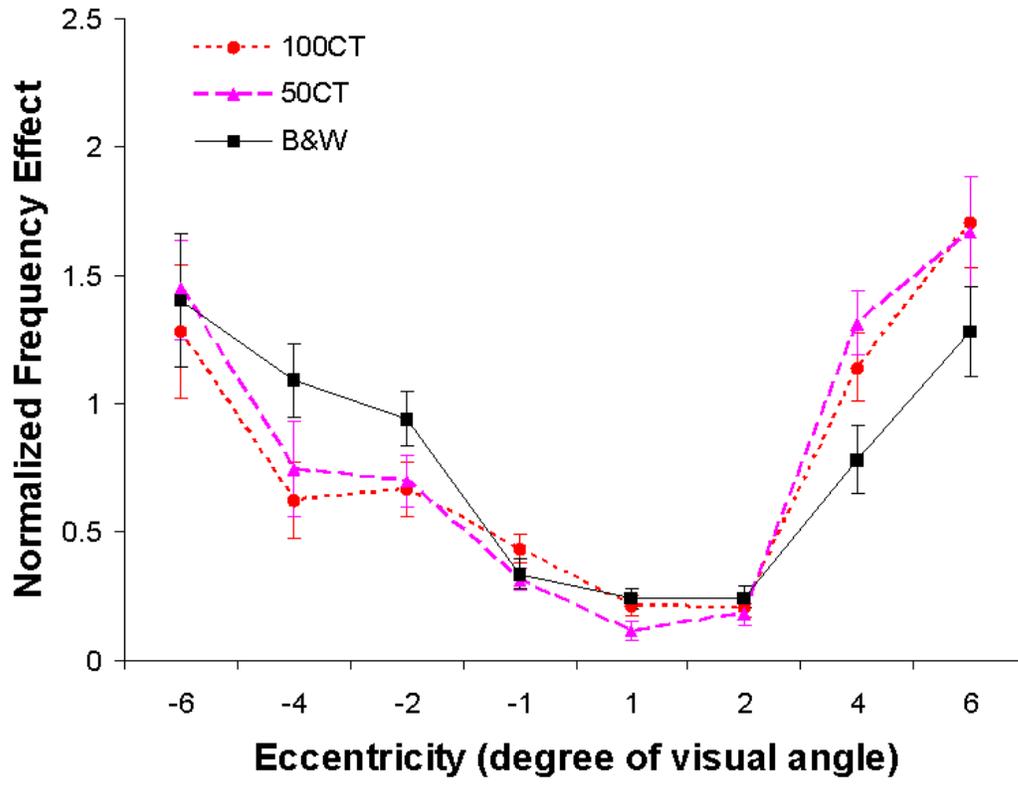


Figure 4

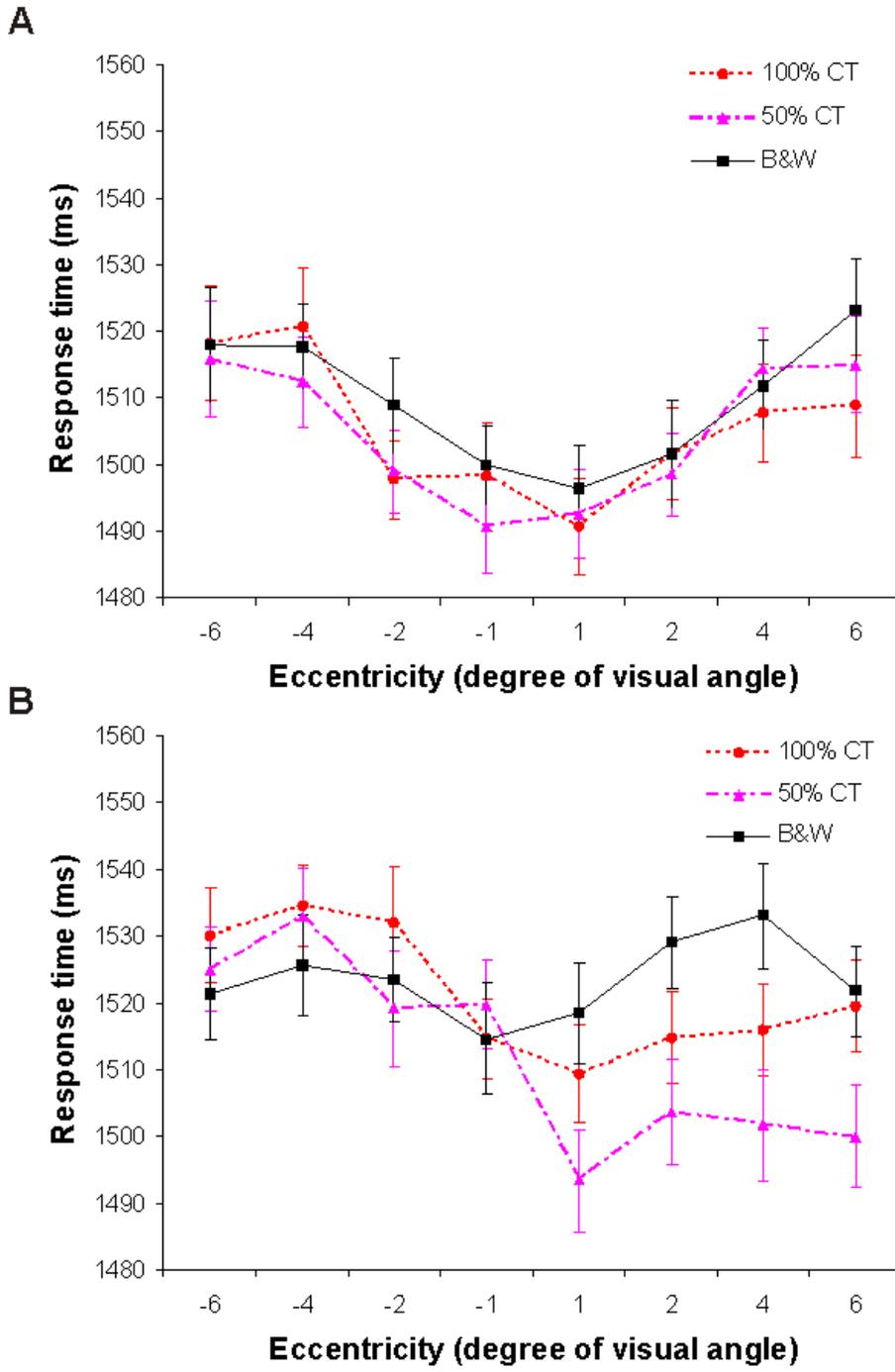


Figure 5

TCA effect on peripheral word identification

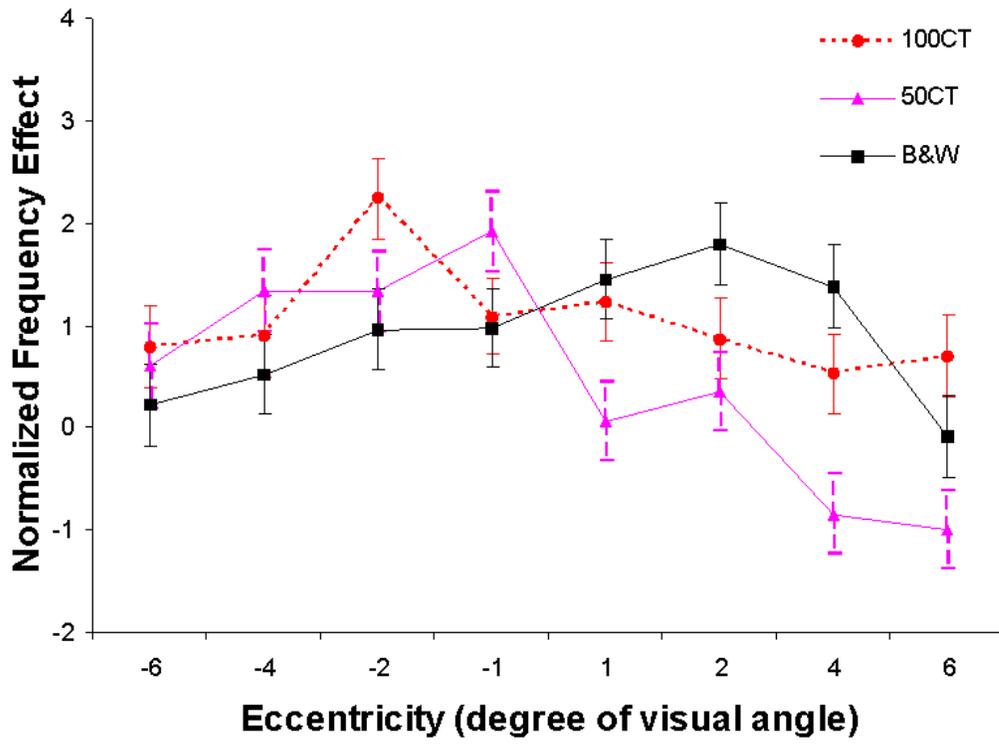


Figure 6

# TCA effect on peripheral word identification

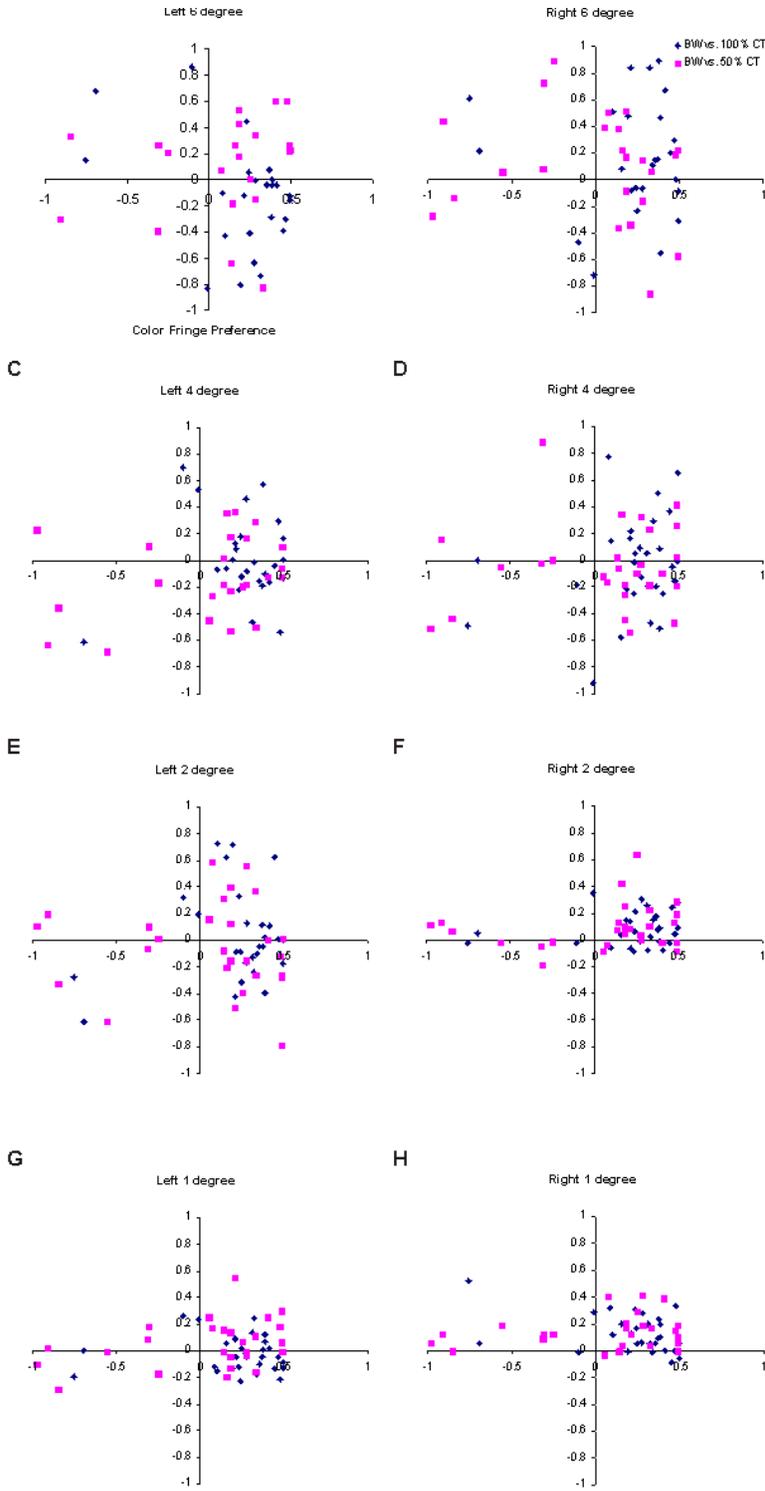


Figure 7