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Binocular coordination of eye movements during reading

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Abstract

Binocular coordination of the eyes during reading was examined. Fixation disparity greater than one character occurred on 47% of fixations, with the disparity being predominantly uncrossed (39%), though a small proportion of fixations were crossed. The average magnitude of disparity, measured at the end of fixation, was 1.1 characters for all fixations. For the 47% of non-aligned fixations the average magnitude of disparity was 1.9 characters. Vergence movements that reduced fixation disparity occurred during fixations, and their magnitude was positively correlated with fixation duration. Finally, eye dominance did not modulate fixation disparity magnitude or the proportion of disparate fixations.

Keywords: Eye movements; Binocular coordination; Reading

1. Introduction

During reading, the eyes move more or less in synchrony (Williams & Fender, 1977; Ygge & Jacobson, 1994) with the movement of each eye beginning (and ending) in close temporal approximation of each other. While a great deal has been learned about the general characteristics of eye movements during reading (Liversedge & Findlay, 2000; Rayner, 1978, 1998), there are important issues that remain somewhat unclear. In the present article, we examine the spatial characteristics of binocular coordination of eye movements during reading.

The vast majority of the research investigating reading has involved recording the movements of one of the two eyes. This convention to record the movements of only a single eye during reading has developed for a number of reasons. The first reason is pragmatic, in that the cost of purchasing the equipment required for recording eye movements can often be doubled if the movements of two eyes are recorded rather than a single eye (though we note that modern eye tracking systems often permit both binocular and monocular recording). Second, many researchers have implicitly assumed that when readers fixate a word during reading, each eye fixates on the same point within the word. Thus, it has been assumed that to record the movements of both eyes would result in a data set of which half would be redundant and represent a waste of effort. Third, given that left and right eye fixation durations are very highly correlated, for researchers investigating numerous psycholinguistic issues that involve establishing differences in reading times, very little is to be gained from recording the movements of both eyes.

It is generally accepted that the purpose of binocular coordination is to keep the visual axes aligned with the material being viewed and thus promote fusion. The vergence system is linked to the accommodative system and may also be subject to top-down control (proximal vergence). However, the principal stimulus for vergence is disparity between the two retinal images (Rashbass & Westheimer, 1961). Much research investigating binocular coordination has used simple discrete stimuli or random dot stereograms. It has been shown that the vergence response is dissociated from perceived depth (Erkelens & Collewijn, 1985), it can occur extremely rapidly, particu-

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larly following a saccadic eye movement (Bussetini, Miles, & Krauzlis, 1996; Busettini, FitzGibbon, & Miles, 2001), and it is controlled predominantly by the disparity in the foveal region (Popple, Smallman, & Findlay, 1998). Binocular coordination is essential during visual scanning of three dimensional arrays but its importance during reading is less obvious. Ordinarily readers read text that is two dimensional with each of the words of a sentence presented (at least approximately) the same distance from the eyes. Consequently, non-conjugate vergence eye movements that are required to permit fixation of objects presented at different distances from the eyes are not necessary. Given this, it seems reasonable to question why it might be important to investigate binocular coordination during reading at all.

We believe that binocular coordination during reading requires careful examination for a number of reasons. First, the assumption that readers fixate the same location within a word is exactly that—an assumption (admittedly, a widely held assumption, but an assumption nonetheless). Clearly, it would be far more satisfactory to empirically demonstrate that this assumption is either correct or false. Second, within the literature there exists very little by way of unambiguous normative empirical data characterising basic behavioural aspects of how the movements of both eyes are coordinated during reading. Third, quite apart from the question of binocular movements, there exists surprisingly little data describing whether, and if so how, each individual eye moves during fixations while reading (though there has been considerable interest in such movements in non-reading tasks, see Martinez-Conde, Macknik, & Hubel, 2004; for a review). Of course, if monocular recordings are used, it is impossible to distinguish between eye drift (where the net movement of the eyes during a fixation is of an equal amount in the same direction) and eye vergence. Finally, the work has important implications for theories based on foveal splitting of information. Proponents of recent split fovea accounts of both word identification and eye movement control during reading have made a number of significant claims concerning how the anatomy of the retina significantly constrains psychological processing during written language comprehension (e.g., McDonald & Shillcock, 2005; Monaghan, Shillcock, & McDonald, 2004; Shillcock, Ellison, & Monaghan, 2000).

According to proponents of the split fovea model, the anatomical fact that the left and right hemi-fields of the retina project to opposite sides of the brain has consequences for subsequent psychological processing (both in terms of saccadic guidance and linguistic processing). Importantly, central to all current explications of the split foveal position is the claim that the splitting of the foveal signal is perfect, with the perceived input being split precisely into two halves and with the split occurring precisely at the centre of the fovea. An additional (usually implicit) assumption is that the points of fixation of both eyes are perfectly aligned such that projections from the vertical midlines of the left and right retina fall perfectly on top of each other. Clearly in such a situation, the visual information that projects to the left hemi-field of the left eye will perfectly match the visual information that projects to the left hemi-field of the right eye and vice-versa. In this sense, central to split foveal theorising is the assumption of a "cyclopean" perceptual situation. On this basis, proponents of the split fovea theory argue that words will be perfectly split into two portions about the (single) point of fixation, and this splitting constrains subsequent psychological processing. However, if it were demonstrated that both eyes do not fixate the same location within a word, then clearly, perfect splitting of words into the same two portions by both eyes cannot be a realistic claim. Consequently, if fixation disparity is shown to occur during reading, then it suggests that current foveal splitting accounts of word identification and oculomotor control are, at best, oversimplified, and at worst potentially unrealistic.

Although there have been many studies examining the nature of binocular coordination in non-reading situations (see Collewijn, Erkelens, & Steinman, 1988, 1997; Yang & Kapoula, 2003), there have been a relatively small number that have examined binocular coordination during reading. Some experiments have focussed on the eye movements of special populations (Bassou, Pugh, & Granié, 1993; Cornelissen, Bradley, Fowler, & Stein, 1991; Cornelissen, Bradley, Fowler, & Stein, 1992; Cornelissen, Munro, Fowler, & Stein, 1993). In particular, such experiments have focussed on the possibility that dyslexia and poor reading performance, more generally, may occur in children due to poor oculomotor coordination (Stein & Fowler, 1981; Stein & Fowler, 1993; Stein, Richardson, & Fowler, 2000). Stein and colleagues' suggestion is that dyslexic children have impaired transient sensitivity producing unstable binocular coordination. It is argued that this in turn could produce symptoms of "wandering letters" within words that dyslexic children sometimes apparently report. However, while some experiments have produced data in favour of this suggestion, other studies have not. For example, Cornelissen et al. (1993) examined vergence movements of normal school children and compared them with those of two groups of poor readers; those with good vergence control and those with poor vergence control (as measured by the Dunlop Test, see Cornelissen et al., 1993, for details). Binocular eye movements were recorded as lists of single words were read. Results indicated that vergence movements were of a similar magnitude for all three groups of participants suggesting that poor reading performance is not a consequence of poor vergence control per se.

A few studies have examined binocular coordination in normal participants during reading. Hendriks (1996) reported three experiments and reviewed earlier literature. She discussed a study by Schmidt (1917) who reported convergent movements of the eyes during a fixation in reading. This claim is consistent with findings from research employing non-reading tasks (Collewijn et al., 1988; Zee, FitzGibbon, & Optican, 1992), which have shown that the eyes tend to diverge during saccadic movements and compensate this with a subsequent convergence during fixation.

Hendriks also pointed out that in contrast to the findings of Schmidt (1917), Clark (1935), and Taylor (1966) reported that readers in their studies made divergent vergence movements during fixations. Hendriks investigated this conflict in findings by examining vergence movements during fixations in a number of different reading tasks (processing individual word lists, reading with and without subvocalisation, repeated reading). Her results supported the findings of Schmidt (1917) showing clearly that convergent rather than divergent vergence movements predominated within fixations during reading. Note, however, that while the data Hendriks reported concerned the nature of the movements made during fixations in reading, she reported very little data concerning the magnitude of fixation disparities at either the beginning or the end of fixations.

Another study that is perhaps most relevant to the research we report here is that of Heller and Radach (1999). In their study, they reported that the eyes do not necessarily fixate the same point within a word and that there is quite substantial variability in the fixation location of the two eyes during reading. Heller and Radach recorded eight readers' binocular eye movements as they read. They reported fixation disparity 150 ms after fixation onset and found that the fixation positions of the eyes were most often between 1 and 2 characters apart. However, Heller and Radach provided no indication of the proportion of fixations on which the points of fixation were crossed or uncrossed. Also, readers read 20 paragraphs of six line texts in Heller and Radach's study. Since readers made approximately 12 fixations per line, this means that, on average, they made over 70 eye movements between calibrations of the eye tracker. This methodological issue raises the possibility that at least some of the disparity observed in Heller and Radach's study may have been due to eye tracker inaccuracy. Since no indication of the proportion of fixations that were crossed and uncrossed is provided, it is difficult to know for certain whether the reported fixation disparities simply reflect a normal distribution of noise about a mean of zero disparity.

An interesting aspect of Heller and Radach's data is their finding that the magnitude of the difference in saccade amplitudes (with larger amplitudes for the abducting eye) was related to the amplitude of the preceding saccade (5% of saccade length for a 10–12 letter saccade, 15% of a 2–3 letter saccade). Additionally, the net drift rate of the eyes during a fixation was linearly related to the amplitude of the immediately preceding saccade. They also reported that at the start of a fixation, when the two fixation points were disparate, there was a relatively slow vergence movement (1 deg/s) that persisted throughout the first 150 ms of fixation in 80% of cases (although they note that the two eyes were still apart at the end of the fixation). Intuitively, one might anticipate that such vergence movements were driven by a fusional response bringing the fixation points onto the same letter within a word, however, this did not appear to be the case. Vergence movements persisted in an identical manner to those that occurred when a word was fixated binocularly even when text was viewed monocularly. Heller and Radach, therefore, argued that vergence movements during reading do not appear to be necessitated by binocular viewing.

Heller and Radach also reported that readers made longer saccades for text presented normally than for MiXeD case text. The implication of this is that since fixation disparity varies as a function of the preceding saccade amplitude, then average fixation disparity was greater for normal text than for mixed case text. Consequently, on the basis of Heller and Radach's data, it appears that when normal text is read the visual system is able to tolerate a greater magnitude of fixation disparity than when mixed case text is read (though we note that nowhere in the paper do the authors present any formal statistical analyses of their data). Thus, while the study reported by Heller and Radach is important and interesting, their data should be regarded as preliminary.[1]

In the present article, we report an experiment in which we systematically investigated binocular coordination during reading.[2] In particular, we were interested in determining whether the default assumption that both eyes fixate the same location during reading (i.e., the same letter) is actually correct. Addressing this question also provided an opportunity to replicate Heller and Radach's findings. If the eyes did become misaligned during reading, as Heller and Radach claim, then we wanted to assess the nature and extent of the misalignment across both individual readers and individual fixations. In particular, we wanted to determine the frequency with which the points of fixation are (1) crossed (with the left point of fixation to the right of the right point of fixation by more than one character), (2) uncrossed (with fixations divergent by more than one character), or (3) congruent across fixations.

Within our binocular data set, we also examined vergence movements made throughout fixations (not just during the first 150 ms). To do this we compared the precise eye positions at the beginning of a fixation with those at the end of a fixation.[3] In this way we were not only able to analyse the movements of the eyes during fixations, but also analyse

[1] In fact, a recent study by Juhasz, Liversedge, White, and Rayner (2006) directly investigated whether processing difficulty during reading reduced the magnitude of binocular disparity. Their results showed that regardless of whether processing difficulty was induced through a visual manipulation (mIxEd CaSe TeXt), or a linguistic manipulation (word frequency), it did not reduce binocular disparity. These data provide a further reason why the data from Heller & Radach should be treated with caution.

[2] See also Rayner and Liversedge (2004) for a preliminary report of pilot binocular data based on recordings from three participants. Unfortunately, due to a software labelling error, the data reported in this paper were mislabelled such that the crossed data are actually uncrossed, and the uncrossed data are crossed. Given this, the data from the present paper, and the preliminary data reported in Rayner and Liversedge are entirely consistent.

[3] Throughout this paper we computed vergence movements by comparing fixation positions at the beginning of fixations with fixation positions at the end of fixations. We note that actual movements of the eye during a fixation may not be smooth and of constant direction and velocity. However, this measure does provide an index of the net amount of vergence movement that occurred during the fixation.

those movements in relation to the nature and magnitude of any fixation disparity that might occur at fixation onset. Thus, the present study attempted to provide rigorous descriptive data concerning the binocular coordination of eye movements, and in particular, we set out to answer five specific questions with respect to binocular disparity during reading: (1) What proportion of fixations is disparate during reading? (2) Does the proportion of disparate fixations change as the eyes move from left to right through a sentence? (3) What is the magnitude of fixation disparity, and do all readers exhibit similar magnitude of fixation disparity during reading? (4) Does the magnitude of fixation disparity change as the eyes move from left to right through a sentence? (5) Does eye dominance modulate fixation disparity during reading? In addition, we set out to address four specific questions concerning vergence movements during fixations: (6) Does alignment and fixation disparity change during a fixation? (7) What is the nature of any vergence movement that does occur? (8) Does the nature of fixation alignment at the beginning of a fixation influence movement during a fixation? (9) Does the duration of a fixation influence the amount of vergence that occurs during a fixation? Taken as a whole, we believe that the analyses of the data we report in this article provide the most comprehensive and accurate characterisation of binocular coordination during reading to date.

2. Methods

2.1. Participants

Fifteen students[4] at the University of Durham were paid to participate in the experiment. All participants had normal vision and were naïve regarding the purpose of the experiment.

2.2. Apparatus

The sentences were displayed as white letters (in lower case except for where capital letters were appropriate) on a black background on a Philips 21B582BH 24 in. monitor at a viewing distance of approximately 85 cm: each character subtended 0.29 deg of visual angle. Movements of both eyes were monitored using left and right Dual Purkinje Image eye trackers. The resolution of the eye trackers is less than 10 min of arc and the sampling rate was every millisecond. The monitor and the eyetracker were interfaced with a Philips Pentium III PC that controlled the experiment.

2.3. Materials and design

One list of 77 items was constructed. The list included five filler sentences and 72 experimental sentences all with a variety of syntactic constructions (see Table 1 for example sentences).

The sentences were all between 48 and 74 characters in length and contained between 8 and 14 words. Twenty-four of the sentences were followed by a comprehension question that addressed the semantic content of the sentence and required participants to form a full interpretation to provide a correct response.

Table 1
Examples of the experimental sentences

1. Everyone scattered as the infamous cowboy drew his gun.
2. The janitor cleaned the filthy blackboard in the classroom.
3. The boy popped the crunchy peanut into his mouth.
4. John often used the specialised darkroom to develop his photos.

2.4. Procedure

Participants were told to read the sentences normally for comprehension. A bite bar and head restraint were used to minimise head movements Prior to participants reading any sentences the eye trackers were calibrated for each eye in turn using a nine point display. Participants were required to fixate each point for approximately one or two seconds and a sample of the eye position was taken at the end of this period for each calibration point. The calibration procedure is based on the values of the eyetracker output at each point and a set of linear interpolation routines that assign a horizontal and vertical eye direction measure to any eyetracker output values. Assuming that the eye fixates accurately during the calibration, and the eyetracker remains stable, this ensures that measures taken when the eye refixates each calibration position are entirely accurate. Measures when the eye fixates an intermediate location between calibration points may be potentially affected by recording non-linearities, although in practice these are very small. During the left eye tracker calibration procedure, the right eye was occluded and during the right eye calibration procedure the left eye was occluded. Before the presentation of each sentence, the accuracy of each eyetracker was carefully checked and re-calibrated (monocularly) whenever necessary.[5] After reading each sentence, participants pressed a button to continue and used a button box to respond yes/no to comprehension questions. The experiment lasted about 45 min.

[4] Of the 15 participants, the smallest mean fixation disparity for a participant was 0.8 characters, and the largest mean fixation disparity was 1.6 characters (both measured at the end of fixation). For the fixations that were not aligned, the largest proportion of uncrossed fixations for a participant was 97% and the smallest proportion was 49%.

[5] In our view, it is extremely important to conduct monocular rather than binocular calibrations when conducting binocular eye tracking experiments. It is for this reason that we occluded the left eye when calibrating the right eye and vice-versa. Monocular calibrations are important because only under monocular viewing conditions can the experimenter be confident that the eye fixation position is based on visual input from that eye alone. For example, if viewing is binocular during the calibration of, say, the left eye, then it is quite possible that the participant may fixate the fixation point accurately only with their right eye (because for some reason their preferred visual input is from the right eye when fixating that point). Thus, the position of the left eye when binocularly viewing that fixation point will not accurately reflect the position of that eye when it is positioned according to its own input (i.e., under left eye monocular viewing conditions). Thus, monocular calibrations permit the experimenter to be sure that the position of the eye when viewing a calibration point is based exclusively on the visual input of only that eye.

We acknowledge, however, that for any calibration procedure there is an assumption that when the participant is requested to fixate a particular point, then they do as they are instructed. Clearly, it is not possible to know with absolute certainty that participants did actually fixate each particular point that they were requested to during a calibration procedure. Participants could choose not to follow the experimenter's instructions and look at a point elsewhere within the calibration matrix. However, on the basis of directly observing the participants' eye movements (via a video display) and on the basis of their comments when questioned during and after the experiment, we believe that the possibility of participants failing to carefully follow the experimenter's instructions extremely unlikely. It is also possible that participants are not aware that they are not fixating accurately. Fixation offsets below a certain magnitude are not always corrected and this tolerance may increase with eccentric viewing.

2.5. Analyses

Eye movement records were analysed using customised computer programs. Fixations were manually identified to avoid contamination by dynamic overshoots (Deubel & Bridgeman, 1995). Five percent of trials were excluded due to tracker loss. Fixations under 80 ms and over 1200 ms were discarded (8% of fixations) and fixations in which the disparity was greater than 2.5 standard deviations above the mean for each participant were also discarded (2% of fixations).

3. Results

In the first instance we report some basic normative data to illustrate that the binocular analyses that we report below are based on eye movement data that reflect normal reading behaviour. The mean fixation duration in our study was 287 ms (*SD* = 129), the mean saccade extent was 7.9 chars (*SD* = 5.6), and on average, participants made 3.2 regressive saccades (*SD* = 1.7) per trial of which 1.5 were interword regressions (*SD* = 1.0). Also, the mean number of progressive saccades that participants made was 7.1 per trial (*SD* = 2.3). Although the mean fixation duration is slightly long, in general the data values are representative of normal reading behaviour in an adult population (Rayner & Pollatsek, 1989).

For many of our analyses we were quite conservative in reporting measures of fixation disparity during reading. Given Hendriks, 1996 demonstration of vergence movements during fixations, we computed fixation disparity at the beginning and the end of fixations to provide an index of net vergence movements that occurred during a fixation (see Table 2). We base all our statistical analyses on the end of fixation disparities as these measures of disparity are the most conservative since vergence movements during fixations reduced overall disparity magnitude. Thus, our analyses of fixation disparity below reflect the disparity that exists after vergence movements have been completed. Also, for all the analyses we report, we categorised fixations as being *aligned* where the disparity of the fixation points subtended less than or equal to one character of each other (0.29 deg of visual angle). Those fixations that were not aligned were categorised as *crossed* when the point of fixation of the right eye was more than one character to the left of the left point of fixation, or *uncrossed* where the left point of fixation was more than one character to the right of the right point of fixation. We adopted this categorical definition because in most eye tracking research investigating reading, fixation positions on words are usually described in terms of which letter of the word a fixation is on. Unless otherwise stated, one sample *t* tests (test value = 50%) were used to test for differences between alignment proportions (e.g., aligned vs unaligned, crossed vs uncrossed). Paired samples *t* tests were used to test for differences between conditions (e.g., for effects of different types of alignment on other measures). The mean error rate on the comprehension questions was 9% indicating that participants read the sentences properly and understood them.

3.1. What proportion of fixations is disparate during reading?

For these analyses we computed whether fixations were aligned, crossed, or uncrossed for two data sets: fixations made within the central 10 degrees of vision (i.e., ±5 deg eccentricity), and fixations made across the entire length of the sentences. We selected fixations within the central 10 degrees of vision because within this portion of the visual array, eye movement recordings are most accurate and the differences in stimulus distance from the two eyes because of screen geometry are negligible. Another issue is that there is no possibility that nasal occlusion of the text could occur in this region (the nose occludes the nasal visual field from about 20–30 deg). Thus, any fixation disparities within this region are very unlikely to be due to inaccurate tracking and could not be caused by blocking of the visual input to either eye.

As can be seen from Table 3, for both fixations made in the central 10 degrees of vision, and for fixations made throughout the sentence, readers made aligned fixations most often, uncrossed fixations slightly less often, and crossed fixations least often. Thus, the data indicate that 45% of fixations made in the central 10 degrees of vision and 47% of fixations made across the entire sentence were disparate by one character or more at the end of a fixation. While it is true that on the majority of fixations, readers do fixate within the distance of one letter with each eye, it appears that for a substantial proportion of fixations made

Table 3
Percentage of fixations that are aligned, uncrossed, and crossed for the central 10 degrees of vision and for fixations at any point in the sentence

	Type of fixation		
	Aligned	Uncrossed	Crossed
Central 10 degrees	55	40	5
All data	53	39	8

Table 2
Proportion of fixations that end aligned, uncrossed or crossed as a function of fixation alignment at fixation onset

Proportion of fixations	Start of fixation	Aligned ($M = 0.5$, $SD = 0.3$)	Uncrossed ($M = 2.0$, $SD = 0.9$)	Crossed ($M = 2.2$, $SD = 1.7$)
End of fixation	All data	*0.53*	*0.39*	*0.08*
Aligned ($M = 0.5$, $SD = 0.3$)	*0.48*	0.89	0.2	0.22
Uncrossed ($M = 1.9$, $SD = 0.7$)	*0.44*	0.06	0.8	0.01
Crossed ($M = 1.9$, $SD = 1.0$)	*0.08*	0.05	0.0	0.77

Mean disparities are shown in parentheses. The overall proportions of aligned, uncrossed, and crossed fixations at the start and end of fixations are shown in italics.

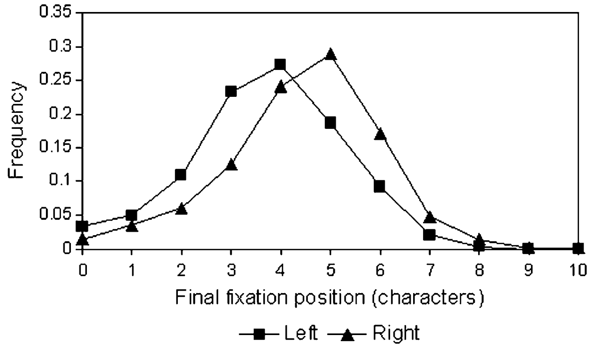

Fig. 1. Mean landing positions on the critical 6, 8 or 10 letter word that was included in each item for the left eye and the right eye. The data are pooled across all 15 participants.

during reading the assumption that the eyes fixate within a one character distance does not hold. Of those fixations in which the eyes were not aligned, fixations were more likely to be uncrossed than crossed both for all of the data, $t(14) = 7.9$, $p < .001$, and for fixations within the central 10 degrees of vision, $t(14) = 9.39$, $p < .001$.[6] This finding is important in that it indicates quite clearly that the disparity effects reported here are unlikely to be due to eye tracking inaccuracy since variability in fixation disparity is not crossed and uncrossed to an equivalent degree about a central point.

A further illustration of fixational mean disparity is apparent from the distribution of landing positions on words for the left and the right eye. To obtain these data, we selected a critical target word for each sentence that was either 6, 8 or 10 letters long that appeared at approximately the same position within the sentence. For this word we computed the distribution of landing positions for the left eye and the right eye separately. These data are shown in Fig. 1.

Clearly, the distribution of landing positions for the right eye is shifted to the right of that for the left eye. Consistent with the aligned, crossed, and uncrossed data described above, on average, participants fixated less far into the critical word with the left eye ($M = 4.2$ chars, $SD = 1.5$) than they did with the right eye ($M = 4.9$ chars, $SD = 1.5$), $t(14) = 7.08$, $p < .001$. The direction of the difference between the distributions is consistent with the fact that the most prevalent type of disparate fixation is uncrossed. Note that the disparity for the critical word was somewhat smaller than that observed when computed for all of the words in the sentence. This was because the target words were always embedded in the middle of the sentence and disparity was reduced for centrally located words relative to more peripheral words.

[6] Note that in their recent paper Kliegl, Nuthmann, and Engbert (2006) observed more crossed than uncrossed fixations during reading. At present, it is not clear why this difference between the present data and those of Kliegl et al. occurred. Clearly, further research is required to more fully understand this interesting difference.

3.2. Does the proportion of disparate fixations change as the eyes move from left to right through a sentence?

Fig. 2 shows the proportion of crossed, uncrossed, and aligned fixations made at different character positions within the sentences. It is clear from the figure that there is substantial variability in the proportion of each type of fixation that occurs at different points across the field of view. Note also that fewer data points contribute to the distribution for the bins beyond 50 characters due to the use of sentences of different lengths. Thus, differences at these points of the distribution should be interpreted with caution. However, broadly speaking, aligned fixations predominate, with fewer uncrossed and least crossed fixations. Additionally, the proportion of aligned fixations peaks at central fixation, tailing off at more eccentric leftward and rightward points. Another trend that may be observed in the data set is a gradual increase in the proportion of crossed fixations at the left and right extremes of the sentence. It appears that when points to the left extreme of the sentence were fixated, there was a greater tendency for the right eye to fixate to the left of the left eye than when central portions of the display were fixated. Similarly, when points to the right extreme of the sentence were fixated, again the right eye had a tendency to fixate to the left of the left eye more than when central portions of the display are fixated. The result is in the opposite direction to the small (estimated 0.2 deg maximum) increase in divergence expected from the geometry of viewing a flat screen tangentially. This finding may be related to a result reported recently by Vitu, Kapoula, Lancelin, and Lavigne (2004). They conducted an experiment examining the distribution of landing positions on words located at different positions on a video monitor. Participants were always required to make a saccade from a fixation marker presented a constant distance to the left of the target word. The fixation markers were presented at four eccentricities: 7.6 deg or 3.8 deg to the left of centre, centrally, or 3.8 deg to the right of centre. Vitu et al. found that the distribution of fixation locations on words was shifted to the left when saccades were initiated from the right of the monitor, and to the

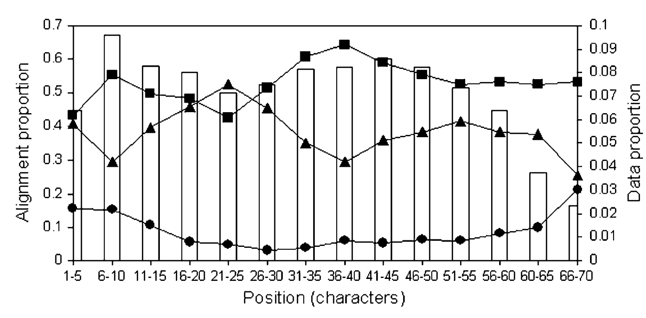

Fig. 2. The left vertical axis and the lines show the proportion of aligned, uncrossed and crossed fixations for all the data available in five character bins across the first 70 characters of the sentences. The right vertical axis and the bars show the proportion of data that contributed to each bin.

right when saccades were initiated from the left of the monitor. Vitu et al. recorded only the movements of the right eye. Given our binocular data, it does seem possible that systematic differences in the proportion of crossed and uncrossed fixations that occurred at the different eccentricities could systematically influence the landing position distributions on words. Clearly, further research is required in order to better understand the relationship between, fixation disparity, the retinal eccentricity of a word and landing position distributions on that word.

3.3. What is the magnitude of fixation disparity, and do all readers exhibit similar magnitude of fixation disparity during reading?

Fig. 3A shows the mean unsigned magnitude of fixation disparity at the end of fixation for all fixations and Fig. 3B shows the mean disparity magnitude when the data are categorised as aligned, crossed, and uncrossed fixations for all 15 participants. The data in A show that the mean disparity when collapsed over aligned, crossed, and uncrossed fixations was of a similar order for each participant, with a mean disparity of 1.1 characters ($SD = 0.9$). The data in Fig. 3B show that while the mean magnitude of disparity was of a similar order for both uncrossed and crossed fixations, the magnitude of disparity was slightly greater for the uncrossed than the crossed fixations for 10 of the 15 participants (though note that many more data points contributed to the mean for the uncrossed than the crossed fixations). The magnitude of fixation disparity was 1.9 characters for both crossed ($SD = 1.0$) and uncrossed ($SD = 0.7$) fixations when they are considered separately from the aligned data.

3.4. Does the magnitude of fixation disparity change as the eyes move from left to right through a sentence?

To examine this question, we segmented the data into five character bins and computed the magnitude of fixation disparity at five character intervals. The data are shown in Fig. 4. It is clear from the figure that fixation disparity occurs across the full field of view during reading. For uncrossed fixations the magnitude of disparity seems quite stable at approximately 1.9 characters across the entire sentence. The data for the crossed fixations show some suggestion of slightly more disparity in the left than the right hemi-field. However, the data for crossed fixations should be interpreted with caution because of the proportion of fixations (8%) that contributed to this distribution.

3.5. Does eye dominance influence fixation disparity during reading?

For each of our participants we measured eye dominance. To do this we required participants to look at a fixa-

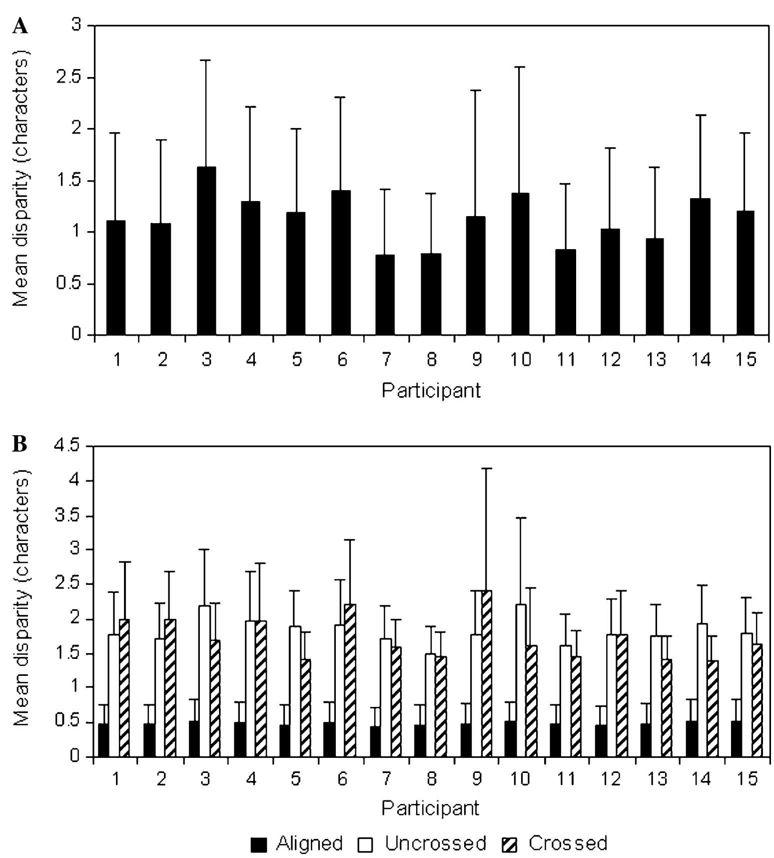

Fig. 3. (A) The mean fixation disparity (for both crossed and uncrossed fixations) measured in characters for each participant with error bars (+1 SD). (B) The mean disparity in characters for aligned, uncrossed and crossed fixations for each participant with error bars (+1 SD).

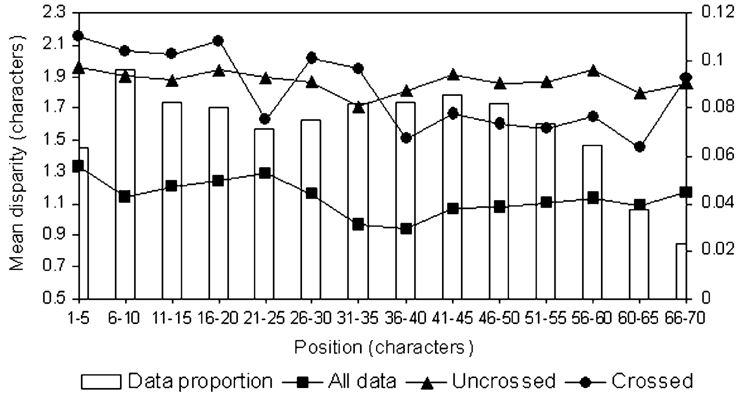

Fig. 4. The left vertical axis and the lines show the mean magnitude of fixation disparity for uncrossed and crossed fixations as well as for all the data available in five character bins across the first 70 characters of the sentences. The right vertical axis and the bars show the proportion of data that contributed to each bin.

tion point approximately 85 cm away. Participants sighted the fixation point through a small hole in a card held approximately 200 mm from the face. Participants were required to close the left eye and report whether they could still see the fixation point. This procedure was then repeated for the right eye. The dominant eye was recorded as that eye with which the participant could still see the fixation point through the card when viewing monocularly.

Five of the participants were left eye dominant and 10 were right eye dominant. We carried out a series of analyses comparing the characteristics of fixation disparity in left and right eye dominant participants. Our analyses showed that there was no influence of eye dominance on fixation disparity magnitude (Left Eye Dom $M=1.1$ chars, $SD=0.9$, Right Eye Dom $M=1.2$ chars, $SD=0.9$) (ts < 1). Eye dominance did not significantly influence the proportion of aligned fixations (Left Eye Dom 56%, Right Eye Dom 52%) (ts < 1). Of the non-aligned fixations there was also no significant difference in the proportion of uncrossed (Left Eye Dom 71%, Right Eye Dom 87%) or crossed (Left Eye Dom 29%, Right Eye Dom 13%) fixations between the left and right eye dominant participants, $t(13)=1.74$, $p=.106$.

To summarise, the data concerning fixation disparity during reading show a number of important findings. First, and perhaps most importantly, fixation disparity is prevalent during reading and is close to two characters in magnitude when it occurs. This finding is consistent with data reported by Heller and Radach (1999). However, the current data are also informative concerning how often disparate fixations were due to crossed and uncrossed lines of gaze with the latter type of disparity occurring at least four times more often than the former. Also, given these differences, it seems unlikely that the disparity effects we report are due to inaccurate eyetracking. Fixation disparities occur at all points within a sentence displayed across the monitor, although there tended to be more aligned fixations for central fixations. The proportion of aligned, crossed, and uncrossed fixations was approximately equivalent for all 15 readers and there was also some suggestion that crossed disparate fixations may be more prevalent in fixations made towards the beginning and end of sentences. Also, the magnitude of fixation disparity appears to be roughly constant regardless of where within the sentence the reader was fixating. Finally, eye dominance did not modulate the magnitude of fixation disparity, or the proportion of aligned, crossed and uncrossed fixations that occurred. We now turn to the questions we posed concerning vergence movements made during a fixation.

3.6. Do alignment and fixation disparity change during a fixation?

To address this question, we compared the proportion of fixations that were aligned at the beginning of a fixation with the proportion that were aligned at the end of a fixation. We found that the proportion of aligned fixations was greater at the end of a fixation (53%) than at the beginning of a fixation (48%), $t(14)=9.18$, $p<.001$. We also compared the magnitude of fixation disparity at the beginning and end of a fixation and found that fixations were more disparate at the beginning of a fixation (($M=1.3$ chars, $SD=1.1$) than at the end of a fixation ($M=1.1$ chars, $SD=0.9$), $t(14)=4.67$, $p<.001$). Thus, the data are consistent with those of Hendriks (1996) in that they clearly show that vergence movements do occur during fixations in reading and that on average vergence movements serve to reduce disparity during a fixation.

3.7. What is the nature of any vergence movement that does occur?

To characterise vergence movements, it was necessary to first classify different types of movement that occurred during a fixation. To do this we first defined no vergence movement as a difference between eye position at the end of fixation and that at the beginning of fixation of less than or equal to 0.1 characters. Using this definition, we then settled on four categories of vergence movement[7] (or non-movement), each representing a different type of oculomotor

[7] Note that vergence movements can arise from both eyes moving in different directions, one eye moving alone, or both eyes moving in the same or different directions by the same or differing amounts.

behaviour. The four categories were: (1) stable fixation (both eyes move less than or equal to 0.1 characters); (2) drift, where the net movement of the eyes was of an equal amount in the same direction (i.e., the difference in movement between the eyes was less than or equal to 0.1 characters); (3) convergence, where one or both eyes move more than 0.1 characters and the points of fixation were closer together at the end of the fixation than at the beginning of the fixation (in fact for a small proportion of crossed fixations, the eyes can be more crossed after convergence than before. Obviously, for this small set of fixations this definition of convergence is not strictly speaking correct); and (4) divergence, where one or both eyes move more than 0.1 characters and the points of fixation were further apart at the end of a fixation than at the beginning of a fixation. We found that the most frequently occurring form of vergence movement was convergence (52% of fixations). Divergence occurred approximately half as frequently as convergence (25% of fixations). Drift movements (13% of fixations) and stable fixations (10% of fixations) occurred approximately equally often. These data extend existing findings in that they demonstrate that, whilst convergent vergence movements predominate during fixations, other different types of vergence movement, as well as stable fixations, do also occur during reading.[8]

3.8. Does the nature of fixation alignment at the beginning of a fixation influence movement during a fixation?

To address this question, we first investigated the probability that readers made a convergent or divergent vergence movement of the eyes contingent upon whether their fixation was aligned or non-aligned at fixation onset. The data showed that when the eyes were aligned at fixation onset, such movements occurred on 76% of fixations, whereas when the eyes were not aligned, vergence movements occurred on 79% of fixations. This small difference was statistically reliable, $t(14) = 2.85$, $p < .05$.

In a second set of analyses we investigated the likelihood of convergent vergence movements contingent on whether the eyes were initially aligned, crossed, or uncrossed. Our analyses showed that for those fixations during which vergence movements occurred, the initial alignment of the eyes did modulate the extent to which the eyes made a convergent movement, $F(2,28) = 57.12$, $p < .001$. The eyes made convergence movements on a larger proportion of fixations when the eyes were initially uncrossed (77%) than either when they were crossed (42%), $t(14) = 8.65$, $p < .001$, or aligned (63%), $t(14) = 5.04$, $p < .001$, at fixation onset. These data indicate that vergence movements are not random, but instead are, at least to some extent, made in response to the particular alignment of the eyes at fixation onset. Indeed, it appears that for those cases when the eyes are uncrossed, vergence movements serve to reduce disparity that exists at fixation onset.

3.9. Does the duration of a fixation influence the amount of vergence that occurs during a fixation?

The final question that we examined in relation to vergence movements concerned whether there was any relationship between the amount of vergence movement during a fixation and its duration. To do this, we performed a median split on the fixation durations of each participant and compared vergence movements for short ($M = 197$, $SD = 50$) and long fixations ($M = 377$, $SD = 121$). As one might anticipate, there was no effect of fixation duration on the magnitude of disparity at the beginning of both long ($M = 1.3$ chars, $SD = 1.1$) and short ($M = 1.3$ chars, $SD = 1.0$) fixations ($t < 1$). However, at the end of fixation, there was a tendency for less disparity for long ($M = 1.1$ chars, $SD = 0.9$) than for short ($M = 1.2$ chars, $SD = 0.9$) fixations, $t(14) = 1.90$, $p = .078$. We also correlated the duration of a fixation with the net amount of vergence made during that fixation. This analysis produced a positive correlation ($r = .049$) and a one sample t test showed that the correlations for each of the participants were significantly different from 0, $t(14) = 2.65$, $p < .05$. Clearly, the longer the fixation duration, the more vergence movement occurred in the fixation.

To summarise, these data are consistent with the findings of Hendriks (1996). They show that vergence movements do occur during fixations in reading and that such movements are non-random. Clearly there are systematic patterns within the data, with particular types of movement more likely given initial fixational disparities. Furthermore, given that disparities are reduced at the end of a fixation compared with the beginning, it appears that the visual system works to reduce binocular disparity during a fixation. In addition it might also be appropriate to conclude that the amount of vergence movement made during a fixation is proportional to the duration of a fixation.

4. Discussion

From the current data we are able to form a number of important conclusions. The first, and perhaps most significant, is that the basic assumption that is widely held within the community of researchers measuring eye movements to investigate reading, that the fixation points of each eye fall on the same character within a word, is actually incorrect for almost half of the fixations that readers make. The eyes do fixate on different characters within words, and the lines of gaze may be crossed or uncrossed, as well as aligned during reading. This finding suggests that slightly different visual representations of the text will be delivered to higher

[8] The mean size of movement during a fixation was 0.3 characters for both the left ($SD = 0.3$) and the right ($SD = 0.4$) eyes. Of those cases in which both the eyes move, the left eye moves to the right for 53% of cases and the right eye moves to the right for 33% of cases. Of the cases in which at least one eye moves, in 45% of cases there is no movement in the other and in 35%, the other moves in the same direction. Only in 20% of cases do the eyes move in opposite directions.

order processing systems by each eye. Since readers do not experience diplopia when they read, then the visual system is somehow dealing with the slightly different visual representations from each eye such that the reader experiences a single unified percept of the text.

There appear to be two means by which the visual system may do this. Either, one of the two visual inputs is suppressed, or alternatively, the two disparate representations are fused at a relatively early stage of visual processing. It is usually accepted that stimuli with a small disparity can be fused but above a certain limit, termed Panum's area, fusion breaks down and diplopia results. When tested under conditions of steady fixation with small point targets, Panum's area is quite small (0.1–0.2 deg). However the area is increased for stimuli of low spatial frequency (Schor, Wood, & Ogawa, 1984) and seems likely to be larger under normal viewing since we are rarely aware of diplopia whilst using vision under natural conditions. The current data would be compatible with either a suppression, or a fusion, account.

These data also have implications for current theories of eye movement control during reading (e.g., see Juhasz et al., 2006). To date, all such models (Engbert, Nuthmann, Richter, & Kliegl, 2005; Legge, Hooven, Klitz, Mansfield, & Tjan, 2002; Legge, Klitz, & Tjan, 1997; Rayner, Ashby, Pollatsek, & Reichle, 2004; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 1999; Reichle, Rayner, & Pollatsek, 2003; Reilly & Radach, 2003; Yang & McConkie, 2001) describe saccadic control of one eye. Ultimately, to provide an absolutely comprehensive account of oculomotor control during reading, such models will presumably need to be expanded to account for the movements of both eyes.[9]

The current data are perhaps more problematic for split fovea accounts of word identification and eye movement control (e.g., McDonald & Shillcock, 2005; Monaghan et al., 2004; Shillcock et al., 2000). To briefly recapitulate, such accounts place great emphasis on the fact that the retina is precisely split vertically at its centre, with the left hemi-field initially projecting to the right side of the brain, and the right hemi-field projecting to the left. A default assumption underpinning such accounts is that both eyes fixate exactly the same position within the word, such that it is split neatly into two portions, each of which is independently used in the process of lexical identification for at least some period. Importantly, the current data indicate that such an assumption is only correct for a proportion of fixations made during reading. Indeed, it is not immediately clear how split fovea models might operate given visual inputs from each eye differing by varying degrees. What is clear is that when fixation disparity does occur, the foveal split will occur at a different point in the word for the two eyes. Consequently, the visual information from the left and right hemi-field of the left eye will not exactly match the information from the left and right hemi-field of the right eye. This situation is far more complex than is the cyclopean position that is assumed to exist in current split fovea formulations. Furthermore, since the magnitude of disparity varies from fixation to fixation, then the degree and nature of overlap in the hemi-fields of each eye will also vary. Consequently, it is not possible to simply modify current split fovea accounts by introducing a fixed amount of disparity between the eyes.

Recall, however, that a possible mechanism by which a diplopic state may be avoided is suppression of the visual input from one of the two eyes. If such suppression did occur, then processing could proceed as specified in current split fovea accounts. However, this possibility would itself then raise a critical question for split fovea accounts, namely, which eye supplies the visual representation of the word on any particular fixation. This question is critical, because the exact position of the split is important in determining the hemi-field that the different portions of the word fall in (and in turn the effects that proponents of this account argue it produces). A fixed suppression relationship could exist such that, for example, the input of either the left or the right eye was always suppressed. Another possibility is that the input might always be provided by the dominant eye. It is even possible that a different eye might supply the split representation from one fixation to another. All these possibilities are simply conjecture at present. Clearly, if suppression does occur during reading, then further research is required to determine which eye does provide the single visual representation on a fixation by fixation basis during reading.

The alternative mechanism by which a diplopic state may be avoided, is through the process of fusion. If fusion occurred early during a fixation, then a single fused percept of a word could be acted upon by subsequent linguistic processors. This possibility is much more difficult to incorporate within a split fovea account. Clearly, if fusion did occur, then it would be happening at a very early stage of visual processing, and this would undermine the possibility that processing of word portions falling in different hemi-fields occurs independently until relatively late during word identification. Again, given that we have now precisely characterised fixation disparity during reading, an important issue for future research is to determine whether fusion or suppression is the mechanism by which the single visual representation of the text is experienced as we read.

In summary, as is clear from the data reported here, on a substantial proportion of fixations during reading, fixation disparity does occur. The data show that disparate fixations were predominantly uncrossed, though a small proportion of fixations were crossed. Also, systematic vergence movements occurred during fixations. These movements reduced fixation disparity, with the magnitude of the reduction being proportional to the duration of a fixation (longer fixations resulted in greater vergence movements). Despite these vergence movements, the average magnitude of dis-

[9] Note, the present data are not problematic for such accounts, as they currently make no attempt to account for binocular coordination during reading.

parity at the end the fixation was still at least one character for all of the data, and close to two characters for those cases in which the eyes were not aligned. Finally, binocular coordination was not affected by eye dominance during reading.

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