

Periodic letter strokes within a word affect fixation disparity during reading

Stephanie Jainta

Leibniz Research Centre for Working Environment
and Human Factors, Dortmund, Germany



Wolfgang Jaschinski

Leibniz Research Centre for Working Environment and
Human Factors, Dortmund, Germany



Arnold J. Wilkins

Visual Perception Unit, University of Essex, Colchester, UK



We investigated the way in which binocular coordination in reading is affected by the spatial structure of text. Vergence eye movements were measured (EyeLink II) in 32 observers while they read 120 single German sentences (Potsdam Sentence Corpus) silently for comprehension. The similarity in shape between the neighboring strokes of component letters, as measured by the first peak in the horizontal auto-correlation of the images of the words, was found to be associated with (i) a smaller minimum fixation disparity (i.e. vergence error) during fixation; (ii) a longer time to reach this minimum disparity and (iii) a longer overall fixation duration. The results were obtained only for binocular reading: no effects of auto-correlation could be observed for monocular reading. The findings help to explain the longer reading times reported for words and fonts with high auto-correlation and may also begin to provide a causal link between poor binocular control and reading difficulties.

Keywords: fixation disparity, stripes, auto-correlation, fixation duration, vergence

Citation: Jainta, S., Jaschinski, W., & Wilkins, A. J. (2010). Periodic letter strokes within a word affect fixation disparity during reading. *Journal of Vision*, 10(13):2, 1–11, <http://www.journalofvision.org/content/10/13/2>, doi:10.1167/10.13.2.

Introduction

Striped images are known to result in perceptual distortions (Wilkins, 1995) and people experiencing these distortions usually read more slowly (Wilkins, 2003). Due to the similarity between neighboring letter strokes, words in a text exhibit a striped shape, which differs between different words and typefaces. Wilkins et al. (2007) measured the “stripiness” of word shape in terms of the horizontal auto-correlation. They showed that the first peak of the horizontal auto-correlation function predicted the appearance of a word as striped, and argued that the auto-correlation provides a simple way of measuring the extent to which the image of a word approximates a pattern of stripes. For example, the German word “Baum” consists of a repetitive pattern of vertical lines and the corresponding first peak of the auto-correlation function reaches a value of around 0.6 (in Times New Roman); the word “Spiel” is less “stripy” and has a smaller value (about 0.3 in Times New Roman). Wilkins et al. (2007) showed that the first peak of the horizontal auto-correlation function predicted the speed of reading randomly ordered common words. In the present study we asked participants to read meaningful sentences silently for comprehension and identified fixated words *a posteriori*. For all sentence presentations we collected eye movement data and analyzed the disconjugate eye movements, i.e. vergence, during fixations.

Binocular reading of a text requires that the vergence angle between the two visual axes is adjusted for appropriate fusion of the two retinal images. In (theoretically) optimal binocular vision, the principle visual directions of both eyes intersect at the fixation point; slight departures from this optimal state—fixation disparities (FD) or vergence errors—typically amount to a few minutes of arc and are thus smaller than Panum’s fusional area, and double vision is avoided. Vergence eye movements differ from saccadic eye movements in several respects: (1) they are not ballistic movements but are (2) slower and (3) controlled by continuous feedback; the movement is (4) more unstable with a (5) less predictable shape (Howard, 2002; Howard & Rogers, 2002). Further, the static vergence error, i.e. vergence fixation disparity, is (6) different for different observers and might be related to resting states of the vergence system, dynamic vergence properties (Patel, Jiang, & Ogmen, 2001) and/or the coupling of accommodation and vergence (Howard & Rogers, 2002).

It was the aim of the present study to determine whether vergence adjustments (fixation disparities) after a saccade depend upon the auto-correlation of the fixated words as speculated by Wilkins et al. (2007). The vergence adjustments during reading are one possible cause of the slower reading of words with high horizontal autocorrelation because vergence eye movements are controlled by feedback during the process of fusion. As long as fusion is not

achieved, the vergence system adjusts the angle between the visual axes of the two eyes—and even beyond perceptual fusion the vergence angle is further adjusted due to remaining binocular disparity between the images of the words in the two eyes (Collewijn, Erkelens, & Steinman, 1995; Howard, 2002; Liversedge, Rayner, White, Findlay, & McSorley, 2006; Liversedge, White, Findlay, & Rayner, 2006).

For targets with higher spatial periodicity, i.e. greater “stripiness”, it might be more difficult to achieve fusion because the repetitive structure of the pattern allows the possibility of erroneous fusion. To completely fuse a word with repetitive spatial structure, a more exact matching of the two images must be provided to avoid ambiguity. We hypothesized that the higher the auto-correlation, the longer the time to achieve these smaller vergence errors and, the longer the fixation duration. The aim of our study was to test this speculation empirically. We conducted two separate experiments: the first (major) experiment involved a simple reading task during which we collected binocular eye movement recordings in order to describe fixation disparity for words with different auto-correlations. In this first experiment reading was binocular, and therefore vergence adjustments were made to achieve a fused, single image of each word. In the second experiment we included both binocular viewing and also a more “unnatural” viewing condition in which the sentences were read by the right eye only and no adjustments of vergence were necessary. The aim of the monocular condition was to test the hypothesis that any longer fixation durations were attributable to a fusional process and consequent vergence adjustments.

General methods

Participants

In total, 32 young adults participated in both experiments: we collected data for 18 participants in [Experiment 1](#), 22 in [Experiment 2](#) and 8 participated in both studies. All participants had an uncorrected visual acuity of 1.0 or better (in decimal units) in each eye. Participants’ ages ranged from 18 to 37 years (mean: 24 years). Myopic, hypermetropic, or astigmatic refractive errors did not exceed 0.5 D (median across participants: 0.25 D) and no refractive corrections were worn. Each participant gave informed consent before the experiments; the research followed the tenets of the Declaration of Helsinki and was approved by an ethics committee.

Eye movement measurement and calibration

We recorded eye movements with the video-based EyeLink II, which tracks both eyes simultaneously at a sampling frequency of 500 Hz. The system tracks the

dark center of the pupil by an algorithm similar to a centroid calculation with a theoretical noise-limited resolution of 0.01 deg (0.6 min arc) and velocity noise of <3 deg/s for two-dimensional eye-tracking (details provided by SR Research Ltd., Osgoode ON, Canada). In previous work (Jainta, Hoormann, & Jaschinski, 2009; Jainta & Jaschinski, 2010) we included data showing specifically that changes in the vergence angle in the range typically observed during reading studies can be reliably measured with the EyeLink II—at least in the present experimental conditions in which we fixed the head with a chin and forehead rest including a narrow temporal rest to minimize head movements. Further, we used the raw data of the EyeLink II system and performed a separate calibration for each eye in order to transfer pixel-coordinates into degrees.

During the calibration procedure, the targets were presented monocularly in a haploscopic arrangement resembling a Wheatstone mirror stereoscope (Howard & Rogers, 2002) with two mirrors at right angles and two VDU screens (CRT Sony F500 T9). These screens were placed at a viewing distance of 60 cm and for each individual inter-pupillary distance (mean \pm SD: 63.5 \pm 3 mm) we adjusted the disparity of the stimuli to have a baseline vergence of 6 deg, at which we presented the sentences. We were mainly interested in vergence changes during reading so we optimized our setup in order to keep constant vergence demands for each participant, while as a consequence the stimuli for accommodation and for vergence were slightly different. In other words the viewing distance was 60 cm considering the sentences as stimuli for accommodation, while the sentences as stimuli for vergence were slightly (and virtually) in front or behind the viewing distance of 60 cm depending on the inter-pupillary distance of the participant (for our sample, the difference between the two planes for vergence and accommodation ranged from 0 to 3.9 cm. Note that concerning the accommodative deviation, the effect for the largest deviation ranged up to 0.1 D, which is still smaller than typical figures of the depth of focus (Howard & Rogers, 2002)). Participants were requested to carefully fixate calibration targets that appeared for 1000 ms with 100 ms temporal gaps randomly at one of the nine positions within a 3 \times 3 calibration grid. The displacement between the calibration points was 8 deg, so that the calibration grid covered a central space of 16 \times 16 deg. Presentations to the right and left eye separately were randomly interleaved and because of the haploscopic viewing arrangement the targets appeared monocularly while the remainder of the screen appeared binocularly. This feature of a haploscope guarantees monocular calibrations which are essential if one aims to describe fixation disparities (Bucci & Kapoula, 2006; Liversedge, Rayner, et al., 2006). In order to draw attention to the calibration targets and to facilitate fixation, the diameter of the spot initially subtended 1 deg and over the course of 1000 ms shrank to a cross of 8.1 \times 8.1 min arc (stroke

Als Kapitalanlage ist Gold nicht zu empfehlen.

Figure 1. Example of the sentences in [Experiment 1](#) to show the font of the presented words.

width: 2.7 min arc) which remained visible for 400 ms during which calibration data were stored.

We calculated a standard deviation for each measured eye position during the task which reflected the quality of the measurement estimated with respect to the corresponding calibration (Hoormann, Jainta, & Jaschinski, 2008). We accepted only those eye position measurements that showed an uncertainty due to calibration that was less than a character width, i.e. less than 20 min arc.

Procedure, stimuli and apparatus

Participants were required to read sentences from the Potsdam Sentence Corpus (PSC; Kliegl, Nuthmann, & Engbert, 2006). We selected sentences containing 7 to 8 words and the sentence sequence was random for each participant. [Figure 1](#) shows a sentence to indicate the font used. Sentences were presented until the participant clicked on a mouse button to indicate that he/she had finished reading. Before and after sentence presentation, a fixation cross appeared. Between sentence presentations these crosses were replaced on 1/3 of the trials at random by a three-alternative multiple choice question pertaining to the immediately preceding sentence. For example, the sentence in [Figure 1](#) was followed by the question: “*Was eignet sich nicht als Kapitalanlage?*”.

We measured eye movements for blocks of 10 sentences; before the first and after the 10th sentence we undertook a complete calibration and combined both regressions to a unique calibration for each block of 10 sentences. After such a block of 10 sentences we included breaks of a few minutes, so that the participants could rest and relax their eyes.

All stimuli were presented on a white background (full screen of a 19 inch display) with a luminance of 33 cd/m² at 100 Hz, and dark border in a room lit by incandescent lamps to a level of 43 lux.

Data selection and parameter extraction

Eye movement data were screened for loss of measurement and blinks. We marked saccades within each sentence and selected each saccade with its subsequent fixation period. For saccade detection, we defined saccade onset as the time when the velocity of the version signal ((left eye + right eye)/2) reached 5% of the saccadic peak velocity; the offset of the saccade was defined as the time when the eye velocity dropped below 10 deg/s (see, for example, Bucci & Kapoula, 2006; Liversedge, Rayner, et al., 2006). Next, we

excluded saccades with amplitudes smaller than 10 min arc and with fixation phases shorter than 80 ms or longer than 1200 ms (Liversedge, Rayner, et al., 2006) and analyses were restricted to initial fixations on words in first-pass reading. We included only data sets from participants who gave more than a critical number of fixations (150 for [Experiment 1](#) and 30 for [Experiment 2](#), respectively). We were only interested in the fixation phases and marked them as starting from saccade offset to the next saccade onset. We extracted fixation durations and the (absolute) minimum fixation disparity that was reached during fixation (based on the disconjugate eye movement: left eye–right eye signal). Note that for all fixation disparity calculations we took the actual fixation position from the version signal and the inter-pupillary distance of each subject to accurately calculate the theoretically expected vergence angle; then we subtracted the measured vergence angle from this theoretical angle. For our purposes, we took only the absolute amount of fixation disparity irrespective of the direction of vergence error (crossed or uncrossed). Further, we marked the moment in time, when this minimum fixation disparity was reached. For comparison, we also extracted the moment in time when the minimum in version was reached, i.e. the minimum in the conjugate drift of the eyes after a saccade.

Calculating auto-correlations for each presented word

For an image M pixels high and N wide, the horizontal auto-correlation of the image, r , is a function of the shift or lag, h :

$$r_h = \frac{\left[\sum_{i=1}^M \sum_{j=1}^{N-h} (d_{i,j+h} - \bar{d})(d_{i,j} - \bar{d}) \right]}{\left[\sum_{i=1}^M \sum_{j=1}^N (d_{i,j} - \bar{d})^2 \right]}, \quad (1)$$

where each pixel has a density, d . In effect, the horizontal auto-correlation is the covariance of the density of corresponding pixels in the proportion of the image common to the original image and the same image shifted horizontally by a given lag, divided by the variance of the density of pixels in the original image. In the above formula the lagged image decreases in size with lag. To keep the lagged and original images similar in size for all lags the image was correlated with another, generated by a process equivalent to moving a column of white pixels from the right hand extreme of the image to the left hand extreme. The process was repeated 30 times, one column of pixels at a time, so as to provide a maximum lag of 30 pixels.

The words, 421 in all, ranged in length from 2 to 15 letters (average: 5.53). An image 100 pixels wide by

30 high contained each word in black pixels (value 0) against a white background (value 255) with a sufficient margin.

Experiment 1: Binocular reading

Task and methods

In [Experiment 1](#), 18 participants were required to read 60 sentences from the Potsdam Sentence Corpus twice. Reading was binocular and the analysis of the eye movement signals provided data for 4116 fixations.

All letters of the presented words were written within a matrix of 9×7 pixels, on average 24 min arc high by 20 min arc wide, as illustrated in [Figure 1](#). The size of the image necessary to accommodate the longer words was larger than that for the smaller words, resulting in a reduction in the variance of the image for the small words relative to the large. Additional analyses were therefore undertaken using a smaller image (30 pixels wide) that cropped the ends of the longer words. The correlation between the first peak in the horizontal auto-correlation obtained from an analysis using large windows and one using small was 0.824. The correlation between word length and the size of the first peak in the horizontal

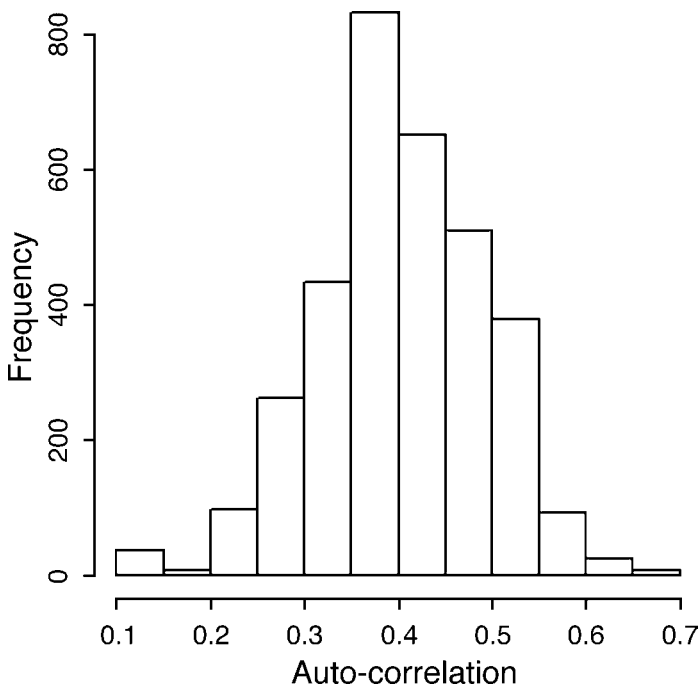


Figure 2. Histogram of the auto-correlation of all fixated words during binocular reading in [Experiment 1](#). The histogram represents the distribution of auto-correlations for all occurrences of all words.

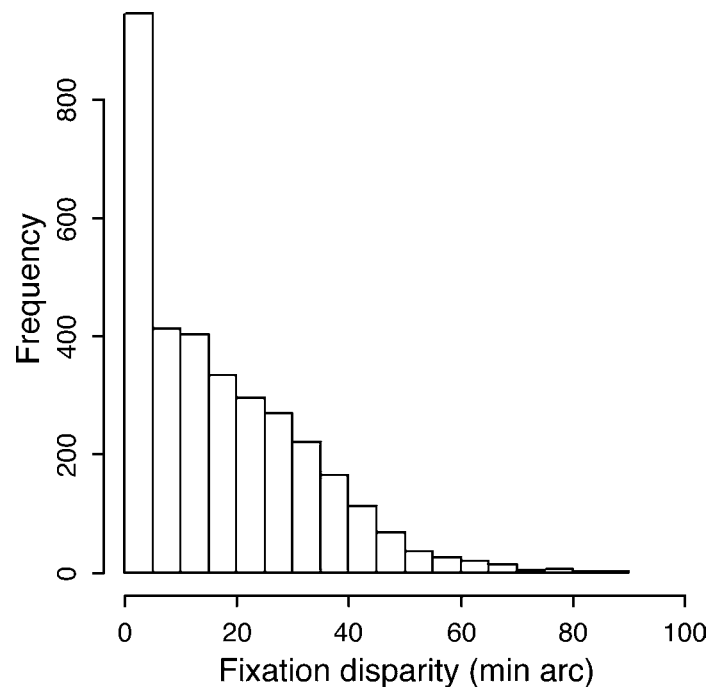


Figure 3. Histogram of the minimum fixation disparity (min arc).

auto-correlation was -0.21 for the larger image and -0.29 for the smaller.

For our analysis of the fixation disparity during reading, we selected all words that were targets of fixations. [Figure 2](#) shows the distribution of auto-correlations for these words. We divided the entire data set into 8 categories according to this distribution, which represented the auto-correlation range from 0.2 to 0.6. For auto-correlations smaller than 0.2 or larger than 0.6 too few observations were found. Further, we built up categories of 0.05 steps in auto-correlation and sorted all extracted eye movement parameters accordingly. Note that for all figures we have used the midpoint of each category for the purposes of illustration.

Results

The average lag at which the horizontal auto-correlation function reached its first peak was 5.5 pixels (SD 0.9) (14.9 min arc) and the average correlation coefficient was 0.41 (SD 0.09). There was a negative correlation across words of -0.21 between the lag and the auto-correlation coefficient.

The smallest fixation disparity reached during the complete fixation phase was 14.3 min arc (± 15.5 ; see [Figure 3](#)) on average, which was slightly smaller than the average width of a character. The moment in time during fixation when the smallest fixation disparity was reached deviated from the average fixation duration: on average the minimum fixation disparity was reached at 121.1 ms

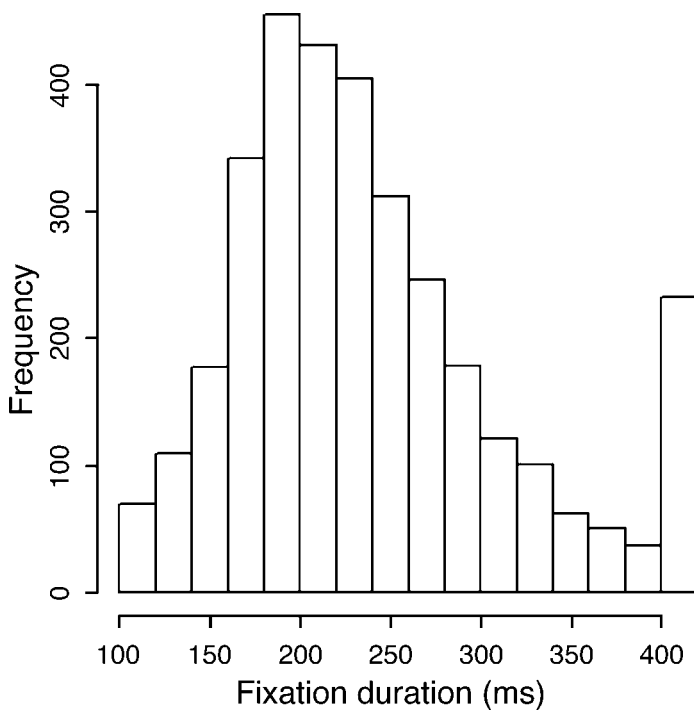


Figure 4. Histogram of the fixation duration (ms) during reading in Experiment 1; note that reading times longer than 500 ms were put into the last category on the right side.

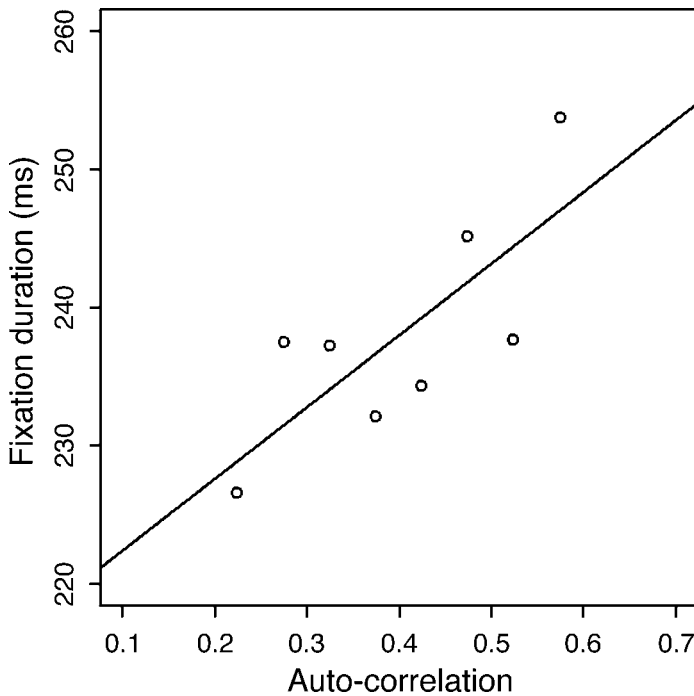


Figure 5. Fixation duration (ms) as a function of auto-correlation of the fixated words. The line represents the regression line, with the equation: fixation duration = 217.3 + 51.8 * auto-correlation. Standard-deviations for the mean values of fixation duration per bin of auto-correlation ranged from 35.8 ms to 39.6 ms.

(±89.8) and average fixation duration was 238.5 ms (±81.6) (see Figure 4).

After categorizing fixation duration according to the value of auto-correlation, average fixation duration was longer for words with high auto-correlation ($F_{1,6} = 8.55$, $p = 0.03$). Figure 5 shows the data, including the regression line ($R^2 = 0.52$).

The time when the minimum fixation disparity was reached during fixation increased with auto-correlation, though not significantly ($F_{1,6} = 2.12$, $p = 0.19$; $R^2 = 0.14$; see Figure 6). To explore whether this increasing fixation duration with auto-correlation was only connected to vergence regulation during the fixation of a word, we additionally extracted the time when the minimum in the version movement during fixation was reached, i.e. the endpoint of the version drift after saccades. This moment in time did not change with the auto-correlation of the fixated words ($F_{1,6} < 1$; $R^2 = 0.02$).

Average minimum fixation disparity showed a tendency to decrease when the auto-correlation increased ($F_{1,6} = 2.75$, $p = 0.11$; $R^2 = 0.33$; see Figure 7).

In a previous study we showed that the average fixation disparity a participant revealed during the scanning of a sentence was biased by his or her heterophoria, i.e. the vergence state without a fusion stimulus (Jainta & Jaschinski, 2010). We therefore calculated the average

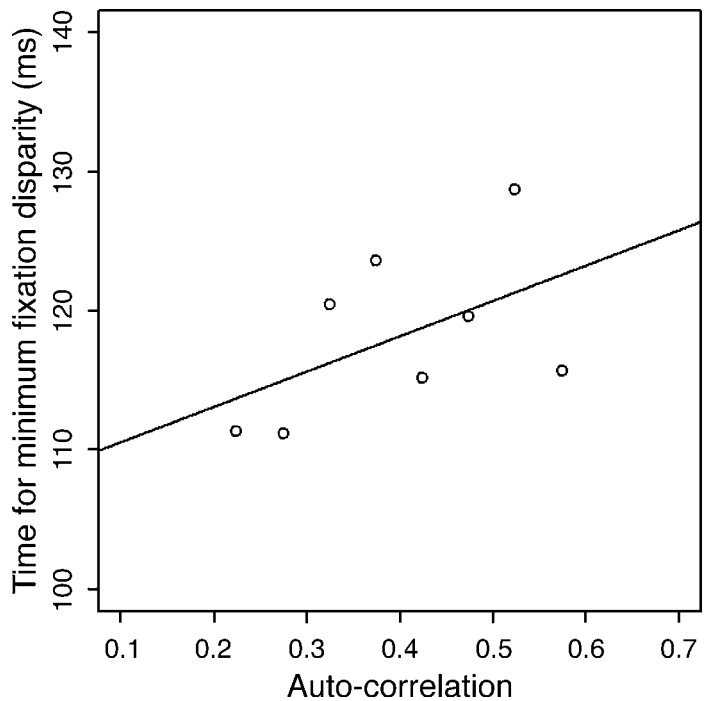


Figure 6. The moment in time (ms), when the minimum fixation disparity was reached, as a function of auto-correlation of the fixated words. The line represents the regression line, with the equation: time of minimum fixation disparity = 108.1 + 25.4 * auto-correlation. Standard-deviations for the mean values of time for minimum fixation disparity per bin of auto-correlation ranged from 64.2 ms to 71.3 ms.

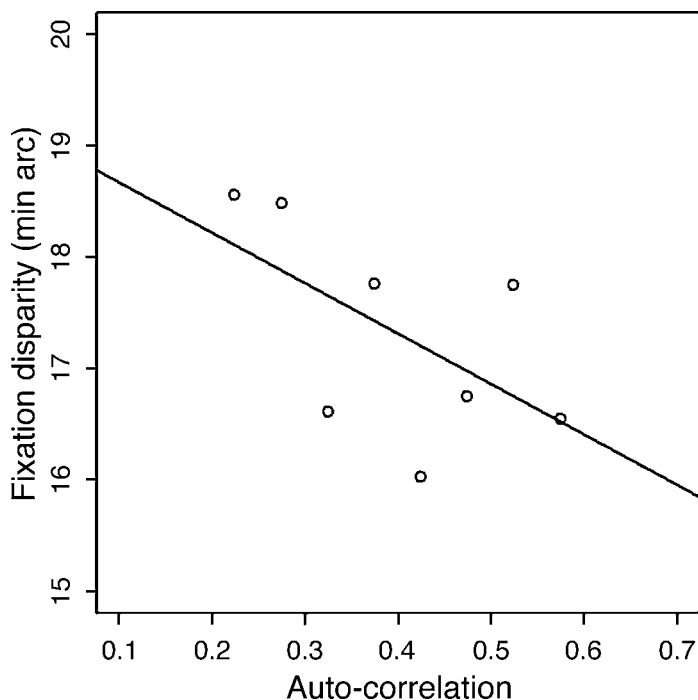


Figure 7. Average (minimum) fixation disparity (min arc) as a function of auto-correlation of the fixated words. The line represents the regression line, with the equation: fixation disparity = $25.2 - 4.4 * \text{auto-correlation}$. Standard-deviations for the mean values of fixation disparity per bin of auto-correlation ranged from 14.8 min arc to 17.2 min arc.

(minimum) fixation disparity per sentence for each participant and subtracted it from all corresponding fixation disparities within a sentence.

Based on this “state” fixation disparity (see Jainta & Jaschinski, 2010), we divided the data set again into the categories of different auto-correlations of fixated words. A significant reduction of the fixation disparity was observed when the auto-correlation increased ($F_{1,6} = 3.26$, $p = 0.02$; $R^2 = 0.64$; see Figure 8).

Interim discussion

In Experiment 1 we showed a clear tendency for fixation disparity to decrease with an increase in the first peak in the horizontal auto-correlation function. Further, we found that fixation duration during reading increased if the fixated words had higher auto-correlations. The low negative correlation between word length and the peak in autocorrelation indicates that the effect of the auto-correlation cannot be attributed to word length. The finding is consistent with the decrease in reading speed, which was initially measured using passages of randomly ordered words (Wilkins et al., 2007). The present results indicate that the effect extends to the silent reading of meaningful sentences, and that vergence adjustments

during reading might contribute to the observed increase in reading and fixation duration. In other words, for words with higher auto-correlations, both observations, a smaller fixation disparity and a longer duration to reach it during fixation, might reflect a simple regulative process: the more repetitive the pattern of a word, the smaller the tolerated fixation disparity necessary to avoid ambiguous fusion. The regulative process takes time and ultimately increases fixation duration.

Such a basic effect needs to be discussed in a broad context—considering all plausible mediating or confounding variables. Reading is a highly skilled and complex task, during which eye movements are made systematically (Blythe et al., 2006; Bucci & Kapoula, 2006; Kirkby, Webster, Blythe, & Liversedge, 2008; McConkie, Kerr, Reddix, & Zola, 1988; McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; Rayner, 1998) and it is well established that several variables contribute to fixation duration, as for example, the frequency, predictability and length of the fixated words (Kliegl et al., 2006; Rayner, 1998). Our interpretation of the increase of fixation duration as a consequence of a time consuming process of vergence adjustment is indirect in nature. We therefore conducted a second experiment which contained binocular and monocular reading conditions. If the increase of fixation duration is independent of vergence adjustments we would expect

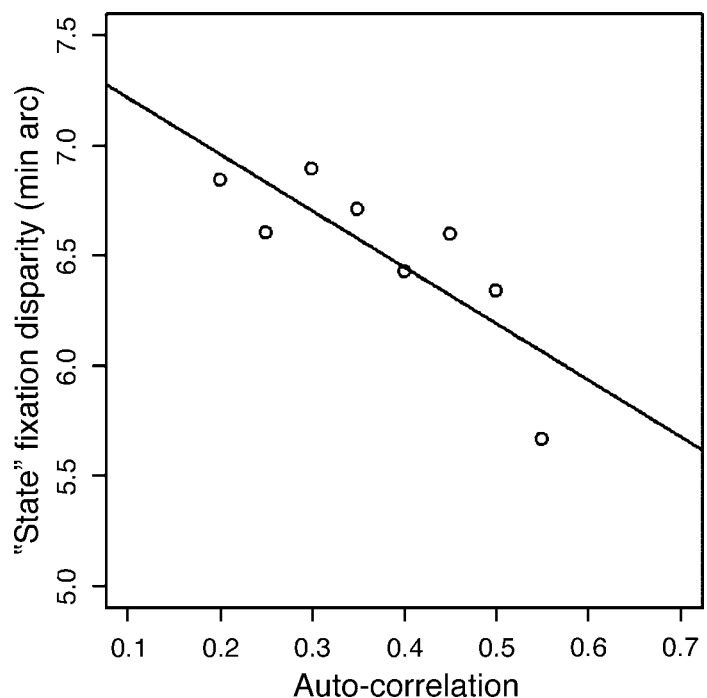


Figure 8. “State” fixation disparity (min arc) as a function of auto-correlation of the fixated words. The line represents the regression line, with the equation: “state” fixation disparity = $7.5 - 2.6 * \text{auto-correlation}$. Standard-deviations for the mean values of “state” fixation disparity per bin of auto-correlation ranged from 4.7 min arc to 5.8 min arc.

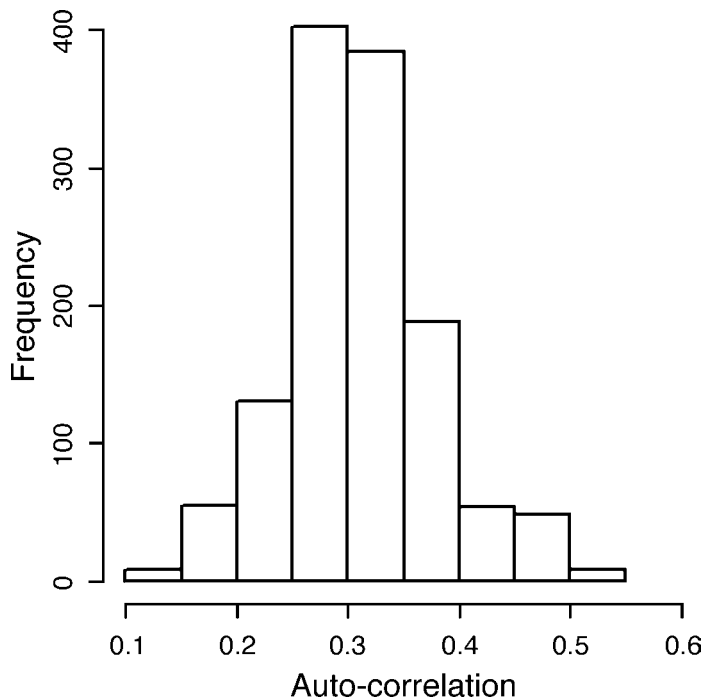


Figure 9. Histogram of the auto-correlation of all fixated words during binocular and monocular reading in [Experiment 2](#). The histogram represents the distribution of auto-correlations for all occurrences of all words.

the same increase in fixation durations for both monocular and binocular viewing conditions. Alternatively, if the increase in fixation duration is related to simple regulative processes in vergence there should be no increase in fixation duration in monocular reading since no vergence adjustments are required, i.e. vergence is operating “open-loop” (Howard, 2002).

Experiment 2: Binocular and monocular reading

Task and methods

In [Experiment 2](#), 22 participants were required to read 30 sentences from the Potsdam Sentence Corpus, while blocks of monocular and binocular sentences were presented in random order. By presenting the sentences in a stereoscope (see [General methods](#) section) the participants were most of the time not aware of the change between monocular and binocular presentations. For monocular reading the sentences were always presented to the right eye only. For both viewing conditions the same sentences were presented, so that the 30 sentences were read twice. For further analysis we selected only those fixated words for which we had both

binocular and monocular data, which was true for 1279 fixations.

In [Experiment 2](#) we presented the sentences with a standard font: we used Times New Roman created on a matrix 15 pixels high and with width ranging from 3 pixels (letter “i”) to 14 pixels (letter “M”). The x-height was 8 pixels. The letters were on average 24.6 min arc high and 19.8 min arc wide. The 251 words ranged in length from 2 to 18 letters with a mean of 5.36 and standard deviation 2.64. The auto-correlation was calculated as before using a Matlab program based on a matrix of sufficient length to encompass the longest word (140 pixels). [Figure 9](#) shows the distribution of auto-correlations for the words written in Times New Roman. Again, we divided the entire data set into categories (width 0.05), which represented the auto-correlation range from 0.2 to 0.5.

Results

The average lag at which the horizontal autocorrelation function reached its first peak was 5.2 pixels (SD 0.9) (14.4 min arc) and the average correlation coefficient was 0.32 (SD 0.07). Across words, there was a positive correlation between the lag and the autocorrelation coefficient of +0.46.

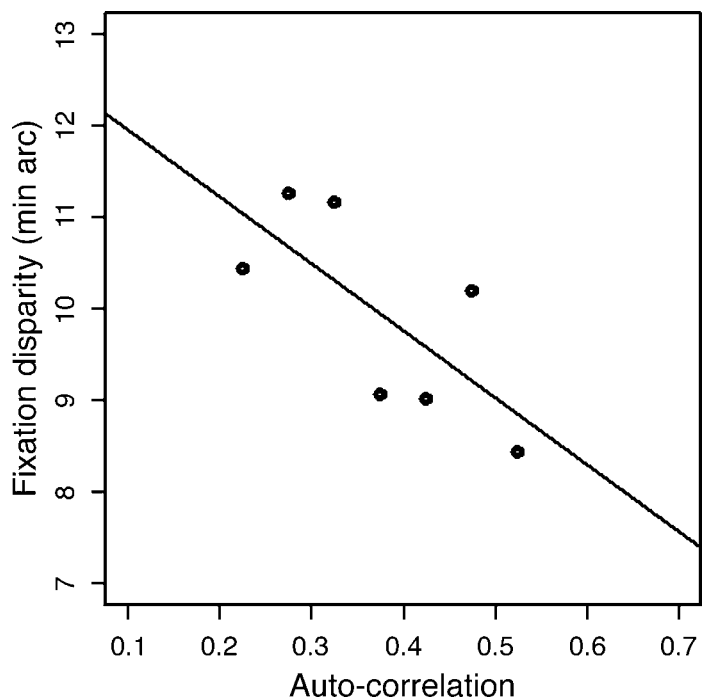


Figure 10. Average (minimum) fixation disparity (min arc) as a function of auto-correlation of the binocular fixated words in [Experiment 2](#). The line represents the regression line, with the equation: fixation disparity = 12.7 – 7.3 * auto-correlation. Standard-deviations for the mean values of fixation disparity per bin of auto-correlation ranged from 23.6 min arc to 26.3 min arc.

The smallest fixation disparity reached during the complete fixation phase for binocular reading was 10.5 min arc (± 25.2), on average, which was smaller than the average width of a character and smaller than in Experiment 1. As expected from the results of Experiment 1, average minimal fixation disparity showed a tendency to decrease when the auto-correlation increased ($F_{1,5} = 5.01, p = 0.07; R^2 = 0.50$; see Figure 10).

Calculating the “trait” fixation disparity (see Jainta & Jaschinski, 2010) showed a tendency of “state” fixation disparity reduction when the auto-correlation increased ($F_{1,5} = 3.12, p = 0.14; R^2 = 0.38$; see Figure 11). The lack of significance of the regression in Experiment 2 might therefore be due to the smaller sample size.

In binocular reading, the average moment in time during fixation when the smallest fixation disparity was reached was at 128.3 ms (± 102.8) and average fixation duration was 258.6 ms (± 81.0) (see Figure 12).

Average fixation duration for monocular reading was 275.1 ms (± 108.2) and, thus, significantly longer than for binocular reading ($t_{21} = 4.31; p < 0.01$). This result is in line with previous reports (Heller & Radach, 1998).

After categorizing fixation duration according to auto-correlations, average fixation duration during binocular reading was longer for words with high auto-correlation ($F_{1,5} = 7.40, p = 0.04$). Figure 13 shows the data, including the regression line ($R^2 = 0.59$). In contrast, for

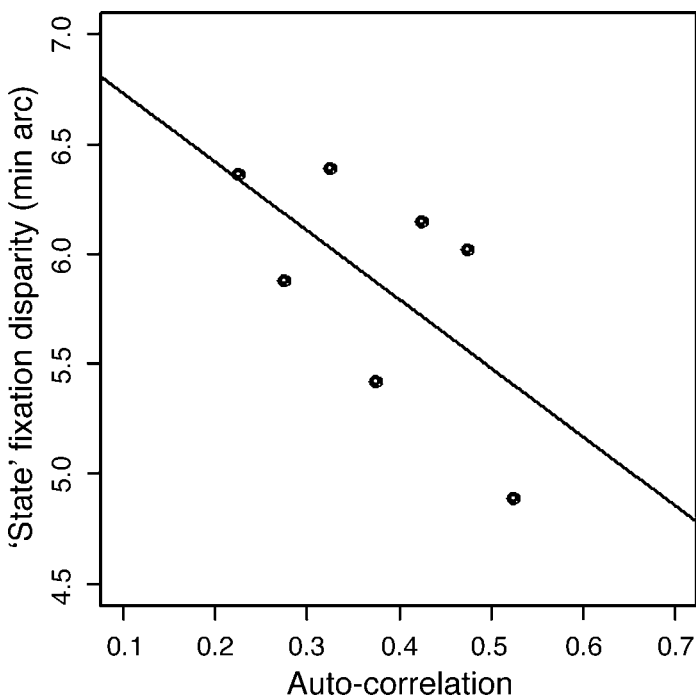


Figure 11. “State” fixation disparity (min arc) as a function of auto-correlation of the fixated words. The line represents the regression line, with the equation: “state” fixation disparity = $7.1 - 3.1 * \text{auto-correlation}$. Standard-deviations for the mean values of “state” fixation disparity per bin of auto-correlation ranged from 4.4 min arc to 5.1 min arc.

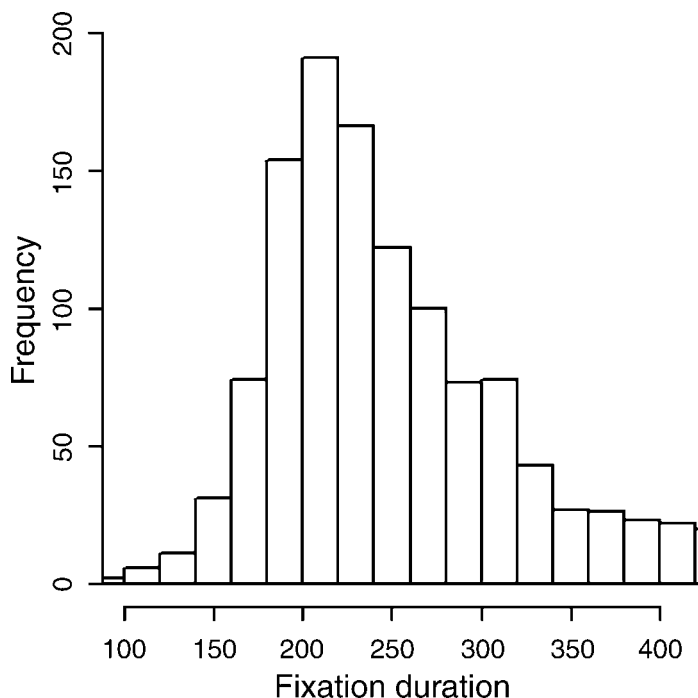


Figure 12. Histogram of the fixation duration (ms) during binocular reading in Experiment 2; note that reading times longer than 500 ms were put into the last category on the right side.

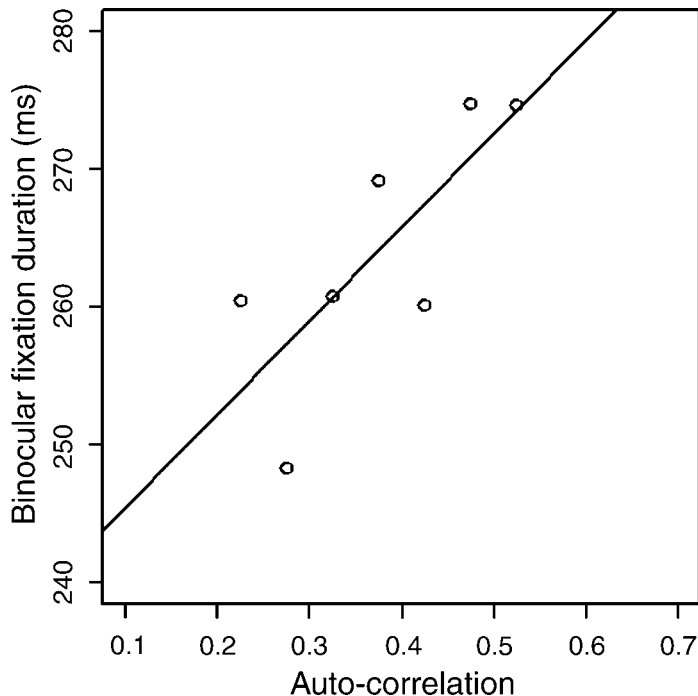


Figure 13. Fixation duration (ms) as a function of auto-correlation of the fixated words for binocular viewing conditions in Experiment 2. The line represents the regression line, with the equation: fixation duration = $238.5 + 68.1 * \text{auto-correlation}$. Standard-deviations for the mean values of fixation duration per bin of auto-correlation ranged from 81.7 ms to 96.2 ms.

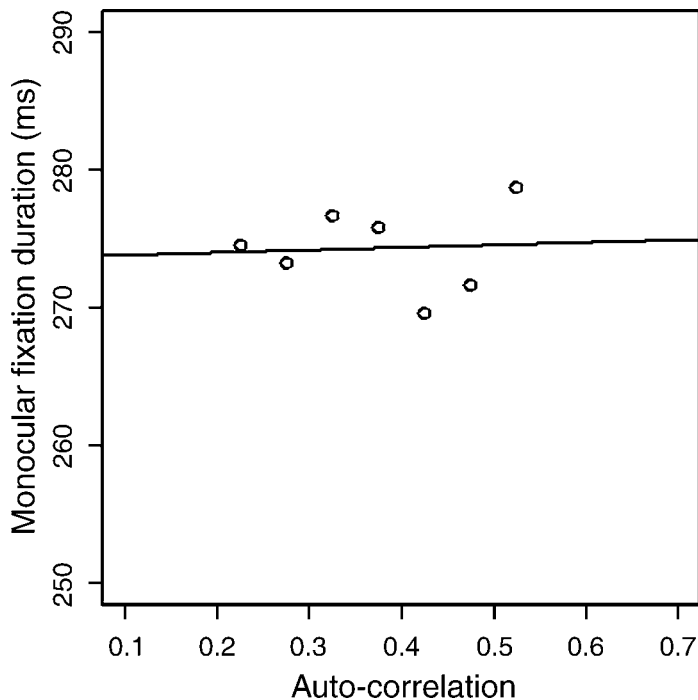


Figure 14. Fixation duration (ms) as a function of auto-correlation of the fixated words for monocular viewing conditions in Experiment 2. The line represents the regression line, with the equation: fixation duration = 273.6 + 1.8 * auto-correlation. Standard-deviations for the mean values of fixation duration per bin of auto-correlation ranged from 95.3 ms to 107.5 ms.

monocular reading no change of average fixation duration with higher auto-correlations could be observed ($F_{1,5} < 1$, $p = 0.89$; see Figure 14).

General discussion

The striped appearance of a word is due to the similarity between neighboring letter strokes, which can be quantitatively described by the first peak in the horizontal auto-correlation (Wilkins et al., 2007). In both experiments of the present study, we found that fixation duration during binocular reading increased if the fixated words had higher auto-correlations. This finding is consistent with the decrease in reading speed observed for words with higher auto-correlation by Wilkins et al. (2007). The decrease in speed was initially measured using passages of randomly ordered words. The present results indicate that the effect extends to the reading of meaningful sentences. Even though the observed prolongation of single fixations (a few milliseconds) might not be sufficient to account for the overall decrease in reading speed (several seconds), it will nevertheless contribute to it.

It might be argued that text with high autocorrelation offers greater potential for the masking of contours of

letters by the neighboring letter contours, and that the differences we observed between text with high and low autocorrelation can be attributed to such masking (Liu & Arditi, 2000). We consider this explanation unlikely for two reasons: (1) crowding has been demonstrated to be greater with closely spaced contours, and not with contours that are periodically spaced, as in words with high horizontal auto-correlation; (2) we observed the effect of autocorrelation only under binocular viewing conditions. It is not clear from the literature (e.g. Stifter, Sacu, Benesch, & Weghaupt, 2005) that crowding effects are any greater for binocular than for monocular viewing, and, if they were to be so, how best to allow for the differences between binocular and monocular acuity.

Repeated vertical strokes offer opportunities for inappropriate binocular matching (as occurs in the so-called “wallpaper effect” of Brewster). While part of the series of vertical strokes in a word may match well and form a stable percept, those at the beginning or end of the series may suffer binocular rivalry, because the first or the last vertical strokes in one eye may match up with curved or oblique strokes in the other eye. Such mismatches may hinder recognition of the letters of the word and may cause a delay in recognizing the word. This additional explanation of the reported increase in fixation durations might be independent of vergence adjustments—since it deals with sensory fusion and binocular rivalry mechanisms—or it might follow from an explanation of the observed effects in vergence described below.

The size of the first peak in the horizontal auto-correlation function of a word is one measure of the extent of the inappropriate binocular matching possible between the images in the two eyes, and the lag at which the first peak occurs is a measure of the disparity at which that binocular mismatch might occur. There was a correlation between the size of the peak and the lag, but the correlation was negative in the first experiment and positive in the second. The two experiments nevertheless gave similar results, suggesting that in these experiments the effect of the auto-correlation is not related to the size of the disparity at which any binocular mismatch may have occurred. It is possible that slower reading occurs because of recognition difficulties (i.e. existing vergence errors causing more binocular mismatches in stripy words than in non-stripy words) but it is more parsimonious to attribute the slower reading to the regulative process of vergence adjustment described below.

We showed a tendency for fixation disparity to decrease with an increase in auto-correlation. We selected the minimum fixation disparity reached during fixation because it reflects the moment in time when fusion should be best achieved by means of vergence adjustments. Correcting the minimum fixation disparity for the average fixation disparity an observer revealed during reading (Jainta & Jaschinski, 2010), strengthened our results. Correcting each fixation disparity for individual differences and for a possible influence of heterophoria revealed a significant

decrease in fixation disparity when fixated words became more “stripy”. In other words, the greater the similarity between letters within a word, the lower the vergence error relative to the average for an observer. We speculate that because of the repetitive structure of the pattern, a more exact matching of the two images must be provided to avoid ambiguous images during fusion.

The moment in time when the minimum fixation disparity is reached varies from fixation to fixation and in most cases it is not at the end of fixation (Vernet & Kapoula, 2009). We found that the moment at which minimum fixation disparity occurred showed a tendency to be delayed when the auto-correlation of the fixated words was high. For words with higher auto-correlations, both observations, a smaller fixation disparity and a longer duration to reach it during fixation, might reflect a simple regulative process: the more repetitive the pattern of a word, the lower the fixation disparity tolerable in avoiding ambiguous fusion. The regulative process needs time and ultimately increases fixation duration. We showed that this suggested mechanism occurs only with binocular viewing. During monocular reading no effect of auto-correlation on fixation duration could be observed and we interpret this finding as indicating that more “stripy” words indeed require more precise binocular alignment.

The regulative process is described here for data obtained from a group of individuals with normal binocular vision. It is known that some individuals (e. g., children, often those with dyslexia) can have a particular weakness in vergence control (for a review see, Kapoula, Vernet, Yang, and Bucci (2008). In clinical optometry, temporal instability in binocular fixation is considered as a specific disorder (Evans, 2002), that can be assessed with dichoptically presented nonius lines (Jaschinski & König, 2006). For these subjects with poor vergence control, the auto-correlation of text might be particularly relevant. Since the auto-correlation varies not only with words but with fonts (Wilkins et al., 2007)—some fonts are more “stripy” than others—it is possible that fonts with low auto-correlations may be advantageous for readers whose binocularity is compromised by poor vergence control. Indeed there is preliminary evidence that the effects of autocorrelation are more readily observed in poor readers (Wilkins et al., 2007).

We acknowledge that our reading task could be considered atypical due to the haploscopic viewing conditions; but in other respects such as text size and content the reading conditions were typical of normal reading and similar to those in previous reading research (Kliegl et al., 2006; Liversedge, Rayner, et al., 2006; Nuthmann & Kliegl, 2009).

The eyes remain closely aligned vertically so that only smaller and easily compensated horizontal fixation disparities remain after the execution of horizontal saccades during reading (Nuthmann & Kliegl, 2009). Therefore, the vertical binocular coordination during the horizontal eye movements across a line of text might be less affected by the vertical auto-correlation of words, if present to

different extent. Within the vertical dimension, the spatial periodicity results mainly from the successive lines of text, and here the spatial frequency is low. Both the low frequency and the coarse binocular coordination in the vertical dimension (Howard, 2002) suggest that vertical disparities are less likely to impede reading, unless large.

Our fixation disparity measurements amounted to about one character width and are comparable to those reported previously (Liversedge, Rayner, et al., 2006; Liversedge, White, et al., 2006; Nuthmann & Kliegl, 2009) Apart from aligned fixation disparities (52%) we found more crossed fixations (36%) than uncrossed (12%) ones, relative to character width. The vergence system assumes for each observer, a “state” fixation disparity within a sentence as precise as needed given the typical width of Panum’s fusional area. This is despite a large “trait” fixation disparity (the average for each sentences), which seems to be related to the general error range, as mentioned above and described recently (Jainta & Jaschinski, 2010). Considering classical optometric research this observation is not at all surprising. In addition, our present study showed that the “state” fixation disparity was clearly affected by auto-correlation, which is in line with the idea that “state” fixation disparity is adjustable within the sequence of reading fixations (Jainta & Jaschinski, 2010).

In conclusion, we have shown for the first time that binocular control during reading fixations requires a continuous regulation of vergence and that the design of text affects this regulation.

Acknowledgments

The experiments were conducted and supported at the IfADo by grants DFG Ja 747/4-1,2 and DFG Ja 1921/3-1. Arnold Wilkins was supported by Grant 80274 from the Wellcome Trust.

Commercial relationships: none.

Corresponding author: Stephanie Jainta.

Email: jainta@ifado.de.

Address: IfADo - Leibniz Research Centre for Working Environment and Human Factors, Ardeystrasse 67, 44139 Dortmund, Germany.

References

- Blythe, H. I., Liversedge, S. P., Joseph, H., White, S. J., Findlay, J. M., & Rayner, K. (2006). The binocular coordination of eye movements during reading in adults and children. *Vision Research*, 46, 3898–3908.
- Bucci, M. P., & Kapoula, Z. (2006). Binocular coordination of saccades in 7 years old children in single

- word reading and target fixation. *Vision Research*, *46*, 457–466.
- Collewijn, H., Erkelens, C. J., & Steinman, R. M. (1995). Voluntary binocular gaze-shifts in the plane of regard: Dynamics of version and vergence. *Vision Research*, *35*, 3335–3358.
- Evans, J. R. (2002). *Pickwell's binocular vision anomalies*. London: Butterworth.
- Heller, D., & Radach, R. (1998). Eye movements in reading: Are two eyes better than one? In W. Becker, H. Deubel, & T. Mergner (Eds.), *Current oculomotor research: Physiological and psychological aspects*. New York: Plenum Press.
- Hoormann, J., Jainta, S., & Jaschinski, W. (2008). The effect of calibration errors on the accuracy of eye movement recordings. *Journal of Eye Movement Research*, *1*, 1–7.
- Howard, I. P. (2002). *Seeing in depth: Basic mechanisms* (vol. 1). Toronto, Canada: Porteous, I.
- Howard, I. P., & Rogers, B. J. (2002). *Seeing in depth: Depth perception* (vol. 2). Toronto, Canada: Porteous, I.
- Jainta, S., Hoormann, J., & Jaschinski, W. (2009). Accommodation modulates the individual difference between objective and subjective measures of the final convergence step response. *Ophthalmic Physiology Optics*, *29*, 162–172.
- Jainta, S., & Jaschinski, W. (2010). “Trait” and “state” aspects of fixation disparity during reading. *Journal of Eye Movement Research*, *3*, 1–13.
- Jaschinski, W., & König, M. (2006). Vergence dynamics and variability of fixation disparity in children and adults. *Strabismus*, *14*, 81–84.
- Kapoula, Z., Vernet, M., Yang, Q., & Bucci, P. (2008). Binocular coordination of saccades: Development, aging and cerebral substrate. *Journal of Eye Movement Research*, *2*, 1–19.
- Kirkby, J. A., Webster, L. A., Blythe, H. I., & Liversedge, S. P. (2008). Binocular coordination during reading and non-reading tasks. *Psychology Bulletin*, *134*, 742–763.
- Kliegl, R., Nuthmann, A., & Engbert, R. (2006). Tracking the mind during reading: The influence of past, present, and future words on fixation durations. *Journal of Experimental Psychology, General*, *135*, 12–35.
- Liu, L., & Arditi, A. (2000). Apparent string shortening concomitant with letter crowding. *Vision Research*, *40*, 1059–1067.
- Liversedge, S. P., Rayner, K., White, S. J., Findlay, J. M., & McSorley, E. (2006). Binocular coordination of the eyes during reading. *Current Biology*, *16*, 1726–1729.
- Liversedge, S. P., White, S. J., Findlay, J. M., & Rayner, K. (2006). Binocular coordination of eye movements during reading. *Vision Research*, *46*, 2363–2374.
- McConkie, G. W., Kerr, P. W., Reddix, M. D., & Zola, D. (1988). Eye movement control during reading: I. The location of initial eye fixations on words. *Vision Research*, *28*, 1107–1118.
- McConkie, G. W., Kerr, P. W., Reddix, M. D., Zola, D., & Jacobs, A. M. (1989). Eye movement control during reading: II. Frequency of refixating a word. *Perception & Psychophysics*, *46*, 245–253.
- Nuthmann, A., & Kliegl, R. (2009). An examination of binocular reading fixations based on sentence corpus data. *Journal of Vision*, *9*(5):31, 1–28, <http://www.journalofvision.org/content/9/5/31>, doi:10.1167/9.5.31. [PubMed] [Article]
- Patel, S. S., Jiang, B. C., & Ogmen, H. (2001). Vergence dynamics predict fixation disparity. *Neural Computation*, *13*, 1495–1525.
- Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychology Bulletin*, *124*, 372–422.
- Stifter, E., Sacu, S., Benesch, T., & Weghaupt, H. (2005). Impairment of visual acuity and reading performance and the relationship with cataract type and density. *Invest Ophthalmology and Visual Science*, *46*, 2071–2075.
- Vernet, M., & Kapoula, Z. (2009). Binocular motor coordination during saccades and fixations while reading: A magnitude and time analysis. *Journal of Vision*, *9*(7):2, 1–13, <http://www.journalofvision.org/content/9/7/2>, doi:10.1167/9.7.2. [PubMed] [Article]
- Wilkins, A. J. (1995). *Visual stress*. Oxford: Oxford University Press.
- Wilkins, A. J. (2003). *Reading through colour*. Chichester, Sussex: John Wiley and Sons.
- Wilkins, A. J., Smith, J., Willison, C. K., Beare, T., Boyd, A., Hardy, G., et al. (2007). Stripes within words affect reading. *Perception*, *36*, 1788–1803.