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BINOCULAR COORDINATION IN READING WHEN CHANGING BACKGROUND BRIGHTNESS

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Contradicting results concerning binocular coordination in reading have been reported: Liversedge et al. (2006) reported a dominance of uncrossed fixations, whereas Nuthmann and Kliegl (2009) observed more crossed fixations in reading. Based on both earlier and continuing studies, we conducted a reading experiment involving varying brightness of background and font. Calibration was performed using Gabor patches presented on grey background. During the experimental session, text had to be read either on dark, bright, or grey background. The data corroborates former results that showed a predominance of uncrossed fixations when reading on dark background, as well as those showing a predominance of crossed fixations, when reading on bright background. Besides these systematic shifts, the new results show an increase in unsystematic variability when changing the overall brightness from calibration to test. The origins of the effects need to be clarified in future research.

Key words: *vergence, binocular coordination, fixation disparity, background brightness, reading.*

INTRODUCTION

When we look, we fixate on an object of interest with both eyes. The process of aligning both focus points is referred to as binocular coordination, the result of this process is termed vergence. That is, a vergence point is defined as the position where both lines of sight meet. Understanding the alignment of both lines of sight is important also for the understanding of binocular vision, that is, the motor coordination of the eyes as well as the perceptual coordination like, for example, in image fusion. In visual tasks, vergence points are expected to occur where an image is depicted. Therefore, when presenting images on a screen, the fixation location of both eyes is measured on the screen. The resulting difference between fixation locations of both eyes is referred to as fixation disparity. That is, fixation disparity is the difference between the two lines of sight at a given distance, which informs about the spatial accuracy of aligning both lines of sight.

Binocular coordination is performed also in seemingly two-dimensional tasks like, for example, in reading. This raises the question of whether two eyes are better than one, as Radach and Heller (1999) put it. With regard to fixation disparity in reading, there are contradictory results. Liversedge *et al*. (2006) reported that about half of the fixations accompanying reading are unaligned. The authors characterised these fixations as crossed or uncrossed, depending on their disparity: fixations were counted as crossed when the right eye fixated more than one character left of the left eye, and as uncrossed when the right eye fixated more than one character right of the left eye. Expressed as vergence, crossed fixations were described as a vergence point spatially in front of the screen, and uncrossed fixations as a vergence point behind the screen. Liversedge *et al.* (2006) found more uncrossed fixation disparities than crossed ones, that is, a mean vergence point behind the screen.

In contrast, a dominance of crossed fixations and hence, vergence points, which are typically in front of the screen, was reported by Nuthmann and Kliegl (2009). With regard to binocular coordination, one might wonder how image fusion can take place on the basis of such huge amounts of not aligned fixations. In order to understand binocular visual functioning, it is therefore important to distinguish systematic variations of fixation alignments from random variability.

There were already various reasons suggested as potentially being responsible for the differences in the findings of Nuthmann and Kliegl (2009) as compared to Liversedge *et al.* (2006): differing eye-trackers, calibration procedures, viewing distances and also letter sizes. The former used a chin rest, the latter a bite bar, and participants had to read in different languages (German vs. English). These differences and several more (e.g., glasses, contact lenses, eye colour, eyelashes...) were already mentioned as possible sources of variation in other studies (Nyström *et al.* 2013). Kirkby *et al.* (2013) investigated the hypothesis that one potential source for the contradictory findings may be related to different devices used to collect the data as well as the different methods used for analysis. Therefore, they compared the results produced by different eye trackers (SR Research EyeLink 1000 versus Fourward Technologies Inc. DPI binocular eye-tracking systems) during reading and dot scanning. For both trackers, as described in Liversedge *et al.* (2006), also Kirkby *et al.* (2013) observed a majority of uncrossed fixations. Hence, clear evidence for the origins of the opposite fixation disparities in reading is still missing.

The study of Nuthmann and Kliegl (2009) reported an opposite effect of brightness of text and background. In the studies by Liversedge *et al.* (2006) and Kirby *et al.* (2013), texts were presented bright on dark background, while in the study of Nuthmann and Kliegl (2009) texts were presented dark on bright background. Hence, the brightness of text might be an important factor influencing binocular coordination; a factor which had been already suggested by Kirkby *et al.* (2013). If this factor has an effect, then the data suggest that reading bright text on dark background leads to vergence points behind the surface whereas reading dark text on bright background leads to a vergence point in front of the surface.

However, how might binocular coordination be linked to such brightness differences? Potential sources for effects of brightness on binocular coordination can be hypothesised. Assuming that our eyes are moved to ensure good vision, we might expect that both lines of sight meet on the object of interest. Even when the exact position might be subject to some tolerance, avoiding double images should be assumed as one important goal for vision tasks. In this respect, vergence points indicate the perceived position of an object. Hence, one might speculate that the texts in the above mentioned studies differed in their perceived position, or subjective reading distance. Another hypothesis concerns the effects of background brightness on pupil dilation. In reading, adjusting the mechanisms of the near triad (which is vergence), accommodation, and pupil diameter (constriction if near objects are fixated), is necessary. One can assume that changes in pupil diameter due to brightness can affect depth of focus, which directly changes the accommodation and, possibly, also vergence response. Therefore, this might cause changes in vergence with varying brightness. One might even argue for another factor changing vergence when changing brightness, arising from an artefact when measuring eye movements with video-based eye trackers (Drewes *et al.*, 2012).

Differences in brightness often go along with variations in contrast. Since our visual system is optimised for detecting relative differences but not absolute intensities, contrast may be regarded as the better suited variable when characterising a visual stimulus. However, as outlined above, most arguments regarding the issue of binocular coordination are concerned with pupil reaction, which is strongly affected by brightness.

In the present study, we experimentally test the hypothesis that brightness affects binocular coordination in reading. In the experiment, text was presented, once dark on bright background, once bright on dark background, as well as both bright and dark letters on grey background. Eye movements were recorded, and proportions as well as mean fixation disparities were measured. This allowed to compare effects of overall brightness as well as effects of font brightness.

MATERIALS AND METHODS

Participants. Twelve participants (mean age: 21 years, standard deviation 2.7, ranging from 20 to 29) from Ulm University participated in the experiment in exchange of monetary compensation or for course credit. All participants were native German speakers and had normal or corrected-to-normal vision with binocular visual acuity of 1.0 (in decimal units) or better.

Apparatus. The eye tracker (iView XTM Hi-Speed 1250, SMI Teltow, Germany) and data receiving was controlled by one computer; stimulus presentation was controlled by another. Stimuli were presented on a TFT BenQ G2200W Senseye 22" monitor with 60 Hz refreshing rate and a resolution of 1280 × 1024 pixels (410 × 295 mm and in 36° × 26°). Both eyes were tracked using a SMI iViewX HiSpeed with a sampling rate of 500 Hz in binocular mode. According to technical specifications, tracking resolution with these eye trackers is 0.01°.

The experiment was carried out in a windowless room lit by an artificial daylight source (full spectrum bulb, 30 watt) from overhead lighting resulting in 69.3 Lx measured using a luxmeter (Gossen Mavolux 5032) at the position of the chin-rest when the screen was off. Calibration and stimuli were presented with Matlab R2010b and the Psychophysics Toolbox 3.0.9 (Brainard, 1997).

Stimulus material and design. Grey was produced with RGB values of 128, 128, 128, which is the average between dark (RGB: 0, 0, 0) and bright (RGB: 255, 255, 255). The respective luminance values of the screen were 180.0 cd/m² for bright stimuli, 0.2 cd/m² for the dark stimuli and 39.4 cd/m² for grey stimuli, as recorded by a luxmeter (Gossen Mavolux 5032). This experimental setup resulted in a Michelson contrast of 0.99 for the dark and bright backgrounds, 0.64 for the grey background with bright text and 0.98 for the grey background with dark text. The Weber ratios were 899 for the dark background, -1 for the bright background, 3.6 for bright text on grey background, and -1 for dark text on grey background.

Eighty sentences taken from the work of Huestegge *et al.* (2010) were presented one by one. Text was presented in regular Arial font size 16 pt corresponding to 0.24° at the given viewing distance of 60 cm. Each sentence was presented on the horizontal meridian of the screen. No sentence took more than one line.

Procedure. The experimental session started by informing the participants about the experiment and their task. Participants filled and signed a written consent and performed a standardised test for visual acuity examination (binocularly) using the Landolt vision test on a chart. They started the experiment by placing their head in the chin-and-head-rest, which assured a constant viewing distance. Then, participants were familiarised with the experimental setting and the eye tracker. Participants were instructed to read the sentences for comprehension and of the need to answer a question about the prior sentence.

Calibration was executed before starting the experiment, as this has great importance for examining vergence (see, e.g., Nyström *et al*., 2013). Using video-based eye tracking, estimates of the gaze position always relate to the calibrated positions. Hence, if a mislocalisation occurs already during calibration, then the estimated fixation locations during measurement are affected by this mislocalisation. During the procedure of comparing vergence while reading from bright versus dark screens, changes in brightness might cause mislocalisations of stimuli. Therefore, the brightness of calibration targets and background becomes crucial. In order to allow for changes in brightness during the test, calibration was performed using the grey brightness of 39.4 cd/m². Hence, during calibration, grey Gabor patches were presented as calibration points on a grey background, so that during calibration there was no difference in brightness between targets and background. The Gabor patch consisted of bright and dark stripes orientated at 90° with a frequency of 0.2 cycles per pixel and a linear envelope (Fig. 1). A participant-controlled calibration was chosen in order to assure that each Gabor patch had been detected.

The standard producer's calibration software was used. As described in Nuthmann and Kliegl (2009), participants' eyes were calibrated binocularly by using a 13-point calibration, followed by a 4-point validation. When studying eye-movements binocularly, there are two possible ways for calibration: one can either calibrate both eyes separately or one can calibrate binocularly. We used binocular calibration, as described in Nuthmann and Kliegl (2009), although it has been argued that calibrating each eye separately produces more exact measurement of the fixation location for each eye than by binocular calibration (Svede *et al*., 2015). Therefore, it should be kept in mind that absolute fixation disparities should not be interpreted due to the calibration suppositions.

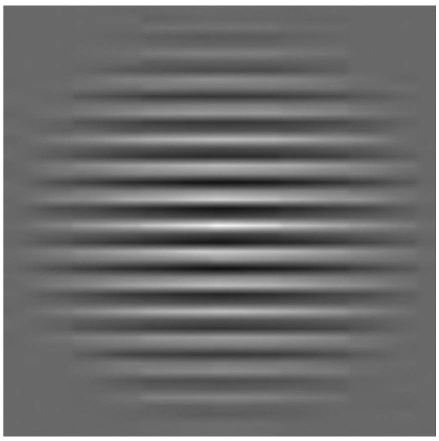

Fig. 1. The Gabor patch (enlarged) used as calibration target.

The four text presentation modes (bright text on dark background, dark text on bright background; bright text on grey background, dark text on grey background) were varied per block. A quarter of the participants started with one block. Participants either performed both grey blocks first or both other blocks. Each block included 10 sentences to read (40 in total by each participant; see Fig. 2). After having read two blocks, a recalibration took place.

Each trial started by presenting the fixation cross on the upper rim of the display to ensure that the eyes always enter the sentences from the same starting position. In order to start the stimulus exposition, participants had to press the spacebar. When the participant finished reading one sentence, they again had to press the spacebar. Then, either the next fixation cross was displayed on the screen or a question concerning the preceding sentence. There was one question presented in each block of ten sentences, posed after the last sentences.

Data analysis. There was no wrong answer given to any question. Hence, no sentence was excluded from data analysis due to misunderstandings. Blinks and vertical eye positions were removed using the SMI event detector.

The data were then treated as in the methods described in Liversedge *et al.* (2006) and Kirkby *et al.* (2013): prior to analyses, data were cleaned from fixations lasting less than 80 ms or more than 1200 ms. For the remaining fixations, disparity was computed. Fixations with a disparity deviating more than two standard deviations from the individual mean were excluded. For data cleaning, MATLAB version R2010b was used. No participant data was completely elim-

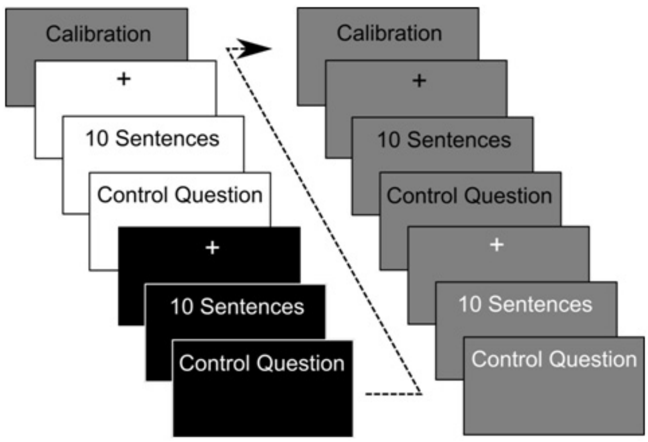

Fig. 2. Calibration and reading conditions realised in the experiment. Reading always started with a grey calibration followed by two blocks consisting of ten sentences each. Blocks included either reading bright text on dark background and dark text on bright background, or reading bright and dark text on grey background.

inated from the analyses. For statistical analyses, mean values were calculated for each participant and then for all participants. Statistical comparisons were performed using t-tests for paired samples via SPSS version 21.

A fixation consists of a horizontal gaze position for the left eye (Lx) and for the right eye (Rx). Horizontal fixation disparity was computed as the difference between left- and right-eye fixation positions:

$$D_x = L_x - R_x$$

following the procedure of Liversedge *et al.* (2006); fixation disparities were computed during phases of binocular fixations only. That is, the disparity was calculated whenever both eyes fixated. Fixation positions were measured in pixels and transformed to differences in visual angle [°] between the left and the right eye (Nuthmann and Kliegl, 2009). Positive disparities represent crossed fixations and negative ones represent uncrossed fixations (Nuthmann and Kliegl, 2009). Fixations were counted as aligned when the deviation between both eyes was less than one letter size.

RESULTS

Mean overall fixation duration was 222.85 ms (standard error (*SE)* = 0.001). This is in the expected range for reading an easy text in the native language (Radach and Heller, 1999).

The amount of aligned, crossed and uncrossed fixations and the mean fixation disparity depending on the brightness of text and background as well as the portions of aligned, crossed, and uncrossed fixations are given in Table 1. As observed in Nuthmann and Kliegl (2009), there was a dominance of crossed fixations when reading dark text on bright background, and there was a dominance of uncrossed fixations, as reported by Liversedge *et al.* (2006), when reading bright text on dark background.

This clear difference was also observed in mean fixation disparities. Mean fixation disparity was –0.63° (*SE* = 0.03°) for reading bright letters on dark background, which differed significantly ($t(11) = 3.645$; $p < 0.01$ from mean disparity of 0.39° (*SE* = 0.02°) when reading dark text on bright background (Fig. 3). These results are similar to those of of Liversedge *et al.* (2006) and Nuthmann and Kliegl (2009).

In addition, also the crossed and uncrossed fixations were more pronounced in the respective brightness modes. As can be seen in the lower part of Table 1, regarding the mean of all crossed and of all uncrossed fixations, crossed fixations produced a larger mean disparity with bright background whereas uncrossed fixations produced a larger mean disparity with dark background. Hence, with dark background, uncrossed fixations were more frequent and more pronounced than crossed fixations. In addition, crossed fixations were more frequent and more pronounced with bright background.

As can also be seen in Figure 3, there was not only a systematic effect on fixation disparities but also an increased unsystematic variability when varying the brightness between calibration and test. Interestingly, when keeping the background brightness constant during calibration and testing, there was no difference in the mean fixation disparities, and also in the portions of crossed and uncrossed fixations. There was no significant difference ($t(11) = 1.636$; $p > 0.13$) between with dark letters on grey background (0.05°; *SE* = 0.01°) and mean disparity with bright letters on grey background (0.14°; *SE* = 0.01°) (Fig. 3).

DISCUSSION

In the present study, effects of brightness on fixation disparities during reading were investigated. It was observed that when reading bright text on dark background, uncrossed fixations were more frequent and more pronounced than crossed ones, and when reading dark text on bright background, crossed fixations were more frequent and more pronounced than uncrossed ones. For reading on a grey background, such asymmetric distributions of disparities were

Table 1

PERCENTAGE OF CROSSED, ALIGNED AND UNCROSSED FIXATIONS SEPARATELY FOR THE DIFFERENT BRIGHTNESS MODES DURING READING (one character = 0.24°)

Proportions(%)	ABC	ABC	ABC	ABC
Aligned	18.4	25.8	32.7	29.7
Crossed	20.8	54.1	36.2	43.2
Uncrossed	60.8	20.2	31.1	27.1
Magnitudes (° | **Char)**				
Aligned	0.00|-0.01	0.01|0.05	0.01|0.03	0.01|0.04
Crossed	0.95|3.94	1.04|4.35	0.66|2.74	0.68|2.84
Uncrossed	-1.37|-5.73	-0.86|-3.58	-0.60|-2.48	-0.57|-2.39

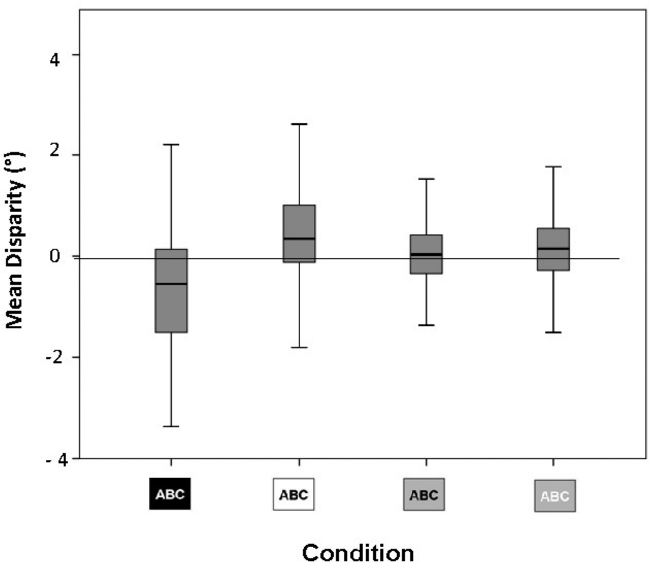

Fig. 3. Estimated disparities in degree (°). Rectangles with the text “ABC” denote the corresponding reading condition.

not observed. Interestingly, in all brightness modes, there was a huge portion of unaligned fixations.

The current data are in line with the observations of Liversedge *et al.* (2006) as well as with those of Nuthmann and Kliegl (2009). Liversedge *et al.* (2006) presented bright text on dark background and found more uncrossed fixations; Nuthmann and Kliegl (2009) reported more crossed fixations when reading dark text on bright background. The same pattern was observed in our data. Of course, one cannot compare absolute effect sizes since respective values always denote differences between calibration and reading and thus never can give estimates of absolute vergence points. Nevertheless, the current data strongly suggest that the contradictory findings between the studies of Nuthmann and Kleigl (2009) and Liversedge *et al.* (2006) might be attributed to brightness.

However, the sources for the effects of brightness on binocular coordination observed in the presented study remain unclear: one may suggest an interpretation in terms of vergence movements that denote systematic variations of perceived distance. Given that for each fixation, the lines of sight of both eyes are brought to a well-suited position to perceive the target, one might assume that the systematic misalignments may be due to systematic misperceptions. This might mean that dark text on bright background is perceived as being closer than bright text on dark background. It might be plausible to attribute such an effect to the mean brightness of the stimulus. In fact, when sorting the reading modes for mean brightness, the proportions for crossed and for uncrossed fixations vary systematically with mean brightness of the stimuli (from dark background via dark text on grey background via bright text on grey background to bright background).

However, the argument that mean brightness affects localisation poses many further questions. Given that distance estimation for a certain image depends on its mean brightness, each established fixation point, no matter whether it is derived through a calibration or through another task, must be assumed to be highly affected by the current brightness conditions. Hence, given that this is true, designing eye movement studies, especially those for binocular coordination, require the same mean brightness of the images during calibration as during performing the task. Regarding this aspect, studies have to be carefully interpreted.

Variations in vergence might also be attributed to adjusting the mechanisms of the near triad, which are vergence, accommodation, and pupil diameter. That is, a higher mean brightness should of course affect the pupil diameter. For near vision, pupil size, accommodation, and vergence have to be adjusted to a certain stimulus and its perceived location. When changing one of these mechanisms of the near triads while stimuli remain constant (e.g., when changing the brightness of a stimulus and thus, also the pupil diameter), the other mechanisms have to be adjusted in order to compensate for this change. From an optical viewpoint, it seems plausible to assume that for bright images, pupil size decreases. With small pupils, accommodation becomes less relevant. Also the impact of vergence might be reduced, in which case greater unsystematic variance might be expected. However, the current data show that the largest variability occurs with the darkest reading mode.

The current results might also be explained by an artefact arising when measuring eye movements with video-based eye trackers, as the estimated gaze positions when one observer fixates one object differs depending on whether fixating with a large or small pupil (Drewes *et al.,* 2012). However, the respective changes in pupil size were observed using different brightness, and the respective data were collected monocularly. In fact, the deviations observed for the left eye occurred mainly towards nasal and lower directions (Drewes *et al.,* 2012) which suggests that vergence shifts might have happened. Hence, whether the deviations produce measuring artefacts or whether they indeed denote systematic variations in vergence movements due to changes in brightness cannot be decided on the basis of the current results. Further investigations should clarify the roles of brightness on binocular coordination.

The present study stresses that calibrating the eye tracker is one of the most important issues in eye tracking research, as previously reported (Nyström, 2013). This is true for various reasons. Given that the fixation disparity can be interpreted as vergence point indicating the perceived location of the target, the systematic variation of fixation disparities with brightness indicates systematic localisation errors. Dark text on bright background seems to be localised closer to a reader than bright text on dark background. Thus, not only can brightness function as a depth cue, but text is often mislocalised during reading.

Vergence points only describe deviations relative to calibration. That is, vergence points always refer to differences relative to the calibrated baseline (e.g. Svede *et al*., 2015). Since it is unclear where exactly observers have verged during calibration, it cannot be estimated where observers absolutely verge during reading. This holds especially for the current study in which the eyes were calibrated binocularly. There are arguments claiming that for an exact estimate of a vergence point, both eyes should be calibrated separately. Since in the current study we did not attempt to accurately measure a binocular focus point, but to examine differences in binocular coordination related to brightness, we cannot estimate absolute errors in distance. Nevertheless, the study shows that it can in no way be taken for granted that readers verge on the text, neither during monocular nor during binocular calibration or during reading. However, to avoid speculation, further similar studies should carried out using monocular calibration.

We observed a huge amount of unaligned fixations, about two thirds, as observed in previous studies on fixation disparities (e.g., Liversedge *et al*., 2006; Nuthmsann and Kliegl, 2009). Hence, one must still wonder how two images are fused given such a distribution of fixation disparities. One important aspect concerns the stability of fixation disparities over time. As a result of eye movement, calibration accuracy decreases as a function of time. Inaccuracies are usually ascribed to movements of the participant's body. The current study suggests that also changes in the estimated distance over time might contribute to the loss in calibration accuracy. Given that the visual system establishes a discrepancy between vergence and accommodation, which is likely to be frequent in reading — it might try shifting the vergence point towards the accommodated depth. This might lead to vergence changes over time. Since the text is usually presented at a relatively constant depth, adaptation strategies might be a plausible mechanism to counteract the fusion challenges.

Mechanisms for the observed effects need to be studied further. The observed variation in vergence during reading must lead to at least some dissociations between vergence and accommodation. Such dissociations are known to result in visual strain and fatigue (Hoffman *et al*., 2008). Brightness has been less often studied than other depth cues, probably since it is usually confounded with contrast. How brightness can affect visual functioning has been mainly discussed in the field of ergonomics of modern display technologies, as reading on screens can cause visual strain and fatigue (Jaschinski *et al*., 1998; Oetjen and Ziefle, 2007), perhaps even myopia (Schaeffel and Howland, 1995). As one important factor contributing to these effects is the difference in brightness relative to real environments (Easa *et al*., 2013; Hone and Davies, 1993). It is possible that brightness of a screen leads to a mislocation in depth by the visual system of the observer. Hence, one might suspect that respective dissociations also contribute to visual strain and fatigue, which have often been reported for reading.

We observed that the brightness of letters only produced minor effects on vergence, which were far from significant. This is surprising, given the importance of the letters in reading. Hence, we suspect that the overall brightness is the main factor affecting vergence movements during reading. Thus, since the background brightness in case of the current presentation conditions (one line of text presented on an otherwise homogeneous background) contributed more to the overall brightness than the text brightness, we suggest that the mean brightness of the screen determines fixation disparities.

Our study confirmed the observation of Liversedge *et al.* (2006) that reading bright text leads to more uncrossed fixations, and of Nuthmann and Kliegl (2009), which found that reading dark text leads to more crossed fixations. It was shown that binocular coordination during reading is affected by brightness. Taken together, we have shown that mean fixation disparities systematically vary with changes in brightness. Given that respective vergence points denote perceived locations, the data strongly suggest that text is often mislocalised during reading, which may contribute to visual strain and fatigue. However, further research is needed to study other factors causing these differences in vergence.

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BINOKULĀRĀ KOORDINĀCIJA LASĪŠANAS LAIKĀ ATKARĪBĀ NO FONA SPILGTUMA

Pētījumos ir pretrunīgi rezultāti par binokulāro koordināciju lasīšanas laikā: Liversedge et al. (2006) norāda, ka lasīšanas laikā novēro biežāk nekrustotu fiksāciju, savukārt, Nuthmann, Kliegl (2009) novēroja biežāk krustotu fiksāciju. Pamatojoties uz abiem pētījumiem un turpinot tos, mēs veicām lasīšanas eksperimentu, mainot fona un burtu spilgtumu. Kalibrēšana tika veikta, izmantojot Gabora režģus uz pelēka fona. Eksperimentu sesijas laikā teksts bija jālasa uz tumša, gaiša vai pelēka fona. Dati apliecina abu iepriekšēju pētījumu rezultātus — nekrustotā fiksācijā dominē, kad lasa gaišu tekstu uz tumša fona; krustotā fiksācija dominē, kad lasa tumšu tekstu uz gaiša fona. Papildus šīm sistemātiskajām izmaiņām dati norāda arī uz nesistemātisko izmaiņu pieaugumu, kad kopējais spilgtums atšķiras kalibrēšanas un testa laikā. Šī efekta izcelsme vēl ir jānoskaidro nākamajā pētījumā.