Binocular Coordination during Reading of Blurred and Nonblurred Text

Stephanie Jainta,[1] Anne Dehnert,[2] Sven P. Heinrich,[2] and Wolfgang Jaschinski[1]

Purpose. Reading a text requires vergence angle adjustments, so that the images in the two eyes fall on corresponding retinal areas. Vergence adjustments bring the two retinal images into Panum's fusional area and therefore, small remaining errors or regulations do not lead to double vision. The present study evaluated dynamic and static aspects of the binocular coordination when upcoming text was blurred.

Methods. Binocular eye movements and accommodation responses were simultaneously measured for 20 participants while reading single, nonblurred sentences and while the text was blurred as if it were seen by a person in whom the combination of refraction and accommodation deviated from the stimulus plane by 0.5 D.

Results. Text comprehension did not change, even though fixation times increased for reading blurred sentences. The disconjugacy during saccades was also not affected by blurred text presentations, but the vergence adjustment during fixations was reduced. Further, for blurred text, the overall vergence angle shifted in the exo direction, and this shift correlated with the individual heterophoria. Accommodation measures showed that the lag of accommodation was slightly larger for reading blurred sentences and that the shift in vergence angle was larger when the individual lag of accommodation was also larger.

Conclusions. The results suggest that reading comprehension is robust against changes in binocular coordination that result from moderate text degradation; nevertheless, these changes are likely to be linked to the development of fatigue and visual strain in near reading conditions. (*Invest Ophthalmol Vis Sci.* 2011;52:9416–9424) DOI:10.1167/iovs.11-8237

Reading is a valuable skill in today's society, and it is used in thousands of day-to-day tasks. Generally, people read information on media that present texts in close viewing distances, and therefore the reading task itself typically evokes a near response of the visual-motor system. The two eyes have to be coordinated relative to the viewing distance (via eye movements), the retinal images have to be focused (via accommodation) and the overall light-levels within the eye have to be adjusted (via pupil adjustments and local adaptations of the receptors on the retina). All these mechanisms interact[1] and may contribute, separately or in combination, to different experiences of visual strain or fatigue, which is sometimes observed for reading tasks. The goal of the present study was therefore to elucidate whether optically degraded text may impair binocular eye movements and thus contribute to long-term visual strain or fatigue.

Reading typically requires different types of eye movements that occur while information is extracted. Saccades bring the eyes from left to right (fixating word after word), whereas in parallel, the angle of vergence between the two visual axes should be adjusted to the viewing distance of the text. Maintaining the vergence angle appropriately establishes that the images in the two eyes fall on corresponding retinal areas and the actual fused percept is the basic ground for higher level processing of letter and word identification. Moreover, maintaining the appropriate vergence angle during reading fixations depends on (1) the quality of the binocular coordination of the preceding saccade and (2) the disparity-driven, fine-tuning vergence movements acting during fixations to adjust the eyes properly for fusion. When the eyes move across the text, a transient disconjugacy (noncongruent horizontal movements of the two eyes) occurs. Typically, the abducting eye performs a larger and faster movement than the adducting eye at the beginning of the saccade.[2–7] This saccade disconjugacy has also been found to be present during reading, and the eyes typically perform a stereotyped pattern of vergence adjustments: the saccade disconjugacy (usually divergent) is followed by a compensatory vergence adjustment (usually convergent) during the subsequent fixation, which passively restores the disconjugacy due to saccade (i.e., a pulse-slide-step activity recorded in abducens neurons).[8,9] A time analysis showed that the vergence adjustment during fixations is high at the beginning, but becomes negligible after approximately 50 to 100 ms[9,10]; thus, the oculomotor system overcomes asymmetric pulse-step mismatches at the beginning of each fixation.

As soon as the oculomotor adjustments due to the saccade are completed, disparity-driven vergence adjustments take place. A fine-tuning vergence movement has to keep the images of words and letters stable and fused during fixation. The latter mechanism takes place within Panum's area, a small range of disparity where sensory fusion of the two retinal images is performed.[1,2] Adjusting the vergence angle for proper fusion of the two retinal images during fixation does not necessarily result in perfect alignment of the images of the two eyes. Small errors within Panum's fusional area are easily tolerated and neither perceived nor eliminated throughout all vergence regulations. These small errors are referred to as fixation disparities. There are, for example, reports that increased fixation disparities coincide with fatigue and eye strain at near vision.[11,12] More generally, fixation disparity might be related to the resting state of the vergence system, even though the influence under closed-loop vergence conditions may be small.[13–16] Further, fixation disparity may be related to vergence dynamics[17–19] and/or the coupling of accommodation

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Supported by Grants BA 877/18 (SPH) and JA 1921/3 (SJ) from Deutsche Forschungsgemeinschaft.

Submitted for publication July 18, 2011; revised October 17, 2011; accepted October 26, 2011.

Disclosure: **S. Jainta**, None; **A. Dehnert**, None; **S.P. Heinrich**, None; **W. Jaschinski**, None

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Investigative Ophthalmology & Visual Science, December 2011, Vol. 52, No. 13

and vergence.[1,20] Recent reports have shown that typical fixation disparities during reading amount to about one character size, without any sign of impaired reading at all (see for example, Blythe et al.,[21] and Kirkby et al.,[22] for a review).

Besides these basic binocular eye movements, the eyes adjust the optical focus; that is, the accommodation system of the eyes changes the refraction of the ocular lens to provide a sharp retinal image of the text at any viewing distance.[23–25] Accommodation is, for example, affected by factors such as contrast, blur, and perceived distance.[25,26] Moreover, during reading, amounts of accommodation errors (i.e., accommodation lags) of 0.5 to 1 D are typically reported for close reading distances.[27–29] Thus, considerable blur due to accommodative lags is usually observed during reading. Note that the measure of total amount of lag of accommodation can depend as well on the considerations of higher order aberrations (see for example, Buehren and Collins[30]); it may be overestimated occasionally. However, blur up to 2 D does not affect reading speed[31] and as long as sufficient spatial frequency information is present within low-pass–filtered text, reading efficiency is not at all reduced by blurring the text images.[32] Nevertheless, accommodative lags and accommodation instability have been discussed within the context of asthenopia and visual discomfort.[29,33,34] Generally, there are two aspects of the accommodative regulation and its relation to visual discomfort: If the accommodative response is not appropriate, the blur-driven feedback loop continually triggers readjustments, which may be tiring on a very basic level; or the under- or overaccommodation leads to a degraded visual percept, which itself may cause difficulty with letter and word identification and thus be more demanding for higher-level processes. Since we used single sentences as a reading task and presented them in nonblurred and blurred conditions, we addressed mainly the influence of a degraded visual input on visual-motor adjustments. This degraded visual text was realized by simulating refractive errors using a Fourier-optical model of defocus. With this technique, the stimuli appeared as if they were seen by a person with a combined error in refraction and accommodation of 0.5 D.[35]

In sum, we would expect slight changes in the binocular coordination when text is presented with intermediate degrees of blur,[36] and since accommodation and vergence are cross-coupled (see, for example, Hung[37]) one might speculate about changes in both functions when the eyes are confronted with blurred text.[38–42]

Methods

Participants

The 20 participants had an uncorrected visual acuity of 1.0 or better (in decimal units) in each eye. Participants' ages ranged from 18 to 34 years (mean ± SD, 24 ± 4). Myopic, hypermetropic, or astigmatic refractive errors did not exceed ±0.5 D (median, +0.25), and no refractive corrections were worn. Each subject gave informed consent before the experiments. The procedures of the present study were approved by the ethics review board of the Leibniz Research Centre for Working Environment and Human Factors and complied with the Declaration of Helsinki.

Stimuli

Participants had to read 30 sentences from the Potsdam Sentence Corpus (PSC[43]). The PSC provides a broad sentence basis in German, from which we choose sentences of intermediate length. Thus, we selected sentences containing seven to eight words, so that sentence length in words would be comparable. The sentences differed in length from 36 to 57 characters. The sentences were presented as black letters on a white background, using the Times New Roman font. The average letter width was 0.33° (20 min arc). This basic set of 30 sentences will be referred to herein as nonblurred text.

The second set contained exactly the same sentences, but this time the text was blurred as if it were seen by a person in whom refraction and accommodation combined deviated from the stimulus plane by 0.5 D. This was achieved by convolving the original stimuli with a blur kernel, the point spread function obtained from a Fourier optical mathematical model of defocus (see Dehnert et al.[35] for details), assuming a pupil diameter of 6 mm. Note that this large pupil diameter emphasized the blur effect for the stimuli. Thus, a 0.5-D blurred stimulus was still readable but already considerably out of focus (Fig. 1). For simplification, the computations were performed for a single wavelength of 550 nm. Blurring the stimulus itself, as opposed to inducing blur via lenses in front of the subjects' eyes, has several benefits. In the context of the present study, it is particularly advantageous that eye-tracking not be complicated by lenses and vergence not be affected by prismatic effects due to eccentric viewing through the lenses. Furthermore, for lens-induced blur not to be cancelled by accommodation, additional lens power would have to be added to account for the finite distance of the stimulus and the individual refractive error. Figure 1 shows an example of both nonblurred and blurred text.

Procedure and Apparatus

After calibration of the eye tracker, a fixation cross appeared at the left side of the calibration grid (8° left; horizontally on eye level). Participants were instructed to read the sentences using the following protocol: After 1000 ms, a sentence was presented so that the first letter of the first word was positioned at the location of the cross. A sentence was then shown until the participants clicked on a mouse button to indicate that they had finished reading. Then, the sentence disappeared, and a second fixation cross was presented at the right side of the calibration grid (8° right; horizontally on eye level). After 1000 ms, this second cross was replaced in one third of the trials by a three-alternative, multiple-choice question pertaining to the content of the current sentence (responses made by mouse click). In the remaining two thirds of the trials, a central fixation cross appeared (midline of the display; horizontally on eye level), which participants fixated for an additional 1000 ms. Thereafter, the left fixation cross appeared again and a new trial started. We measured eye movements for blocks of five sentences. Before the first and after the fifth sentence, we applied a complete calibration phase and combined both regressions to a common calibration for each block of five sentences. After each block of five sentences, we included breaks of a few minutes so that the participants could rest and relax their eyes. The sequence of blocks (six blocks of blurred sentences and six blocks of nonblurred sentences) was randomly interleaved for each participant.

For the purpose of monocular presentation of the calibration targets we used a mirror stereoscope[1] with two half mirrors at right angle and two TFT (thin-film transistor) screens. In addition, a third screen, on which the sentences were presented, was placed straight ahead, (Fig. 2). All these screens were placed at a viewing distance of 60 cm. All stimuli were presented on a white background at a luminance of 33 cd/m^2, with a screen refresh rate of 100 Hz and surrounding room lighting of approximately 40 lux.

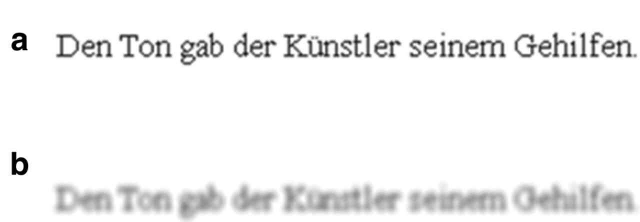

Figure 1. Examples of the presented sentences. (**a**) A nonblurred sentence; (**b**) the same sentence after it was blurred equivalent to a defocus of +0.5 D.

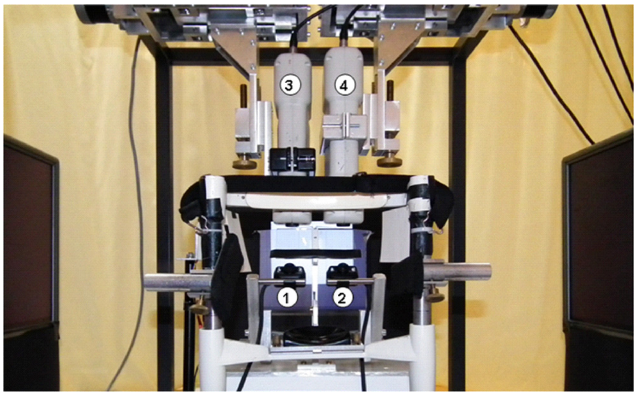

FIGURE 2. The experimental setup. The screen straight ahead presents the sentences for the reading task and the two side screens (turned of in this image) present only the fixation crosses monocularly during calibration phases. (Note that half-silvered mirrors were used so that the images of the left and right screens can be separated for the two eyes during calibration.) The numbers show the positions of the cameras of EyeLink II system (1 and 2) and the Handy-Ref SRH-2000 autorefractometers (3 and 4). Note that the infrared mirrors for the autorefractors where positioned in front of the haploscope mirrors and above the cameras. All placements were positioned as close to the eye as possible to avoid reductions in measurement resolution and field of view.

Eye Movement Measurement and Calibration

We recorded eye movements with a video-based eye-tracking system (EyeLink II (SR Research, Ltd., Osgoode ON, Canada) that tracks both eyes simultaneously. The dark pupil system tracks the center of the pupil by an algorithm similar to a centered calculation with a theoretical noise-limited resolution of 0.01 deg (0.6 min arc) and a velocity noise of less than 3 deg/s for two-dimensional eye-tracking (details provided by SR Research, Ltd.). In prior studies,[10,44] we showed that saccadic changes in eye position of approximately 4 to 6 min arc can be detected using the raw data of the eye-tracking system and our purpose-made monocular calibration procedure and data analysis. During the monocular calibration procedure, participants were requested to carefully fixate calibration targets that appeared (for 1000 ms) randomly with 100 ms temporal gaps at one of the nine positions within a 3×3 calibration grid. The displacement between the calibration points was 8°, so that the calibration grid covered a central area of 16 ° × 16°. Monocular presentations to the right and left eye were randomly interleaved. To draw attention to the calibration targets and to facilitate exact fixation, the diameter of the spot initially subtended 1° and shrank immediately during 1000 ms to a remaining cross of 8.1×8.1 min arc (stroke width, 2.7 min arc); the remaining cross was visible for 400 ms, during which calibration data were stored. Because of the need to calibrate the raw data by physically presented targets, each measured eye position was subject to an uncertainty that can be described by a standard deviation due to the calibration (SDc)[45,46]; these were calculated for our objective measurements (see also, Jainta et al.[10]).

For all measurements, we used a chin and forehead rest, including a narrow temporal rest to minimize head movements. We did not operate the eye tracker as a head-mounted device, rather the cameras were fixed to the chin rest (Fig. 2); the distances between the cameras and the eyes of each observer were then adjusted so that each camera was always in a controlled position relative to the eye (varying only a few millimeters between eyes and observers).

Data Selection and Parameter Extraction for the Eye Movement Data

Eye movement data were screened for loss of measurement and blinks. To exclude data based on inappropriate calibrations, we selected only those sentences for which the standard deviation due to calibration did not exceed 20 min arc, which resembled the character width. We included this criterion because the character width had been identified as a characteristic determinant width of vergence accuracy in previous research.[10,47–49]

From the separate signals of the two eyes we calculated the conjugate eye movement ([left eye + right eye]/2; that is, the version signal) and the disconjugate eye movement (left eye – right eye; i.e., the vergence signal). The onset, or offset, of horizontal saccades was defined as the time when the eye velocity of the conjugate signal exceeded, or dropped below, respectively, 10% of the v_{max}. Next, we excluded saccades with amplitudes smaller than 10 min arc and with fixation phases shorter than 80 ms or longer than 1200 ms.[50] Analyses were restricted to initial fixations on words in first-pass reading.

We extracted several parameters from the eye movement signals. We will explain each of them in detail below. (1) For each detected saccade we calculated its amplitude as the difference in the version signal between the end and beginning of the saccade. More important, (2) we extracted the change in vergence between saccade on- and offset[9,51] (i.e., its disconjugacy) as the difference in the vergence signal between the markers. Further, (3) for each fixation period we calculated the vergence angle at the moment during fixation when the deviation of the observed vergence angle was smallest with respect to the geometrically expected vergence angle; in other words, we searched the total fixation period to find the smallest vergence error with respect to the actual viewing distance. Thus, the vergence adjustments were most efficient for this fixation period. Since the prevalence of more crossed (eso) or more uncrossed (exo) fixations during reading is still a topic of ongoing research (see for example, Liversedge et al.,[50] Nuthmann and Kliegl,[47] and Jainta et al.[10]), we will only briefly report on the amount of fixation disparity for nonblurred text.[4] For each fixation period, we also calculated the amount of vergence adjustment,[9,51] that is, the change in vergence between the beginning of the fixation period and the best adjusted vergence angle (i.e., the minimum fixation disparity). As described above, each saccade introduced a transient disconjugacy and subsequent vergence adjustments correct for it[9,51] until most efficient vergence angles (i.e., smallest fixation disparities relative to the actual viewing distance) were obtained.

Calculation of Heterophoria

During calibration, binocular recordings were stored while one eye fixated the target and the fellow eye was not provided with a target. The resulting vergence angle without a fusion stimulus is known as heterophoria (see also Jainta and Jaschinski[10] or Jaschinski et al.[52]). From each calibration, we had two average heterophoria measures, one for each eye. Because of the high correlation of both measures ($r = 0.98$), we averaged all heterophoria values, which were available for one person and thus described an individual heterophoria as exophore (uncrossed visual axes relative to the target; i.e., behind the target plane; minus sign), esophore (crossed visual axes relative to the target; i.e., in front of the target plane; plus sign) or orthophore (visual axes intersect nearly perfectly at the visual target; 0 heterophoria).

Accommodation Measurement and Data Selection

The Handy Autorefractometer (SRH-2000; Shin-Nippon; Shin-Nippon Commerce Inc., Tokyo, Japan) measures accommodation objectively using infrared light. It focuses bars of light on the retina and applies, in its standard version, image analyses to the reflected shape once it has been refracted by the optics of the eye. We converted our SRH-2000 to allow dynamic recordings.[53,54] The SRH-2000 has a range of at least 10 D in dynamic mode; system noise is low and similar to the widely used Canon R-1 (Canon Inc., Tokyo, Japan) or Grand Seiko WV-500 (Grand Seiko Company, Fukijama, Japan). According to Wolffsohn et al.,[54] the system resolution approximates 0.01 D with pupils larger than 2 mm (whereas in static mode, the accuracy is indicated to be 0.12 D). We operated two SRH-2000s simultaneously (one for each eye; Fig. 2) and collected accommodative data with a sampling frequency of 25 Hz. For the description of the accommodative response during reading, (1) we selected accommodation measures only for the central part of the text; that is, we measured accommodation for only the fixations that were made in a spatial window of ±2° around the center of the presentations. Within this range of 4°, the two Handy Auto Refs were also centered to the gaze direction, thus, allowing for proper recordings. Further, remotely controlled step motors continuously adjusted the Handy Auto Refs (Fig. 2) to the individual interpupillary distance. For fixations with greater eccentricity than ±2 deg, the Handy Auto Ref gave no readings. (2) We pooled the data from both eyes and calculated the accommodative lag (the difference between accommodative stimulus and response) for the actual viewing distance of 60 cm 1.66 D. Accommodation measures were collected for both nonblurred and blurred reading conditions in parallel to the eye movement tracking. See Figure 2 for a photograph of the setup, which allowed for simultaneous recordings of eye movements and accommodation data.

Statistical Analysis

To account for changes in the data due to blurred text, we used a linear mixed-effects model (lmer from package lme4[55,56] in R[57]). Generally, linear mixed-effects models are based on maximum-likelihood methods and are commonly used in many areas of study.[58] One advantage of following a mixed-effects approach in data analysis is that these models lose less statistical power when dealing with unbalanced designs. Classic drawbacks in, for example, ANOVAs (such as missing values or repeated observations) can be eliminated by the use of mixed-effects models for parameter estimations.[58] The statistical package R provides reliable algorithms for mixed-effects parameter estimations, as well as tools for their evaluation.[59] The *P* values and confidence intervals were estimated by using posterior distributions for the model parameters obtained by Markov Chain Monte Carlo sampling, including typically a sample size of 10,000 (see, for example, Baayen et al.[58]).

In our present analysis, we used the eye movement parameters described above as single dependant variables and estimated separate linear mixed-effects models. In detail, for saccade amplitudes and fixation durations, we included the condition of text (blurred vs. nonblurred) and presentation block (1–6) as independent variables into the model estimation. As stated above, mixed-effects models explain data as effects on the first- and second-order statistics with respect to covariates and grouping structures. The covariates in these first two analyses for saccade amplitude and fixation duration were the text condition and the number of presentation blocks, and the grouping factor represented the participants. In other words, we defined the text condition and the presentation block as fixed effects, and treated the participants as random effects (i.e., individual differences in the intercept were taken into account).

In a next step and to analyze the answers given to the control questions, we ran a logistic mixed-effects model analysis (already included in the package lme4 in R), using text condition and the presentation blocks as fixed effects, and participants were again treated as a random effect.

The main analyses of our study then focused on the parameters of binocular coordination. For saccade disconjugacy, the vergence adjustment during fixation, and the overall vergence angle, a more detailed linear mixed-effects model was estimated, including several variables affecting binocular coordination during reading. Presently, our main interest was to compare reading of blurred vs. nonblurred text, so that text conditions were defined as obvious fixed effects. Further, the number of presentations was included as a fixed effect, and participants were treated as random effects. Furthermore, since fixation position (in terms of eccentricity relative to the screen center) and incoming saccade amplitude have been shown to affect vergence adjustments during reading, as well (see, for example, Jainta and Jaschinski,[49] Liversedge et al.,[48] Nuthmann and Kliegl[47]), both variables were added and estimated as additional fixed effects.

For the analysis of the lag of accommodation the simpler model of only including text condition and the presentation block as fixed effects, whereas participants were treated as random effect, was finally applied again to complete the data analysis. Of special interest may be the effect of presentation block in this analysis, because a reduction in the lag of accommodation within several minutes of reading has been reported.[27,60]

We will state the estimated effects (b) with its standard error, the t value, and the P value for each fixed effect.

Results

Saccade Amplitudes, Fixation Durations, and Text Comprehension

Average saccade amplitude was 93 ± 17 min arc for the nonblurred reading condition, resembling approximately four to five character spaces. For the blurred reading condition, the saccade amplitude decreased slightly to 88 ± 12 min arc ($b = 2.96$, SE = 1.15, $t = 2.56$, $P = 0.01$), but remained unchanged across presentation blocks ($b = 0.50$, SE = 0.33, $t = 1.53$, $P = 0.12$).

Further, average fixation durations of 339 ms (±81 ms) increased to 396 ± 76 ms when the text was blurred instead of nonblurred ($b = 35.30$, SE = 7.39, $t = 4.84$, $P < 0.01$), but remained unchanged across presentation blocks ($b = -2.04$, SE = 2.14, $t = -0.96$, $P = 0.33$).

As expected from previous reports, the amount of correctly answered control questions remained unchanged. It was 96% for the nonblurred reading condition and 97% for the blurred reading condition ($b = 0.32$, SE = 0.55, $z = 0.58$, $P = 0.55$), and neither was affected by presentation block ($b = -0.05$, SE = 0.16, $z = -0.35$, $P = 0.72$)

Binocular Coordination for Nonblurred and Blurred Sentences

For nonblurred sentences, the saccade disconjugacy amounted to −6.1 ± 6.0 min arc, on average. This amount of saccade disconjugacy equates to approximately 6.5% of the corresponding average saccade amplitude and thus reflects a good yoking of the binocular saccade as it would be expected for young adults.[6,7] Moreover, this saccade disconjugacy was not affected by reading the blurred text ($b = -0.03$, SE = 0.01, $t = -0.23$, $P = 0.82$). The average disconjugacy for blurred sentences was −5.5 ± 4.6 min arc and resembled approximately 6.2% of the corresponding average saccade amplitude. The disconjugacy did not change because of the actual fixation position within the sentence ($b = 0.001$, SE = 0.001, $t = 0.02$, $P = 0.99$) or the repetition of the measurements throughout the presentation blocks ($b = 0.02$, SE = 0.04, $t = 0.65$, $P = 0.52$). The only variable during reading that affected the saccade disconjugacy was the amplitude of the incoming saccade ($b = 0.057$, SE = 0.002, $t = 22.94$, $P < 0.01$), as one would expect from previous reports, larger saccades increased the observed saccade disconjugacy.

Analysis of the vergence adjustment during fixation revealed a small, albeit significant, difference between both text conditions ($b = -0.31$, SE = 0.13, $t = -2.34$, $P = 0.02$). For nonblurred sentences the adjustment amounted to 5.5 ± 5.4 min arc and was convergent in its direction. It counterbalanced 89.7% of disconjugacy induced by the saccade. For blurred sentences the same convergent adjustment amounted to 4.7 ± 4.3 min arc, counterbalancing approximately 85.7% of the disconjugacy induced by the saccade. Further, the incoming saccade amplitude affected the vergence adjustment during fixation ($b = 0.031$, SE = 0.002, $t = 13.77$, $P < 0.01$), reflecting that the larger the incoming saccade, the larger the vergence adjustment during fixation. In contrast, the fixation position ($b = -0.001$, SE = 0.001, $t = -0.59$, $P = 0.55$) and the number of presentation blocks ($b = 0.039$, SE = 0.037, $t = 1.06$, $P = 0.29$) had no effect on the vergence adjustment during fixation. For both sets of sentences, nonblurred and blurred, the saccade disconjugacy correlated with the vergence adjustment during the beginning of the fixation ($r = -0.99$; $P < 0.01$, and $r = -0.82$; $P < 0.01$), respectively) and thus reflected the stereotyped eye movement pattern of a divergence during saccades, which is followed by a convergent drift at the beginning of fixations.[9,21,51]

The next analysis regarded the overall adjustment of the vergence angle for both reading conditions. For nonblurred and blurred sentences, we extracted the vergence angle at the moment during fixation when the deviation of this angle was smallest with respect to the geometrically expected vergence angle. Across subjects, the average vergence angle for nonblurred sentences was 364 ± 31 min arc. Since the geometrically expected vergence angle for a 60-cm viewing distance and an average pupil distance of 59 mm was 341 ± 20 min arc, averaged across participants, the mean minimum fixation disparity was 16 ± 21 min arc and therefore slightly smaller than the average character width (20 min arc). Most interesting, the observed vergence angle was smaller for blurred text. The vergence angle shifted in exo direction relative to the vergence angle during nonblurred sentence presentation, amounting to 357 ± 32 min arc, on average; this corresponding change of a few minutes of arc was significant ($b = -6.52$, SE = 0.69, $t = -9.42$, $P < 0.01$). Figure 3 shows the vergence angles for blurred sentences as a function of vergence angles for nonblurred sentences. As can be seen, both observations correlated highly ($r = -0.99$; $P < 0.01$), and all participants showed a smaller vergence angle with blurred text presentations.

The sequence of presentation did not change the vergence angle ($b = -0.004$, SE = 0.196, $t = -0.02$, $P = 0.98$). Surprisingly, neither the incoming saccade amplitude ($b = 0.007$, SE = 0.011, $t = 0.65$, $P = 0.52$) nor the actual fixation position ($b = 0.004$, SE = 0.003, $t = 1.22$, $P = 0.22$) showed an effect on the vergence angle in this first analysis. We speculated that an interaction between the text condition and the incoming saccade amplitude or the fixation position might have obscured any single effect. For this reason, we ran a new mixed-effects model analysis, but this time we included both interaction effects. The effect of text condition even increased slightly and both interactions (text condition × fixation position: $b = -0.16$, SE = 0.02, $t = -7.59$, $P < 0.01$; text condition × saccade amplitude: $b = 0.04$, SE = 0.02, $t = 1.96$, $P = 0.05$) were significant. Reducing the mixed-effects model again by analyzing only one level of the variable text condition showed that, for nonblurred text conditions, there was a slight tendency toward an increasing effect of the actual fixation position on vergence angle adjustments ($b = 0.006$, SE = 0.004, $t = 1.86$, $P = 0.06$), whereas, for the blurred text condition the fixation position obviously decreased the amount of adjusted vergence angle ($b = -0.17$, SE = 0.02, $t = -6.72$, $P < 0.01$). For incoming saccade amplitude, the effects disappeared again (nonblurred text: $b = 0.003$, SE = 0.014, $t = 0.18$, $P = 0.86$; blurred text: $b = -0.001$, SE = 0.002, $t = -0.03$, $P = 0.97$).

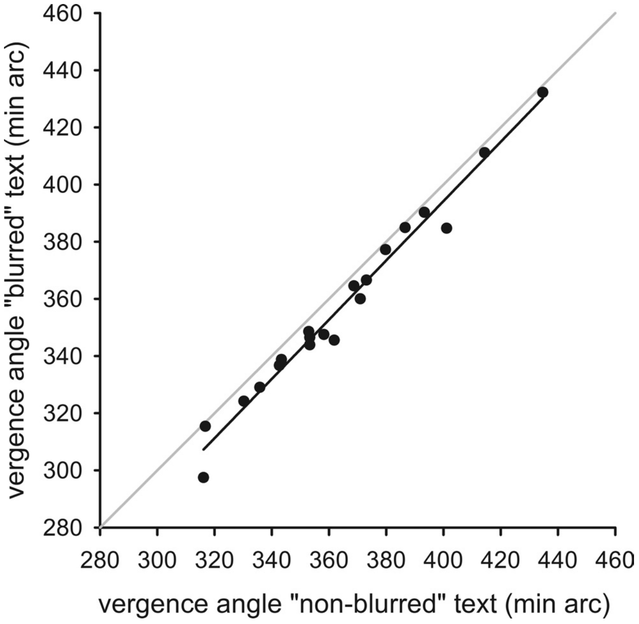

Figure 3. The vergence angle for blurred sentence presentations as a function of the vergence angle measured for nonblurred sentence presentations. Consistently across participants, the vergence angle was smaller for blurred text.

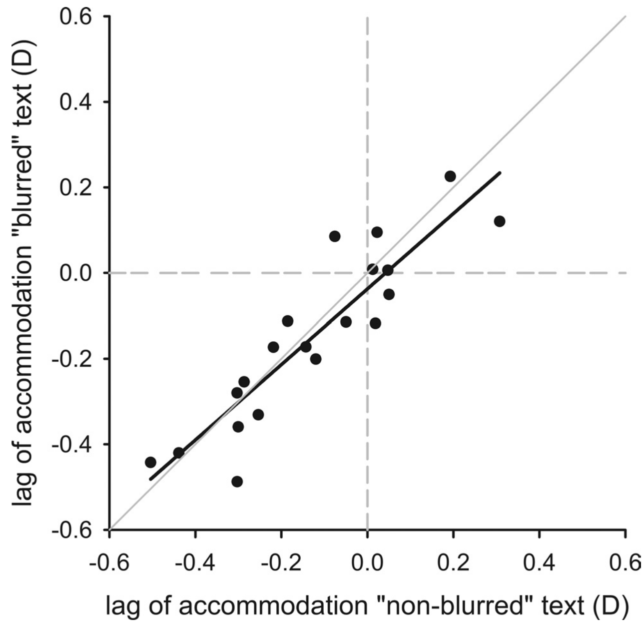

Figure 4. The measured lag of accommodation for blurred sentence presentations as a function of the lag of accommodation for nonblurred sentence presentations. On average, the lag of accommodation slightly larger for blurred text.

The Lag of Accommodation for Nonblurred and Blurred Sentences

Analysis of the accommodation measurements (which were taken from only central fixations while reading) showed an average lag of accommodation (a difference between accommodative stimulus and response) of −0.13 ± 0.21 D for nonblurred sentence presentations. Further, for blurred sentences the lag of accommodation increased slightly to −0.18 ± 0.18 D; even though this difference was very small, it reached statistical significance ($b = -0.05$, SE = 0.02, $t = -2.77$, $P < 0.01$). Figure 4 shows the lag of accommodation for blurred sentences as a function of the lag of accommodation for nonblurred sentences; as can be seen, both observations correlated highly ($r = -0.90$; $P < 0.01$).

Since changes in the lag of accommodation are supposed to be dependent on the time of presentation and a reduction in the lag of accommodation within several minutes of reading has been reported previously,[27,60] we included the sequential presentation of sentences in blocks in the mixed-effects model as the fixed factor for presentation blocks. A slight tendency for a decrease in the lag of accommodation across blocks could be was observed. For the first block of presentations, the lag of accommodation amounted to as much as −0.20 ± 0.24 D and decreased to −0.16 ± 0.26 D for the last block of presentations (b = 0.011, SE = 0.006, t = 1.72, P = 0.08).

Correlating Vergence and Accommodation Measures

An interesting point was to test whether different vergence parameters correlate with changes in the lag of accommodation and vice versa. Therefore, we calculated the change in the lag of accommodation between nonblurred and blurred sentence presentations and correlated it to the corresponding change in vergence angle. The small correlation amounted to $r = 0.38$ ($P = 0.10$). Next, because of only slight changes in the lag of accommodation across nonblurred and blurred sentence presentations, we averaged the lag of accommodation for each participant and correlated the overall lag with the change in vergence angle caused by the blurred text. As can be seen in Figure 5, there is an intermediate correlation between the overall lag of accommodation a participants shows during reading and the effect of blurring on the vergence angle (r = 0.46; P = 0.04).

Further, we correlated the change in vergence angle due to blurred text with the individual heterophoria, which we extracted during calibrations. The heterophoria values ranged from −1.29° to 0.59°, that is, from small amounts of exophoria to very slight amounts of esophoria; these values were altogether slightly smaller than previously reported ones.[49,52] Nevertheless, as Figure 6 shows, the correlation between changes in vergence angle and heterophoria was substantial (r = 0.73; P < 0.01). The more exo the participant's heterophoria the larger the shift in vergence angle due to blurring of the text.

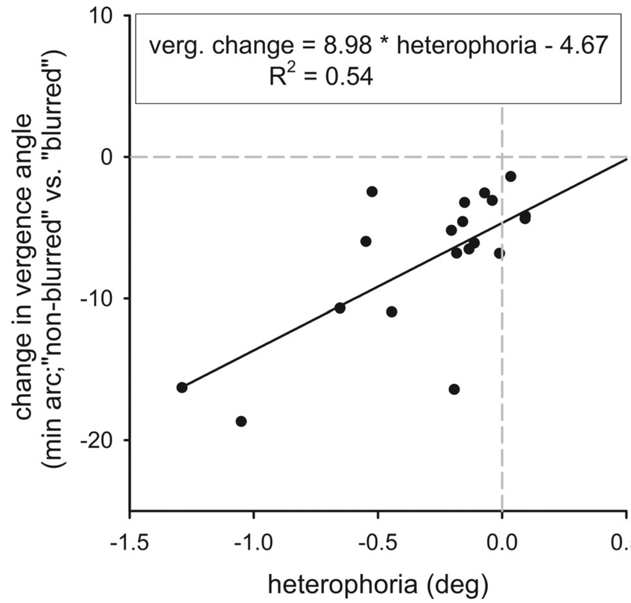

Figure 6. The correlation of the change in vergence angle, which was observed when blurred sentence presentations were compared to nonblurred sentence presentations, and the heterophoria, which was extracted during calibration periods.

Discussion

The present study evaluated dynamic and static aspects of the binocular coordination of the two eyes when upcoming text was blurred: single sentences were degraded in their visual appearance as if the observer was confronted with a refractive error of the eyes or had been over- or undercorrected with glasses. The main findings were that (1) even though the text comprehension was not affected by blur, the fixation durations increased. (2) The dynamic vergence movements during saccades were not affected when reading blurred text; however, the vergence adjustment during the beginning of fixations was reduced. Moreover, (3) the overall vergence angle shifted into the exo direction, and (4) the lag of accommodation was slightly larger for reading blurred sentences. We will discuss these findings in detail below (see Table 1 for a short summary).

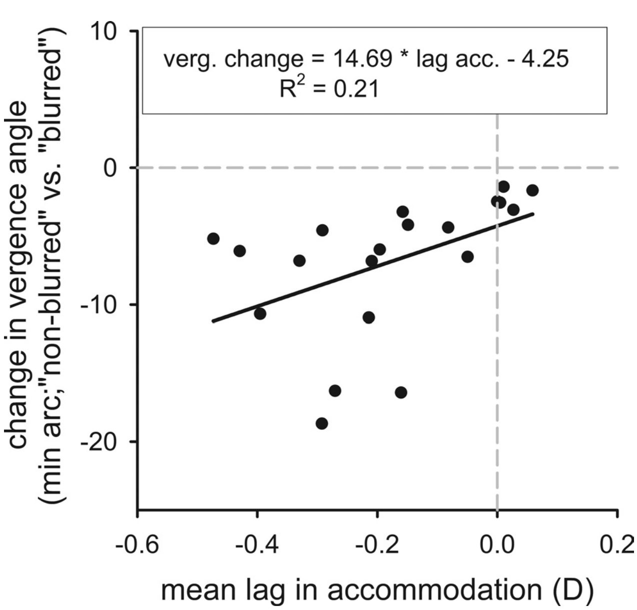

Figure 5. Relationship between the change in vergence angle (blurred text relative to nonblurred text) and the average lag of accommodation observed across all sentence presentations. Both correlated mildly, albeit significantly.

Effects of Blur on General Reading Behavior

It was shown previously that considerable blur due to accommodative lags is usually observed during reading; however, blur up to 2 D did not affect reading speed or reading efficiency.[31,32] Our present study replicated these earlier findings, in that the comprehension of the sentences was neither affected by the induced blur nor did anyone of the participants complain about the degraded images. Nevertheless, average fixation durations were longer with blurred sentences, whereas average saccade amplitude was slightly reduced for reading the blurred ones, compared to the nonblurred ones, showing that the blurring of our sentences affected at least parts of the reading process itself.[43,61]

Effects of Blur on Dynamic Vergence Adjustments While Reading

It was interesting to see that we also replicated the stereotyped pattern of vergence adjustments during saccades and adjacent fixations: the saccade disconjugacies were divergent and followed by a convergent drift at the beginning of fixation.[2,5,9,21,51] The amount of saccade disconjugacy was in a typical range for adult observers[6,7] and, as one would expect, dependent only on the size of the saccade amplitude.[2–7] In contrast to the saccade disconjugacy, the vergence adjustment during the start of fixations was not only dependent on the

Table 1. Summary of the Main Results

Parameter	Nonblurred Text	Blurred Text	*t* Value	*P* Value
Saccade amplitude	**93** min arc	**88** min arc	2.56	0.01
Saccade disconjugacy	−6.1 min arc	−5.5 min arc	0.02	0.99
Vergence angle	**364** min arc	**357** min arc	9.42	<0.01
Vergence adjustment	**5.5** min arc	**4.7** min arc	13.77	<0.01
Lag of accommodation	**−0.13** D	**−0.18** D	−2.77	<0.01
Fixation duration	**339** ms	**396** ms	4.84	<0.01
			z Value	
Text comprehension	96 % correct	97 % correct	0.58	0.55

Data are the average value. Significant results are shown in bold.

incoming saccade amplitude, but was also affected by blurring of the sentences, For blurred sentences the adjustment was reduced. In general, there are two interesting aspects of this vergence adjustment: (1) a late part of the adjustment, which might reflect a fine-tuning of the vergence angle based on remaining disparities,[1,4] and (2) an early part, which might be preprogramed by the saccade execution.[5,9,10] The present observations that the vergence adjustment during fixation was influenced by the amplitude of the incoming saccade might reflect preprogrammed aspects of vergence adjustments during fixations related to saccade execution. In addition, the fact that vergence adjustments during fixations were reduced when blurred text was read suggests an impact of the blurring on the disparity-driven fine-tuning of the vergence adjustments. Since the blurred images are reduced in terms of high spatial frequencies, these vergence adjustments were also likely to be reduced.[1]

Effects of Blur on Vergence Angle Adjustments While Reading

An overall perturbing effect of blur[1] was further manifested in the observed exo shift in the overall vergence angle relative to nonblurred sentence presentations. During the reading of the blurred sentences, the vergence angle decreased systematically in all participants (i.e., their eyes diverged). Such an exo shift in vergence adjustments was found in subjective measures of fixation disparities[36] and might further be related to long-term visual fatigue, since more exo conditions of fixation disparity have been associated with visual strain and asthenopic complaints.[11,62] More generally, the average vergence angle for nonblurred sentence presentations reflected on average an eso fixation disparity of about one character size, which is in line with previous reports (see for example, Nuthmann and Kliegl[47] and Jainta et al.,[10] but Liversedge et al.[50]). Vergence adjustments and especially fixation disparities were shown to be related to the resting state of the vergence system, or more specifically, the heterophoria,[13–16] vergence dynamics,[17–19] and/or the coupling of accommodation and vergence.[1,20] As we included an estimation of the individual heterophoria when analyzing the data during monocular calibrations, we correlated this heterophoria value with the observed shift in vergence angle due to blurred text presentations: the more exophoric the heterophoria the more pronounced was the shift in vergence angle due to the blurred images. These observed effects of blurring were similar to those found with a nonius test of fixation disparity during longer periods of stationary fixation. in the latter condition, Jaschinski-Kruza[36] found that blurring of a fusional target induced an exo shift in fixation disparity and that the individual amount of this shift increased the more the vergence resting position of the observer was behind the near fusion target. They used the dark vergence position as a measure of resting vergence (i.e., when both fusional and accommodative stimuli are eliminated). In the present study, the measure of resting vergence was the heterophoria (i.e., the vergence state with excluded fusional, but included accommodative stimuli). The present heterophoria measure has the advantage that the viewing conditions (with respect to viewing distance, luminance, and proximal vergence) resemble those during fusion. The present results and those of Jaschinski-Kruza[36] both confirm the concept of Owens and Leibowitz[13]: In degraded conditions of the fusion stimulus (e.g., due to blurring), the vergence position shifts toward its individual resting position. This general finding emerged both from objective, video-based recordings of eye position and from subjective nonius measures of fixation disparity. This agreement is interesting in view of the debate on the relation between objective and subjective vergence measures; see Jainta et al.[44] and Jaschinski et al.[52] for an overview. Thus, the induced shift in vergence angle due to blurred text presentations could be plausibly related to optometrically and physiologically well-established parameters of binocular coordination.

Moreover, the vergence angle assumed during reading blurred versus nonblurred sentences did not change across presentation blocks, as one might have expected from previous reports.[38] Presumably, our presentation times were too short and interleaved breaks may have kept vergence regulations in proper limits over time.

Besides the overall blur effect on vergence angle adjustments, neither the incoming saccade amplitude nor the actual fixation position within the sentence showed an effect in a first analysis, in contrast to expectations according to previous reports (see, for example, Jainta and Jaschinski,[49] Liversedge, et al.,[48] and Nuthmann and Kliegl[47]). We showed in a more detailed analysis that an interaction between the text condition and the fixation position obscured the single effects of, at least, fixation position. For nonblurred text conditions, the actual fixation position slightly increased the vergence angle adjustments (see for example, Jainta and Jaschinski,[49] Heller and Radach,[5] and Nuthmann and Kliegl[47] for comparable results), whereas in blurred text conditions, the fixation position obviously decreased the amount of adjusted vergence angle. Keeping in mind that we have already noted for the dynamic changes in vergence adjustments that these were disturbed by blurring the text, it is not surprising that the vergence angle extracted at a single moment in time during fixations also reflected the same pattern. Less accurate vergence drifts during fixation led to a decrease and less optimal fit of the vergence angle. Since saccades during reading are made predominately from left to right, this effect summed up across a sentence (i.e., across the fixations from left to right) reflected the actual fixation position (see also, Nuthmann and Kliegl[47] and Heller and Radach,[5] for comparable reasoning). This later change across fixation positions should have been different for blurred and nonblurred text conditions, since blurring the text did affect the vergence adjustment during fixations differently. The amplitude of the incoming saccade may have contributed only indirectly (less obviously) to these regulatory processes, since it worked on the disconjugacy of the saccade itself and thus caused only indirect changes in the required subsequent vergence adjustment during fixations.[5,9,10]

Effects of Blur on Accommodation and Vergence: Accommodation Relations While Reading

Furthermore, the observed shift in vergence angle due to blurred text presentations correlated with the individual lag of accommodation while reading. The eyes generally try to keep the text in focus; the ciliary muscle changes the refraction of the ocular lens to provide a sharp retinal image.[23–25] However, during reading, the lag of accommodation typically amounts to 0.5 to 1 D.[27–29] In the present study, we also observed small lags of accommodation that increased even slightly when the sentences were blurred (relative to nonblurred presentations). The observed lag of accommodation was in a reasonable range, considering that the viewing distance in the present study was intermediate (i.e., larger than a typical near reading situation).[63] Further, since accommodation and vergence are cross-coupled (see for example, Hung[37]), one might expect changes in both entities when the eyes are confronted with blurred text.[38–42] However, the corresponding correlation between changes in the vergence angle and the lag of accommodation was very small in the present study, probably due to only small changes in the lag of accommodation. Nevertheless, the correlation reflected some realistic cross-coupling while reading sentences at a fixed viewing distance. Furthermore, the lag of accommodation decreased slightly across all presentation blocks; this effect might resemble previous reports of adaptations of accommodation to sustained reading periods.[60,64–66]

In summary, when text was blurred, the binocular coordination of the eyes was mainly affected in two aspects. The vergence angles shifted in the exo direction and the fine-tuning of vergence during fixation was reduced—all relative to nonblurred reading conditions. The observed exo shift in vergence was further related to the magnitude of the individual lag of accommodation while reading and the individual heterophoria. The fact that text comprehension was not perturbed by blur suggests that reading performance is robust against changes in binocular coordination that result from moderate text degradation. Nevertheless, the described changes in binocular coordination are likely to be linked to the development of fatigue and visual stain in near reading conditions, and therefore might be addressed in terms of individual or long-term effects in future studies.

Acknowledgments

The authors thank Patrick Weidling for support during the data collection, Joerg Hoormann for support during the analysis of the eye movement data, and Ewald Alshuth and Matthias Bonacker for arranging all hard- and software setup in the haploscope so that accommodation and eye movement data could be collected in parallel (see Fig. 2).

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