Individual Differences in Binocular Coordination Are Uncovered by Directly Comparing Monocular and Binocular Reading Conditions

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Purpose. We evaluated systematically binocular coordination during a reading task by comparing binocular and monocular reading, and considering the potential effects of individual heterophoria and eye dominance.

Methods. A total of 13 participants (aged 19–29 years, refractive errors −0.5 to 0.125 diopters [D]) read single sentences in a haploscope while eye movements were measured with an EyeLinkII eyetracker.

Results. When reading monocularly, saccade amplitudes increased by 0.04 degrees and first fixation durations became longer by approximately 10 ms. Furthermore, saccade disconjugacies increased, and compensatory vergence drifts during fixation turned into a divergent drift relative to the viewing distance. The vergence angle adjusted for the actual viewing distance became less convergent during monocular reading by 0.5 degrees. Moreover, in participants who were almost orthophoric, only the first fixation duration became longer (by 20 ms) when the reading conditions changed from binocular to monocular. For exophoric participants, all parameters of binocular coordination changed, and first fixation duration decreased by 20 ms. When reading monocularly, no differences between the dominant right eye and the nondominant left eye were found.

Conclusions. Because of obvious differences in binocular coordination between monocular and binocular reading, some vergence adjustments are driven actively by fusional processes. Furthermore, higher demands on these binocular fusional processes can be uncovered only by a detailed evaluation of monocular reading conditions. (*Invest Ophthalmol Vis Sci.* 2012;53:5762–5769) DOI:10.1167/iovs.12-9707

Typically, people read information on media at close viewing distances. Thus, two different general types of eye movements are required while information is extracted: Version eye movements, or saccades, bring the eyes from left to right, and vergence eye movements are needed to adjust the angle between the two visual axes to the actual viewing distance. An appropriate adjustment of the vergence angle enables the images in the two eyes to fall on the corresponding retinal areas, providing a fused percept of the text for higher-level processing of letters and words. When the eyes move across the text, each saccade inherits disconjugacy (a transient vergence eye movement) due to a difference in the horizontal movements of the two eyes. Typically, the abducting eye performs a larger and faster movement than the adducting eye at the beginning of the saccade.[1–6] This saccade disconjugacy also is present during reading, and several studies have shown that the eyes typically perform a stereotyped pattern of vergence adjustments: the saccade disconjugacy (usually divergent) is followed by a compensatory drift in vergence (usually convergent) during the subsequent fixation.[7–10] The vergence drift during fixations is meant to restore passively the conjugacy disrupted by the saccade in the form of a pulse-slide-step activity recorded in abducens neurons.[8,11] If this is the case, saccade disconjugacies and vergence drifts in subsequent fixation periods should be present even when reading is performed under monocular conditions, such as when the text is presented to one eye only. A previous report suggests that vergence velocities during fixations do not differ under monocular and binocular reading conditions.[4]

However, the vergence angles for actively fused binocular stimuli and stimuli presented to only one eye are not identical. Compared to the reading fixations described thus far, the vergence angles are assumed to be different when the binocular system works "open-loop," or in other words, when only one eye is presented with a stimulus.[12–14] When one eye is occluded, the vergence system adopts a resting position, called the heterophoria or dissociated phoria. Individuals differ in their heterophoria, and it has been shown that heterophorias adapt constantly to different viewing conditions.[15–18] Moreover, the heterophoria has an important role in several vergence adjustments and might affect, for example, preprogrammed aspects of the vergence response.[19] The open question of whether the individual heterophoria might have an impact on vergence regulations under natural reading conditions remains to be answered.

Another interesting aspect in the research field of binocular coordination during reading is the consideration of a so-called dominant eye. Poor binocular control during prolonged target fixation has been shown by Stein and Fowler for children with underdeveloped eye dominance,[20] whereas Cornelissen et al. reported no difference in the vergence stability in children who show underdeveloped and fully developed eye dominance.[21] Furthermore, the concept of eye dominance and its potential role in visual or oculomotor processes still is a controversial topic, as reviewed by Mapp et al.[22] Specifically, sighting eye dominance still is the most frequently measured eye dominance in various laboratory and clinical settings. Previous reports doubted that eye dominance might be connected functionally to oculomotor processing in a normal, nonclinical population,[22] but it has not yet been determined if

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Supported by a grant from the Deutsche Forschungsgemeinschaft (JA 1921/3 [SJ]).

Submitted for publication February 15, 2011; revised June 21, July 19, and July 26, 2012; accepted July 26, 2012.

Disclosure: **S. Jainta**, None; **W. Jaschinski**, None

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Investigative Ophthalmology & Visual Science, August 2012, Vol. 53, No. 9

Table 1. Individual Results of the Orthoptic Examination

Participant	Age (Y)	Spherical Equivalent (D)		Near Point of Accommodation (cm)	Near Point of Vergence (cm)	Heterophoria (Deg)	Breakpoint of Divergence at 40 cm (Prism Diopter)	Breakpoint of Divergence at 500 cm (Prism Diopter)	Breakpoint of Convergence at 40 cm (Prism Diopter)	Breakpoint of Convergence at 500 cm (Prism Diopter)
		Right Eye	Left Eye							
1	25	−0.125	−0.25	13	10	−0.45	17.50	4.25	29.00	21.25
2	24	−0.125	0	10	9	−0.56	22.00	13.00	14.25	22.00
3	22	−0.125	−0.125	11	8	−0.59	24.00	4.75	17.50	18.50
4	23	−0.25	−0.125	11	6	−0.65	11.75	10.50	20.75	15.50
5	19	0	−0.125	10	6	−0.67	21.50	5.75	21.00	25.50
6	26	0.125	−0.125	12	10	−0.68	15.25	8.25	20.25	19.25
7	28	−0.125	−0.125	13	9	−0.78	28.00	5.75	19.25	14.00
8	24	0	0	17	10	−0.79	11.75	6.25	23.00	26.00
9	23	−0.25	−0.125	10	8	−0.98	21.00	6.00	18.00	15.00
10	24	−0.125	−0.125	10	11	−1.05	21.00	6.00	26.50	14.50
11	29	−0.5	−0.5	15	10	−1.31	15.25	6.75	21.00	20.00
12	25	−0.25	−0.5	13	10	−2.06	14.00	5.50	10.00	7.00
13	27	−0.5	−0.5	16	11	−2.82	17.50	10.50	6.25	11.00
M ± SD	25 ± 3	−0.17 ± 0.2	−0.20 ± 0.2	12 ± 2	9 ± 2	−1.03 ± 0.68	18.5 ± 4.9	7.2 ± 2.6	18.9 ± 6.2	17.7 ± 5.5

such a sight-dominant eye consistently affects binocular coordination during reading.

In summary, a systematic evaluation of the different parameters of binocular coordination during reading tasks comparing binocular and monocular reading has not been performed to our knowledge. A direct comparison between binocular and monocular reading can be used to investigate the differences between the pre-programmed and disparity-driven adjustments of binocular coordination during reading. Individual differences, such as the heterophoria or eye dominance, could be expected to have a critical role. Therefore, our present study examined binocular coordination when observers read sentences with both eyes, or monocularly with their dominant right eye or nondominant left eye.

Methods

Participants

Six female and 7 male, naïve participants, between the ages of 19 and 29 years (mean ± SD 25 ± 3 years) participated in the study. Each participant gave informed consent before the experiments. The research followed the tenets of the Declaration of Helsinki, and was approved by the ethics review board of the Leibniz Research Centre for Working Environment and Human Factors.

Orthoptic Examination

All participants showed right eye dominance when tested with a sighting test. For this test, participants had to view a black cross target shown at a distance of approximately 5 m through a hole (3 cm in diameter) in the middle of a card (20 cm wide and 12.8 cm high). To prevent a handedness bias, the card was held with both hands at arm's distance. Without moving the head, the task was to align the hole of the card with the target when viewed with both eyes. The experimenter then alternately covered the left or right eye of the participant, who then indicated orally which eye, left or right, kept the object centered in the hole. The reported eye then was registered as the dominant eye.[22,23]

All participants showed good stereovision (60 s of arc or better, tested with the TNO random dot test), and refractive errors ranged from −0.5 to 0.125 diopters (D). Orthoptic evaluation of vergence (by using prisms) and accommodation showed typical ranges (see Table 1 for details).[13]

During monocular calibration of the eye movement recordings, binocular measures were stored while only one eye was fixated on the target. The resulting vergence angle without a fusion stimulus is known as heterophoria[24] (values included in Table 1).

Stimuli

Participants read 30 sentences from the Potsdam Sentence Corpus (PSC).[25] We selected sentences containing 7 to 8 words, and the sentences differed in length from 36 to 57 character spaces. The sentences were presented as black letters using Times New Roman font on a white background with a luminance of 33 cd/m^2 at a screen refresh rate of 100 Hz. The average letter width was 0.33 degrees, which is a 20-minute arc. The surrounding room lighting was approximately 40 lux. The set of 30 sentences was presented binocularly and only to the right eye. For completeness, the set of sentences was presented only to the left eye as well. When viewing was monocular, the nonreading eye was not presented with the text but with a blank screen that represented the homogeneous white background (luminance of 33 cd/m^2).

Note that re-reading is not supposed to affect parameters of binocular coordination.[26,27] For the purpose of monocular presentations, we used a mirror stereoscope (Fig. 1)[28] with two half mirrors at a

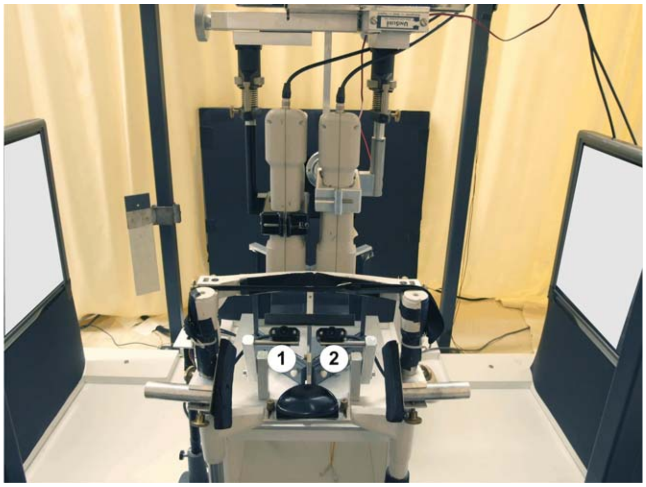

FIGURE 1. Picture of the experimental set-up. Through the use of two mirrors in the center of the set-up, each side screen presents the reading text to one eye only. The *small numbers* show the camera positions of the EyeLinkII system (*1* and *2*, one for each eye). These were positioned as close to the eye as possible to avoid reductions in measurement resolution and field view.

right angle and two thin film transistor liquid crystal display (TFT-LCD) screens. Both screens were placed at a viewing distance of 60 cm.

Eye Movement Measurement and Calibration

We recorded eye movements with the video-based EyeLinkII, which tracks both eyes simultaneously with a theoretical noise-limited resolution of 0.01 (0.6-minute arc) and a velocity noise of <3 deg/s for two-dimensional eye tracking (details provided by SR Research Ltd., Osgoode, ON, Canada). The EyeLinkII was not head-mounted, but the cameras were fixed to the chin- and forehead-rest that were used to stabilize the head (Fig. 1). A narrow temporal rest further minimized head movements.

For the eye tracker calibrations, participants, under monocular viewing conditions, were requested to fixate carefully on targets that appeared randomly for 1000 ms 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 degrees, and presentations to the right and left eye were interleaved randomly. To draw attention to the calibration targets, the diameter of the spot initially subtended 1 degree and shrank immediately during the 1000 ms to a remaining cross of 8.1 × 8.1 minutes of arc (stroke width 2.7 minutes of 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 is subject to an uncertainty that can be described by a standard deviation due to the calibration (SDc).[29,30] These were calculated for our objective measurements and used for data selection.

Procedure

After calibration runs, a fixation cross appeared on the left side of the calibration grid (8 degrees left, horizontally at eye level). After 1000 ms, a sentence was shown and the participants clicked on a mouse button to indicate that they had finished reading the sentence. The sentence then disappeared, and a second fixation cross was presented at the right side of the calibration grid (8 degrees right, horizontally on eye level). After 1000 ms, this second cross was replaced in one-third of the trials by a multiple choice question pertaining to the content of the sentence. In the remaining two-thirds of the trials, a central fixation cross (midline of the display, horizontally at eye level) appeared, 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 5 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 5 sentences. A sequence of 18 blocks (6 blocks presented binocularly, 6 blocks to the right eye, and 6 blocks to the left eye) was interleaved randomly for each participant.

Data Selection and Parameter Extraction

Only horizontal eye movements were analyzed. Eye movement data were screened for blinks. To exclude data based on inappropriate calibrations, we selected only those sentences for which the SDc did not exceed 20 minutes of arc, which is a character width. From the separate signals of the two eyes, we calculated the conjugate eye movement ([left eye + right eye]/2; i.e., the version signal) and the disconjugate eye movement (left eye – right eye; i.e., the vergence signal). The onset and offset of the horizontal saccades was defined as the time when the eye velocity of the conjugate signal exceeded or dropped below, respectively, 10% of the maximum velocity. Next, we excluded saccades with amplitudes smaller than 30 minutes of arc and calculated the fixation times. Fixations shorter than 80 ms or longer than 1200 ms[31] also were excluded, and the analyses were restricted to the initial fixations on words in the first-pass reading.

For each detected saccade, we calculated the amplitude and change in vergence between saccade on- and offset,[32] or its disconjugacy. Furthermore, for each fixation period we calculated the fixation time, vergence angle at the start of fixation, and drift in vergence,[7,8,32] which is the change in vergence between the beginning and the end of the fixation period. Note that for all monocular reading conditions, the vergence parameters are reflecting "open-loop" viewing conditions. Additionally, we calculated the standard deviation for the measurement of each eye's position during fixation.

Statistical Analysis

For data analysis, we used a linear mixed-effects model (lmer from package lme4[33,34] in R[35]).The statistical package R provides reliable algorithms for mixed effect parameter estimations as well as tools for their evaluation.[36] The *P* values were estimated by using posterior distributions for the model parameters obtained by Markov Chain Monte Carlo sampling, which include a typical sample size of 10,000.[37] Predictors were centered, variables were transformed, if necessary, and the model was applied to the non-aggregated data extracted for each fixation. For all analyses, the critical *P* value was set to 0.05.

Our main interest was to compare binocular reading with monocular reading conditions. While reading conditions (binocular versus the right eye only) were defined as a fixed effect, participants and sentences were treated as random effects. The same model was estimated to compare reading with the left versus right eye only. For further analysis, we included the individual heterophoria as additional fixed effects, and tested if heterophoria affected binocular and monocular reading conditions differently as reflected in possible interactions. For all analyses the estimated fixed effect (*b*) with its SE and the *P* value are reported.

RESULTS

Binocular versus Dominant Right Eye Reading

The mean of the saccade amplitudes for binocular reading was 1.37 degrees, which covers 4 letters on average. When reading with the right eye only, the saccade amplitudes increased slightly by less than a letter width (i.e., 0.04 degrees; $b = 0.06$, $SE = 0.02$, $P < 0.01$).

First fixation durations, when the eye lands onto a word for the first time, were an average of 277 ms during binocular

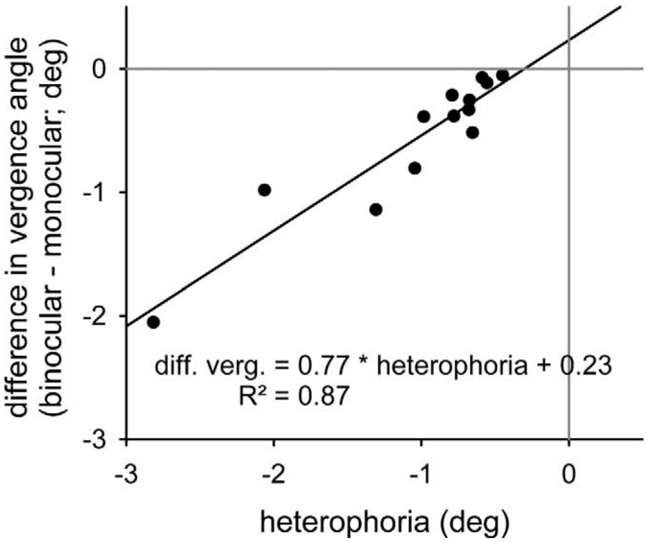

FIGURE 2. The correlation between heterophoria and the change in vergence angle was compared between the binocular and right eye-only reading conditions, as measured objectively during monocular calibrations of the EyelinkII.

reading and increased to 284 ms during monocular reading ($b = 9.05$, SE $= 4.17$, $P = 0.03$).

The mean disconjugacies due to the saccades were divergent by approximately 0.08 degrees for binocular viewing and were approximately 6% of the saccade amplitude. The mean disconjugacies increased when viewing became monocular ($b = 0.008$, SE $= 0.003$, $P < 0.01$). To compensate for the saccade disconjugacy, the drift in vergence during fixations was convergent by approximately 0.04 degrees, approximately 46% of the saccade disconjugacy, during binocular reading and changed to a divergent drift of approximately 0.05 degrees when only the right eye was used for reading ($b = -0.03$, SE $= 0.005$, $P < 0.01$). Furthermore, the standard deviation of each eye's position during fixations increased only for the left eye ($b = 0.006$, SE $= 0.001$, $P < 0.01$) when reading changed from binocular to monocular. The standard deviation for the right eye's position was approximately 0.04 degrees and did not change ($b = 0.0007$, SE $= 0.001$, $P = 0.45$) between viewing conditions.

Moreover, the mean vergence angle at the beginning of the fixations became less convergent and changed from 6.1 to 5.5 degrees when reading changed from binocular to monocular ($b = -0.51$, SE $= 0.01$, $P < 0.01$). Across the participants, this change in vergence angle correlated with the individual heterophoria ($r = -0.93$, $P < 0.01$, Fig. 2).

Comparing Right Eye Reading to Left Eye Reading

To check if the binocular eye movement parameters varied when the dominant (right) eye was reading compared to reading with the nondominant (left) eye, we examined these two conditions directly. The only significant difference between reading with the right eye versus reading with the left eye was in the standard deviations of the eye position measurements. When the right eye was reading, the standard deviation of the right eye's position was smaller than the standard deviation for the left eye's position ($b = 0.009$, SE $= 0.001$, $P < 0.01$), and vice versa for the left eye reading condition ($b = 0.006$, SE $= 0.001$, $P < 0.01$). In other words, the eye that was presented with the text showed standard variations in its eye position measurement comparable to those during binocular reading, while the nonreading eye showed a larger variation during fixations.

The Effect of Heterophoria on Binocular Coordination

A detailed look into the data showed that the participants varied greatly in the change of the vergence angle due to the reading condition (Fig. 3). Therefore, we wondered if large individual differences could be predicted by some general vergence parameter.

For this purpose, we re-analyzed the data by including heterophoria as an additional fixed factor, and modeled additional interactions between heterophoria and the reading condition (binocular and monocular reading). Saccade amplitudes ($b = 0.03$, SE $= 0.03$, $P = 0.38$) and the standard deviations of the eye position measurement (left eye $b = 0.005$, SE $= 0.001$, $P = 0.68$; and right eye $b = 0.002$, SE $= 0.001$, $P = 0.98$, respectively) were not affected differently by heterophoria when reading was changed from binocular to monocular viewing. All other parameters showed clear interactions; the saccade disconjugacies were larger for larger exophorias and reading with the right eye only. In other words, when reading was monocular, the disconjugacy decreased when the heterophorias were closer to zero; that is, when the participants were more orthophoric ($b = 0.05$, SE $= 0.005$, $P < 0.01$). The correlated drift in vergence also became more divergent for larger exophorias and monocular reading ($b = 0.02$, SE $= 0.008$, $P < 0.01$). Furthermore, the vergence angle at the beginning of the fixation periods became less convergent as the participants were more exophoric and with monocular reading ($b = 0.74$, SE $= 0.03$, $P < 0.01$). For the more orthophoric participants, the vergence angle was not noticeably different between binocular and monocular reading. Additionally, for the first fixation duration, the following obvious interaction between heterophorias and the reading condition was found: if the participants were more orthophoric, the first fixation duration was longer for monocular reading, whereas it was shorter under the same conditions for more exophoric readers ($b = 18.42$, SE $= 7.26$, $P < 0.01$).

To illustrate the effect of heterophoria on binocular coordination during monocular and binocular reading, we sorted the sample of 13 participants according to their level of heterophoria (Table 1). Then, we selected two subgroups: the first group contained the 3 participants who showed the smallest heterophorias, or were almost orthophoric, and the second group contained the 3 participants with the largest exophorias. As seen in Table 2, the mean values for the saccade disconjugacies, drift in vergence during fixations, overall vergence angles, and first fixation durations showed clear differences between these two groups when the reading conditions changed from monocular to binocular. These results were expected based on the analysis reported above.

Discussion

Summary of the Results

Generally, when reading with only one eye, the parameters of binocular coordination were different compared to binocular reading. The saccade amplitudes as well as the first fixation durations became slightly longer, and the saccade disconjugacies increased. The vergence drift during fixations became divergent for monocular reading, and the variability of the eye position in the nonreading eye increased. Furthermore, the measured vergence angle for the reading distance became less convergent under monocular reading conditions. More importantly, these changes in binocular coordination were dominated by the heterophoria levels of the participants: smaller heterophorias led to smaller changes in the parameters of

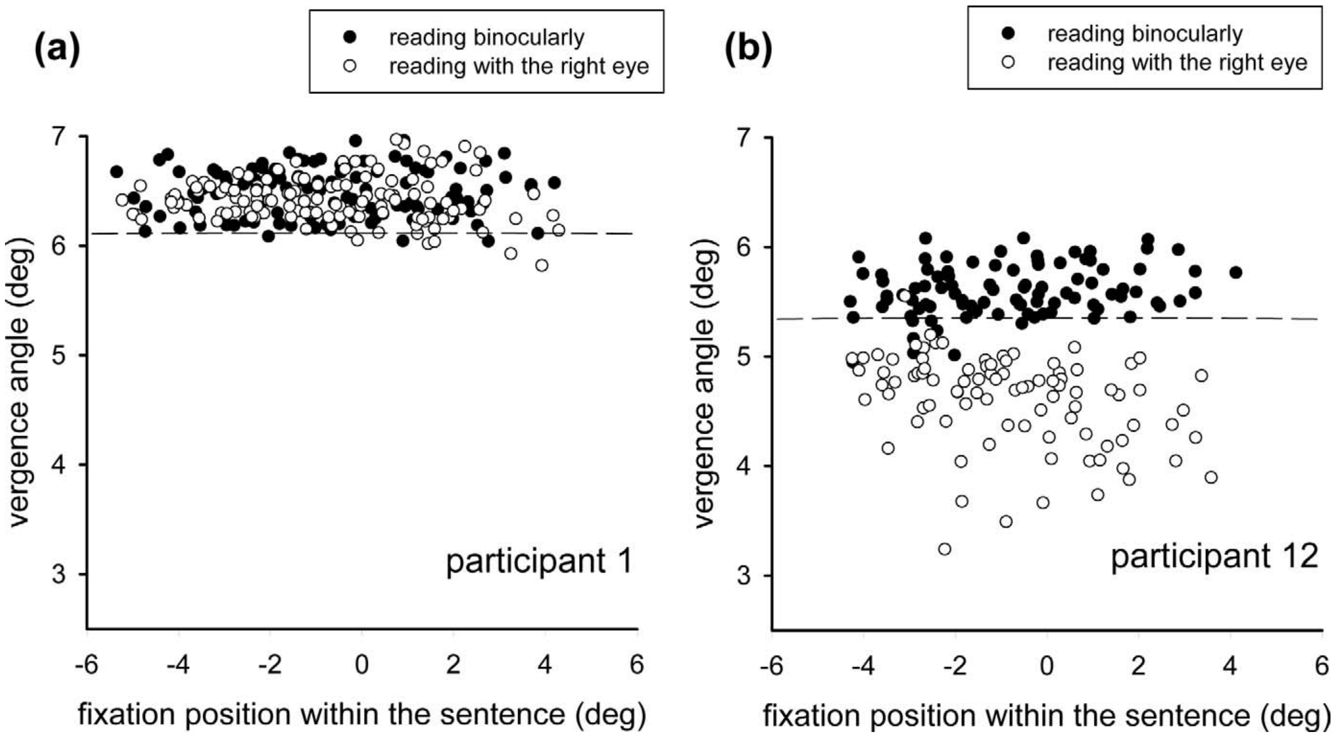

Figure 3. Examples of the vergence angles measured during binocular and monocular reading. The data for participant 1 (**a**) and participant 12 (**b**) are shown. *Dashed lines*: indicate the geometrically expected vergence angle.

binocular coordination for monocular reading. In other words, for the almost orthophoric participants, only the first fixation duration became longer when the reading conditions changed from binocular to monocular viewing. The opposite was observed for more exophoric participants; all parameters of binocular coordination changed dramatically, and the first fixation duration decreased (Fig. 4).

Binocular Coordination for Binocular versus Monocular Reading

When eyes move across the text, the abducting eye performs a larger and faster movement than the adducting eye at the beginning of the saccade.[1–6] This saccade disconjugacy (usually divergent) is followed by a compensatory drift in vergence (usually convergent) during the subsequent fixation and is meant to restore passively the conjugacy.[8,11] Typical values for saccade disconjugacies in adults are reported to be less than 10% of the saccade amplitudes.[5,6] In our study, we found saccade disconjugacies ranging between 4% and 10% for binocular reading, which agree with previous findings. Furthermore, the correlated drift in vergence during fixations was found to be in the expected ranges, reducing approximately 30 to 70% of the disconjugacy caused by saccades, but never reaching a full compensation.[8,38] The saccade disconjugacy and vergence drift during subsequent fixations changed when the reading condition became monocular. The saccade disconjugacies increased, whereas the vergence drift during

Table 2. Results of the Eye Movement Recordings for Two Subgroups

	Disconjugacy during Saccades (Deg*)		Drift in Vergence (Deg*)		Vergence Angle (Deg)		Fixation Duration (ms)	
Participant	Binocular	Monocular (Right Eye)	Binocular	Monocular (Right Eye)	Binocular	Monocular (Right Eye)	Binocular	Monocular (Right Eye)
(a)								
1	−0.08	−0.08	0.06	−0.04	6.5	6.4	272	282
2	−0.10	−0.11	0.05	−0.07	6.1	6.1	277	320
3	−0.09	−0.11	0.03	−0.03	5.9	5.8	273	274
M ± SD	−0.09 ± 0.01	−0.10 ± 0.02	0.05 ± 0.02	−0.05 ± 0.02	6.2 ± 0.3	6.1 ± 0.3	274 ± 22	292 ± 25
(b)								
11	−0.10	−0.15	0.05	−0.12	6.5	5.4	263	222
12	−0.09	−0.16	0.06	−0.13	5.6	4.6	295	292
13	−0.13	−0.12	0.08	−0.10	6.3	4.3	315	298
M ± SD	−0.11 ± 0.02	−0.14 ± 0.02	0.06 ± 0.02	−0.12 ± 0.01	6.1 ± 0.5	4.8 ± 0.5	291 ± 26	270 ± 42

(a), shows data for the 3 participants with the smallest heterophoria; (b), shows data for the 3 participants with the largest heterophoria.
* Minus signs indicate that the vergence changes to the divergent (exo, uncrossed) direction.

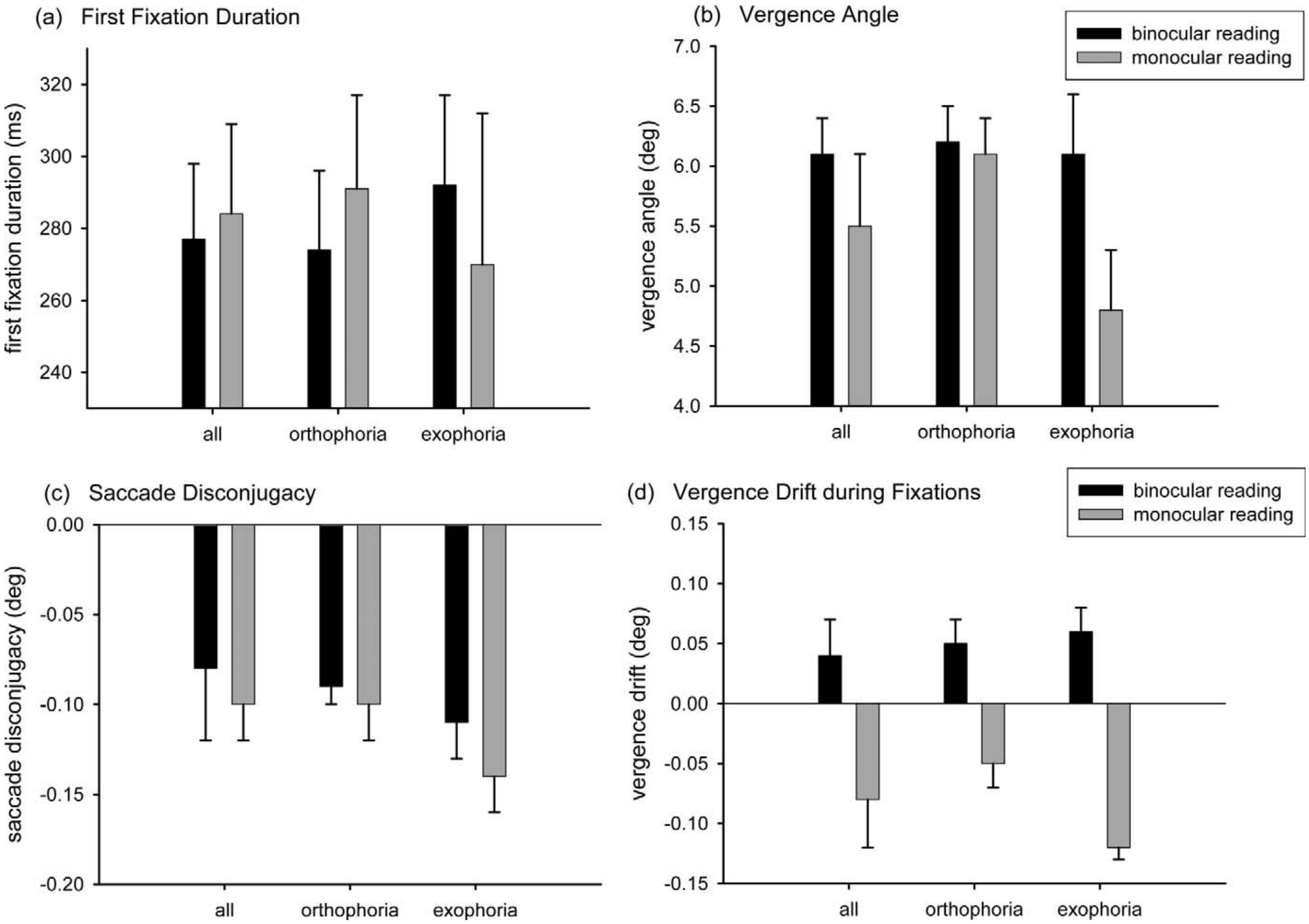

Figure 4. Summary of the main results showing (**a**) the first fixation durations, (**b**) vergence angles, (**c**) saccade disconjugacy, and (**d**) vergence drift during fixations for the binocular and monocular reading conditions. The data also are subdivided into the means for all participants and the two subgroups with an orthophoric or exophoric status.

fixations changed direction and became divergent relative to the viewing distance (and the drifts were observed as differences between the beginning and end of the fixation periods). Thus, our data suggested the following for monocular reading: (1) the coupling of the two eyes during saccades becomes weaker and (2) the vergence system operates on an "open-loop" mode during fixations. Even though mechanisms might passively restore the conjugacy in the early phases of the fixation periods,[8,11,38] the overall drift in vergence appears to be disparity-driven and absent when the reading condition is monocular. This finding seems to contradict a previous finding suggesting that vergence velocities during fixations do not differ between monocular and binocular reading conditions, although this study did not report the amount and direction of vergence drifts.[4]

The existence of a so-called dominant eye has led to speculation about its connection to binocular coordination, but the data on this relationship are not consistent.[20–22] We tried to incorporate the idea of a dominant eye into our study by only selecting participants with a dominant right eye, determined by a sighting test, and comparing directly the effects of reading with only the right or left eye. Our results showed no differences in the binocular parameters when the presentation of the sentences changed from the right to the left eye. The only difference we observed was that the eye that was presented with the sentences always showed smaller standard deviations in eye position measurements. This is not surprising considering the fact that the reading eye was kept in position by a visual feedback loop, while the nonreading eye was just kept in position by the coupling of the two eyes.[28] No changes in fixation durations or vergence adjustments could be observed. Thus, there is no evidence from our study that the simple sighting dominance of one eye would lead to an obvious difference in binocular coordination when the nondominant eye was stimulated.

The Important Influence of Heterophoria

Our study showed that the adjusted vergence angles during reading fixations correlated with the individual heterophoria. The larger the individual heterophoria (exophoria) became, the larger was the difference in vergence between binocular and monocular reading. Because the resting state of heterophoria is expected to be exophoric for a close viewing distance, it is not surprising that the adjusted vergence angle for monocular reading was less convergent, or slightly exophoric (uncrossed), relative to the reading distance. Typically, exophorias for a 60 cm viewing distance are approximately –3 prism diopters (approximately 1.7 degrees relative to the viewing distance),[39,40] and our sample showed mean heterophorias near this expected value. Moreover, this heterophoria allowed us to analyze the possible interactions of heterophoria status and the parameters of binocular status. It also was evident that the more orthophoric the participants were, the less the parameters of binocular coordination changed when the reading conditions changed from binocular to monocular. The opposite was observed for more exophoric participants: all the parameters of binocular coordination changed dramatically. In other words, the more orthophoric a participant was, the less the parameters of binocular coordination indicated if the participant was actually reading with only one eye or with both. The mean first fixation duration for binocular reading became longer with larger heterophorias, and it decreased when changing the visual presentation to monocular reading conditions. We speculate that participants with larger heterophorias experienced higher demands on their binocular system and, thus, needed additional time during binocular fixation to adjust the vergence to the actual viewing distance. As soon as this demand was removed under monocular viewing conditions, the first fixation duration decreased and leveled near the time values observed for binocular reading conditions in almost orthophoric readers. We would like to emphasize that all of these effects were measured in an experimental mode in which participants were required to read only one sentence at a time, and the sentence blocks lasted only a couple of minutes. It remains to be determined whether the same effects are observed for reading paragraphs or for longer periods of time.

Nevertheless, when the heterophorias were small, the readers showed an increase in first fixation durations under monocular reading conditions. This agrees with reports of a binocular advantage due to binocular summation for several visual functions.[13,28] For more exophoric readers, no such binocular summation effects could be observed.

When comparing the variability of the vergence during binocular fixations (as has been done by Jainta and Kapoula for dyslexic and non-dyslexic children[7]), our two subgroups of exophoric and orthophoric readers in our study did not show any differences. Because the monocular visual acuities and stereo acuity were equally good for both subgroups, one would not expect any obvious differences in the binocular coordination. However, after dividing our participants into two subgroups, the subgroup with exophoria also showed smaller vergence reserves (i.e., fusional reserves measured with prisms) for divergence with close viewing conditions and, in general, smaller fusional reserves for the convergence for near and far viewing conditions. Additionally, the near points for accommodation and vergence were slightly farther away for this subgroup. In our study, we observed that the vergence system was weaker for the subgroup with exophorias. Thus, it is likely that higher demands were placed onto the binocular coordination system under near reading conditions. This weakness was obvious only when looking at the clinical optometric tests, including heterophoria measurements, and when directly comparing monocular and binocular reading conditions.

Conclusions

Due to obvious differences in binocular coordination between monocular and binocular reading conditions, some vergence adjustments are driven actively by fusional processes. Furthermore, the potentially higher demands on these binocular fusional processes can be uncovered only by a detailed evaluation of monocular reading conditions.

Acknowledgments

Patrick Weidling provided support during the data collection and Joerg Hoormann provided support during the analysis of the eye movement data.

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