CHAPTER 44

Binocular coordination during reading

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Abstract

The chapter reviews a range of evidence that suggests that the fixation positions of the two eyes are not precisely coordinated during reading, such that fixation disparity is frequently observed. The chapter focuses on three critical issues. First, evidence is reviewed for whether the visual or linguistic characteristics of text can influence binocular coordination. Second, a possible link between developmental factors and binocular coordination is discussed (that is, whether children show different patterns of binocular coordination compared to adults). Third, evidence for and against the possibility that dyslexia might be associated with differences in binocular coordination is assessed. On the basis of the existing evidence we conclude that: fixation disparity is, at most, minimally affected by linguistic processing demands; that binocular coordination develops with age such that by the age of 12 children display patterns of binocular coordination equivalent to that of adults; and that the issue of a possible link between binocular coordination and dyslexia demands much further research. The conclusions also highlight the implications of these findings for our understanding of word processing mechanisms, eye movement control during reading, and research with dyslexic readers.

Binocular vision extends our visual field and allows us to perceive and interact with our environment with greater precision than monocular vision would permit (Jones and Lee, 1981). In reading, saccadic eye movements serve to bring new portions of the text onto the high-acuity region of the retina, the fovea, allowing successful lexical identification of words within the sentence (Liversedge and Findlay, 2000). Critically, reading is a unique visual task, which requires accurate encoding and complex processing of relatively small-sized visual stimuli (letters within words). Consequently, it might plausibly be assumed that, in order for reading to progress undisturbed, two precisely coupled retinal inputs must be necessary for visual encoding and lexical identification. Indeed, much research has been undertaken recording the position of just one of the eyes, on the implicit assumption that the position of one eye accurately represents the positions of both eyes. Throughout this chapter, however, we will review a range of evidence suggesting that the assumption of precise binocular coordination during reading is not, in fact, always correct and demonstrates that fixation disparity is frequently observed during reading.

The aim of this chapter is to provide a concise review of the influential and topical research in the area of binocular coordination during reading in order to address three critical questions: 1) do visual or linguistic characteristics of text influence binocular coordination?; 2) Do developmental factors influence binocular coordination? (see also Luna and Velanova, Chapter 35, this volume); (3) Is there a link between binocular coordination and dyslexia? We begin with a brief review of the literature describing the basic characteristics of binocular coordination during reading and the fusion of disparate retinal inputs during reading. For a broader review of binocular coordination during both reading and non-reading tasks, see Kirkby et al (2008). Note that work in this area has, so far, largely focused on empirical studies and the content of the chapter reflects this. Nevertheless, the chapter will conclude by summarising some recent theoretical work, as well as noting the implications of fixation disparity for studies of eye movement control during reading in general.

Basic characteristics of binocular coordination during reading

Both the distance from and the direction of target locations must be accounted for in accurate saccade programming and, hence, in accurate binocular coordination. Three different types of eye movement have been studied in order to characterize the accuracy and binocular coordination of saccades: 1) pure version (also referred to as conjugate movements, a change in direction while maintaining a constant angle of sight between the two eyes); 2) pure vergence movements (a change in depth only, where the angle of sight between the two eyes changes but there is no directional change in the point of fixation); 3) combined eye movements (also referred to as disjunctive movements, movements with both version and vergence components, such that the point of fixation changes in both depth and direction).

Until recently, the majority of research examining binocular coordination had focused upon analyses of the two eyes' saccades. Among the handful of early studies examining binocular coordination during reading, researchers found that there was frequently disparity between saccades of the two eyes. There was, however, some disagreement regarding the source of binocular disparity. The results of Smith et al. (1971) indicated that subtle temporal differences in the timing of the two eyes' saccadic onsets were observed during reading, leading to disparity during saccades. Williams and Fender (1977) questioned these findings and measured the characteristics of binocular coordination when the eyes were saccading between LEDs rather than during reading. Williams and Fender demonstrated that differences in the two eyes' saccadic velocity occurred frequently; however, in contrast to the results of Smith et al., they did not find differences in the timing of the two eyes' saccadic onset. Further research has established that there are differences between the abducting eye (the eye moving temporally) and the adducting eye (the eye moving nasally) with respect to the timing of saccade onset, peak saccadic velocity, saccade duration, skewness (the relative durations of the eyes' acceleration and deceleration periods during a saccade), and amplitude (Collewijn et al., 1988). As a consequence of the asymmetry of the abducting and adducting eyes' saccadic parameters, the two eyes typically become diverged during a saccade.

With respect to reading, however, it is important to consider binocular coordination during fixations, as it is while the eyes are relatively still that linguistic information is primarily encoded and subsequently processed (Liversedge and Findlay, 2000; but see Yatabe et al., 2009). In recent years there has been an upsurge of interest in binocular coordination during reading, resulting in a number of important empirical findings. Most notably, frequent disparity between the two eyes' points of fixation during reading has now been demonstrated to occur in both sentence reading studies (e.g. Blythe et al., 2006; Heller and Radach, 1999; Hendriks, 1996; Juhasz et al., 2006; Kliegl et al., 2006; Liversedge et al., 2006a) and in single word reading studies (Paterson et al., 2009; Bucci and Kapoula, 2006).

The article published by Liversedge et al. (2006a) provided one of the first demonstrations of the extent to which binocular disparity is found in skilled readers. They described both the magnitude and the direction of fixation disparity that occurred during a single line sentence reading experiment, with the magnitude of disparity measured as the absolute difference between the fixation positions of the two eyes at both fixation onset and offset. On average, fixation disparity at fixation offset was found to be 1.1 character spaces. For nearly half of all fixations the two eyes were more than one character space apart in either direction (categorized as non-aligned). For these non-aligned fixations, the magnitude of the fixation disparity was, on average, 1.9 character spaces. The direction of non-aligned fixation disparity was classified as either crossed (where the left eye was fixated further

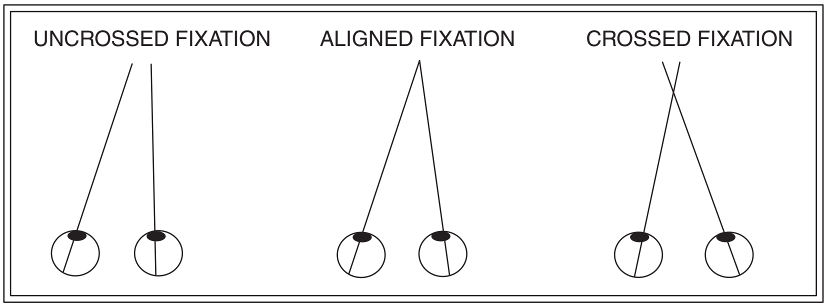

Fig. 44.1 Categories of fixation disparity: *Uncrossed*, fixation disparity greater than one character with the left eye to the right of the right eye; *Aligned*, fixation disparity less than one character; *Crossed*, fixation disparity greater than one character with the left eye to the left of the right eye.

to the right than the right eye), which accounted for 8% of all fixations, or uncrossed (where the right eye was fixated further to the right than the left eye), which accounted for 39% of fixations. The nature of uncrossed, aligned, and crossed fixations is illustrated in Fig. 44.1.

As noted above, Liversedge et al. (2006a) reported fixation disparity at both fixation onset and offset, enabling some estimate of the slow vergence movements (non-parallel movements of the two eyes) that occurred during fixations. Overall, the proportion of aligned fixations was greater at the end of fixations (53%) compared to the beginning of fixations (48%), which resulted from vergence movements during fixations. Liversedge et al. demonstrated that fixation vergence movements were more often convergent than divergent (i.e. moving the points of fixation closer together, thus being in a corrective direction for the uncrossed disparity that was prevalent during the majority of disparate fixations). Overall, their results were consistent with the data reported by Collewijn et al. (1988). Recall that in Collewijn's study the two eyes were shown to diverge during saccades, due to binocular asymmetries in saccadic onset timing, peak velocity, amplitude, duration, and skewness. Thus, the fact that the data from Collewijn's study showed a divergence between the two eyes during saccades complements Liversedge, White et al.'s finding that the two eyes are frequently uncrossed at the start of fixations. Interestingly, despite the observed corrective vergence movements during fixations, Liversedge, White et al. showed that at the end of 47% of fixations the two eyes remained unaligned, of which 39% were uncrossed, with an overall average disparity of 1.1 characters.

To summarize, the results reported by Liversedge, White et al. (2006) revealed that: 1) fixation disparity frequently occurs during reading; 2) fixation disparity is regularly more than one character space; 3) fixation disparity is more often uncrossed than crossed; 4) vergence movements reduce disparity between the two eyes during fixations; 5) despite these vergence movements, at fixation offset some degree of disparity is still evident. While the data from both reading (Liversedgeet al., 2006a) and non-reading studies (Collewijn et al., 1988) are complementary in describing the divergence that occurs during saccades, and the resulting disparity followed by slow convergence during fixations, the presence of fixation disparity during reading raised two critical issues that were investigated further in other studies. First, the observation of large fixation disparities during reading led researchers to consider whether the two eyes might, occasionally, be fixating different words in the sentence. Second, additional studies examined whether the predominant tendency is for unaligned fixations to be crossed or uncrossed in skilled adult readers. We will discuss each of these issues in turn.

The disparities observed during the majority of fixations in reading are not substantial (as noted above, on average, approximately one character space). On some occasions, however, the disparity is much greater than the average; for example, for the non-aligned fixations in the Liversedge et al. study, the average disparity was 1.9 characters. Consequently, particularly for cases in which fixation disparity is larger than normal, disparities may result in the two eyes fixating on adjacent words in a sentence.

Kliegl et al. (2006) found that in 23% of all valid[1] fixations the two eyes fixated separate words within the sentence. Similarly, Kirkby et al. examined the frequency with which the two eyes fixated two separate words as a function of word length (Kirkby et al., 2008). The probability of fixating the same word with both eyes was smaller for shorter words (four-letter words were fixated with both eyes on 79% of fixations) and greater for longer words (eight-letter words were fixated by both eyes on 95% of fixations). Interestingly, these results suggest that previous studies of word skipping, which have measured only one of the two eyes, may have over-estimated the proportion of skipped words. That is, the recorded eye may have skipped words that were, in fact, directly fixated by the non-recorded eye (see Kirkby et al., 2008, for a full discussion on this subject).

A number of studies have also further examined the direction of fixation disparity (i.e. crossed or uncrossed) during reading. Both Kliegl et al. (2006) and Nuthmann and Kliegl (2009) found the direction of binocular disparity to be predominantly crossed, whereas other studies have found it to be predominantly uncrossed for skilled adult readers (Blythe et al., 2006; Juhasz et al., 2006; Liversedge et al., 2006a). The differences in overall fixation alignment across different studies might be accounted for by differences in the physical experimental set-ups. Kliegl at al.'s and Nuthmann and Kliegl's data were recorded using an EyeLink eye tracker (SR Research Ltd), while the data reported by Blythe et al., Juhasz et al., and Liversedge et al. were recorded using Dual Purkinje Image (DPI) eye trackers (Fourward Technologies). These eye tracking systems tend to be used in physical set-ups which differ in, for example, viewing distance, background lighting, and stimulus luminance (Kirkby et al., 2008; Nuthman and Kliegl, 2009, Shillcock et al., 2010).

Further research is needed in order to address which factors impact on the direction of binocular disparity, as no studies have directly examined this and suggestions for contributing factors are based on informal comparisons between papers. Recently, however, Shillcock and colleagues (2010) have developed a theory and computational model of binocular foveation in reading, in which it is argued that binocular disparity is a functional, adaptive response to the relative processing difficulty associated with reading under a range of viewing conditions (rather than being a simple, reflexive response to the visual environment). Shillock et al.'s model is discussed further at the end of this chapter, but critically they argue that uncrossed fixation disparities facilitate binocular fusion more than crossed fixation disparities and, hence, should occur more often under viewing conditions that make fusion difficult. Accordingly, in a review of the eye movement literature, they suggest that the different viewing conditions employed in each study are the reason why a predominance of either crossed or uncrossed fixations was observed. Clearly, further research is needed in order to experimentally determine which factors relating to the physical set-up might influence binocular coordination during reading.

The fusion of disparate retinal inputs and neural control of binocular saccades

Given the established finding of disparity during fixations in reading, several recent studies have examined how disparate retinal inputs might be processed during reading and how information from the two eyes impacts on programming of saccades. Importantly, despite the disparity that occurs during saccades and persists into fixations, readers experience a unified percept. That is, the two eyes frequently fixate different letters within a word, and so the letters of the word fall on slightly different locations on each of the two retinae. The reader is, however, able to fuse the two disparate retinal inputs, resulting in a single percept (as opposed to diplopia—double vision). There are limits to the magnitude of disparity that can be successfully fused, and the range of fuseable disparities (Panum's area) has been widely studied for simple stimuli such as lines and dots presented in an

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[1] A fixation was considered valid if the duration was between 80 and 1200 ms and further, if the disparity between the points of fixation were within two standard deviations of the mean for that individual.

impoverished visual environment (e.g. Ogle, 1952; Fender and Julesz, 1967) (note that the visual characteristics of stimuli also affect the fusional range (Fender and Julesz, 1967)).

A recent study by Blythe et al. (2010) investigated the range of disparities that could be successfully fused for word stimuli in 7- to 11-year-old children compared to adults. Participants' binocular eye movements were recorded as they made lexical decisions for stereoscopically presented words (in a stereoscopic presentation, the same image is presented independently to each eye; see Fig. 44.2). In this experiment, the entire word/non-word was presented to both eyes, but on some trials a horizontal offset (stereoscopic disparity) was manipulated between the two eyes' stimuli. The stereoscopic

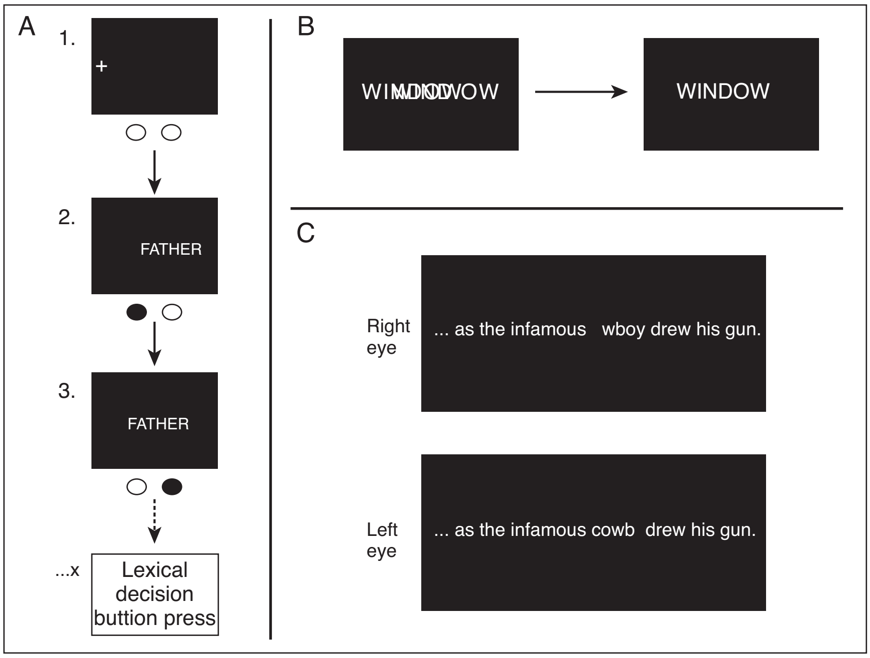

Fig. 44.2 Examples of the stereoscopic presentation used by Blythe et al. (2010), and the dichoptic presentation used by Liversedge et al. (2006a). Panel (A) shows the sequence of events during a trial in the experiment reported by Blythe et al. (2010). The black and white circles under each of the three displays represent the shutter glasses in front of each of the participant's eyes being either open (white) or closed (black), thus allowing stimuli to be presented independently to each eye. A fixation cross appeared on the left side of the screen for 1 s, before disappearing. When the cross disappeared, the target word was presented stereoscopically in the centre of the screen. This example shows a stimulus being presented with 2 character spaces of uncrossed disparity—the word presented to the right eye is 2 character spaces further to the right on the screen than the word presented to the left eye. The two images alternated on the screen every 8 ms, in synchrony with the opening and closing of the shutter glasses. This continued until the participant pressed a button to make their lexical decision. Panel (B) shows the typical perceptual experience for a participant in the experiment reported by Blythe et al. (2010). Again, this represents a trial where the stimulus was presented with 2 character spaces of stereoscopic disparity. The stimulus initially appeared as a jumbled blur of letters, and only when fused could the participant reliably decide whether or not the letter string was a correct word. Panel (C) shows an example of the dichoptic stimulus presentation used in the experiment reported by Liversedge et al. (2006a). Shutter glasses were used to present a different image uniquely to each eye. Here, the positions of these two images on the screen were the same—there was no stereoscopic disparity. This example shows a congruent display, where the initial portion of the target word was presented to the left eye and the end portion of the word was presented to the right eye.

stimuli were, therefore, either presented aligned (thus appearing normally), or with a manipulated disparity of one or two character spaces in either a crossed or uncrossed direction. In addition to this stereoscopic manipulation, following data collection, the recorded fixation disparity for each participant was also taken into account on a fixation by fixation basis. This provided a measure of the total retinal disparity (summed stereoscopic disparity and fixation disparity) experienced during each fixation as participants looked at the letter strings and made a lexical decision. Accurate lexical decisions were only possible if the stimuli were successfully fused (otherwise, the stimuli appeared as a jumbled blur of letters and response accuracy was at chance).

The response accuracy showed clearly that both adults and children could reliably fuse retinal disparities of up to 0.37°, but not retinal disparities of 0.74° (1 and 2 character spaces, respectively; a relatively large font size was used). Thus, no evidence was found for an age-related change in fusional limits for words, despite the established developmental differences in binocular coordination during reading (for details, see the section entitled, 'Do developmental factors influence binocular coordination?'). The fuseable range of disparities was, however, found to be greater than that which typically occurs as a consequence of fixation disparity during sentence reading (0.2–0.3° on average; Blythe et al., 2006; Liversedge et al., 2006). Eye movement data were also reported, comparing the vergence response of participants during their initial saccades onto the stimuli with that during their initial fixations on the stimuli. The data showed that, for both adults and children, stereoscopic disparity (e.g. stimulus disparity) determined the vergence that occurred during the initial fixation directly on the stimulus, but did not affect the vergence that occurred during the initial saccade onto the stimulus. This demonstrated that the vergence system, controlling binocular coordination, was responsive to foveal but not parafoveal stereoscopic disparity cues.

Other work has more specifically examined how the visual input determines saccade targeting for each of the eyes (Liversedge et al., 2006). Such research has sought to establish whether the two eyes' saccades are programmed on the basis of a single neural signal for both eyes or on the basis of an independent neural signal for each eye, as originally debated by Hering and Helmholtz in the early 19th century. One way in which to address this question is to examine whether the saccade programme for the two eyes is determined jointly (on the basis of a single, unified percept), determined on the basis of information from just one of the eyes (due to suppression), or determined separately (on the basis of the visual information available to each particular eye). To address this issue, Liversedge et al. (2006b) presented participants with sentences containing a compound target word, such as 'cowboy', which were presented dichoptically (in a dichoptic presentation, a different image is presented uniquely to each eye, see Fig. 44.2). The first half of the word, 'cowb', was presented to one eye and the second half of the word, 'wboy', was presented to the other eye. The rationale was that if saccades were programmed to a single, unified percept based on the two fused retinal inputs, then the distribution of landing positions on the target word would be unaffected by the dichoptic manipulation. Alternatively, if saccades were programmed independently for each eye on the basis of their own perceptual input, then each eye should have been directed to the word portion that was presented independently to that eye.

In line with previous research, the mean initial landing positions on the critical words in Liversedge et al.'s study were at, or just left of, the word centre, at the preferred viewing position (Rayner, 1979). Note that although most fixations land at the preferred viewing position, saccades tend to undershoot this location when launched from distant launch sites, and tend to overshoot when launched from near launch sites (known as the range effect) (McConkie et al. 1988). In line with previous research showing disparate fixations, and predominantly more uncrossed than crossed non-aligned fixations (Blythe et al., 2006; Juhasz et al., 2006; Liversedge et al., 2006a), mean fixation positions on the critical word in Liversedge et al.'s study (2006b) were disparate such that the fixation position for the left eye were significantly to the left of those for the right eye. Crucially, though, Liversedge et al. (2006b) found no effect of dichoptic viewing condition on initial landing positions on the critical word. That is, regardless of whether the two halves of the target word (e.g. 'cowb' and 'wboy') were each presented independently to different eyes or were presented to both eyes, the landing positions on these target words were the same. These data are, therefore, strong evidence that readers programme their saccades towards a single percept resulting from combination of the information from both of the eyes. These data also indicate that the two eyes' saccades during reading are programmed as a single neural signal (Hering, 1868, as cited in Howard, 1999) rather than being programmed independently (Helmholz, 1910, as cited in Howard, 1999).

Note that the different presentation techniques employed by Blythe et al. (2010) and by Liversedge et al. (2006b) lead to complementary conclusions that might, at first, seem contradictory. Blythe et al. used a stereoscopic presentation, where the content of the two eyes' images were identical but with a horizontal disparity manipulated between the two images. On the basis of their data, they concluded that participants had not fused the images prior to direction fixation (i.e. in the parafovea), thus suggesting that the visual system is either not sensitive to or not responsive to parafoveal disparity cues. Liversedge et al. (2006b) used a dichoptic presentation, where there is no disparity manipulation in the stimuli but the content of the two eyes' images is different (e.g. 'cowb' to one eye and 'wboy' to the other eye). On the basis of their data, they concluded that participants were able to target saccades to the words as a whole, indicating that saccade programming was operating over a combined percept of the two eyes' inputs. Thus, parafoveal information from the two retinal signals seems to be integrated (but not necessarily fused) in order for saccades to be programmed to a single percept.

Supporting the argument for a single neural signal underlying saccades, other research has shown that the degree of synchronization between binocular saccades is independent of whether words are viewed monocularly or binocularly (e.g. Williams and Fender, 1977; Heller and Radach, 1999). Were it the case that saccades for the two eyes are programmed independently, then gross differences ought to be observed between normal, binocular viewing and monocular viewing (where one eye has no visual input by which to guide its saccades). In contrast though, these studies showed that when reading monocularly, saccades of the occluded eye are coordinated with the viewing eye in the same manner as when both eyes are viewing the text. Together with the data from Liversedge et al. (2006b) this work provides converging evidence that binocular saccades are generated on the basis of a single neural signal. Furthermore, these studies also indicate that the frequently observed disparity between the two eyes during reading is not a consequence of the eyes being driven by two independent neural signals. Instead, researchers have argued that differences in neural transmission or in the two eyes' musculature may underlie the characteristic binocular disparity that occurs during saccades (e.g. Bains et al., 1992; Collewijn et al., 1988).

In summary, it appears that the visual system computes saccades on the basis of a single percept of the upcoming word and, during direct fixation, can fuse relatively large retinal disparities for word stimuli (greater than those which naturally occur as a consequence of binocular disparity during reading). We now turn to the three critical questions outlined in the Introduction: 1) do visual or linguistic characteristics of text influence binocular coordination?; 2) Do developmental factors influence binocular coordination?; 3) Is there a link between binocular coordination and dyslexia?

Do visual or cognitive factors influence binocular coordination?

Several studies have investigated which aspects of text processing (if any) may influence binocular coordination (e.g. Blythe et al., 2006; Bucci and Kapoula, 2006; Heller and Radach, 1999; Hendriks, 1996; Juhasz et al., 2006; Liversedgeet al., 2006b; Yang and Kapoula, 2003). These studies specifically manipulated linguistic and/or visual characteristics of text and examined whether they impacted on binocular coordination in skilled adult readers.

One of the first empirical studies to investigate the modulation of binocular coordination during reading was Hendriks (1996). Hendriks assessed the influence of linguistic factors on vergence velocity during fixations. Binocular coordination was compared when participants read prose passages or lists of unrelated words, and were instructed either to read for meaning or to 'sound out' the pronunciations of the words subvocally without reading for meaning. Reading prose passages requires syntactic and semantic processing in addition to the identification of individual words, and thus requires greater depth of processing than reading lists of unrelated words. Similarly, reading text for meaning requires greater depth of processing than simply sounding out words. Hendriks found that the velocity of vergence movements was higher when reading for meaning than when sounding out words, and when reading passages of text than when reading lists of words. Hendriks suggested that under conditions where reading is more dependent on the visual input vergence velocities are slower, compared to conditions where greater top-down information is available to the reader. Hendriks argued, therefore, that the nature of the text and the task demands associated with linguistic processing impacts on binocular coordination, at least in terms of vergence velocities. Critically though, Hendriks' data also showed a relationship between processing difficulty and saccade amplitude, with smaller saccades made when 'sounding out' or reading unrelated words. Non-reading task studies have established that there is a strong relationship between saccade amplitude and fixation disparity, whereby the greater the amplitude of the incoming saccade, the greater the disparity between the two eyes' positions during the subsequent fixation (Collewijn et al., 1988; Kirkby et al., 2010). Hendriks (1996) argued that linguistic processing difficulty affected the amplitude of saccades that were made as the reader progressed through the stimuli, and it was saccade amplitude (rather than processing difficulty per se) that determined the velocity of vergence movements during the subsequent fixation. Thus, although Hendriks' data showed a relationship between processing difficulty and vergence movements, this link may be at least partially attributable to preceding saccade amplitude.

Other studies have directly manipulated the characteristics of text in order to investigate whether binocular coordination is modulated by visual or cognitive processing. Heller and Radach (1999) examined the influence of visual task demands on binocular coordination during reading, by presenting readers with MiXeD cAsE text compared to normal text.[2] They found an increase in fixation durations and the number of fixations being made when reading mixed case text, indicating that mixed case text incurred more processing difficulty than normal text in their study. Heller and Radach also describe an increase in both the magnitude of disparity as well as the velocity of the vergence movements during fixations for normal text compared to that observed during the mixed case condition. However saccade amplitudes were also reduced for mixed case, compared to normally presented text. Similar to Hendriks' (1996) data, therefore, the modulation of binocular disparity shown in Heller and Radach's study may be explained either by an effect of processing difficulty or by differences in saccade amplitude.

Other studies have failed to find effects of processing difficulty upon binocular coordination. Smith et al. (1971) measured the difference in saccade onset asymmetry as a method of assessing binocular coordination. They measured the movements of the two eyes while participants read text that was manipulated for difficulty (although the authors did not specify the nature of this manipulation), as well as for the orientation of the constituent letters (the text was either rotated along the horizontal axis or presented normally). Although saccades of the two eyes were asymmetric during all conditions, in contrast to Hendriks (1996) and Heller and Radach (1999), Smith et al. found no effects of text difficulty on binocular coordination during reading.

One study that has specifically measured the influence of processing difficulty upon binocular coordination in terms of the magnitude and direction of fixation disparity is that of Juhasz et al. (2006). Juhasz et al. aimed to further test Heller and Radach's (1999) suggestion that binocular coordination is modulated by difficulty as induced by MiXeD cAsE text presentation. In addition, to provide a test of whether binocular coordination is modulated by linguistic difficulty, Juhasz et al. also manipulated the frequency of target words within sentences. There were significant effects of both word frequency and case on fixation durations, clearly showing that the processing difficulty manipulations were effective (fixation durations reflect the ease with which words are identified; Liversedge and Findlay, 2000; Rayner, 1998). In contrast to the findings of Heller and Radach,

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[2] Mixed case text is often used in reading research in order to preserve abstract lexical information whilst disrupting the familiarity of the visual input (McConkie and Zola, 1979). Note that although mixed case text can be more difficult to read than normally presented text, such effects diminish with practice (Inhoff et al., 2005).

however, there was no evidence to suggest that processing difficulty influenced the direction or magnitude of fixation disparity. It is not clear, however, whether saccade amplitudes were also shorter during mixed case reading in Juhasz et al.'s study (hence the relationship between processing difficulty, saccade amplitude, and fixation disparity cannot be assessed for this data set).

Given that processing difficulty impacts on fixation durations, this raises the broader question of whether fixation duration in general is linked to the magnitude of fixation disparity and, in particular, whether vergence movements occur throughout the entire duration of a fixation. Liversedge et al. (2006a) showed that the duration of a fixation correlated with the magnitude of disparity reduction during the fixation. On this basis it might be predicted that end of fixation disparities should be smaller for more difficult text as fixation durations are generally longer on more difficult text (Rayner, 1998), thus allowing more time for the eyes to converge and reduce disparity. Two recent studies have examined the time course of vergence movements during fixations (Jainta et al., 2010; Vernet and Kapoula, 2009). Vernet and Kapoula (2009) examined binocular coordination over multiple time periods during reading, these periods were: just prior to a saccade, during a saccade, and at two time periods after a saccade. They found that at fixation onset (defined as the initial 48 ms after the end of the saccade) the disconjugacy between the two eyes' points of fixation was greatest. Over the subsequent 80 ms there was a reduction in disparity and by the end of the fixation the alignment of the eyes was quite stable (but still disparate). Jainta et al. found that the magnitude of fixation disparity at its minimum point in the fixation did not differ significantly from that at the end of fixations and, as such, fixation durations were not found to correlate with the magnitude of disparity. These data indicate that the relationship between fixation duration and vergence during the fixation is more complex than had been suggested by Liversedge et al. (2006a).

To summarize, only a few studies have specifically investigated the effect of linguistic processing difficulty on binocular coordination in skilled adult readers, and these studies have provided mixed evidence. One study (Hendriks, 1996) has shown significant effects of processing difficulty on binocular coordination (specifically, fixation vergence velocities); however, this effect could, at least partially, be attributable to a confounding variable (preceding saccade amplitude). Heller and Radach (1999) also argued that processing difficulty influenced binocular coordination. Similar to Hendriks' data, though, the effects reported by Heller and Radach may also be attributable to differences in saccade amplitudes. In contrast, a more recent investigation using several different manipulations of processing difficulty found no effects of these manipulations on binocular coordination (Juhasz et al., 2006). Finally, there is little evidence to suggest that fixation duration is related to the magnitude of fixation disparity (Jainta et al., 2010; Kliegl et al., 2006; Vernet and Kapoula, 2009). Given these mixed results in the literature, further research is needed to clarify whether or not visual/cognitive manipulations influence binocular coordination, as well as to determine the role of any mediating variables (e.g. saccade length, fixation duration).

Do developmental factors influence binocular coordination?

Research comparing the binocular coordination of children and adults has revealed differences in both the magnitude and the direction of fixation disparity. An important question to consider is whether these differences are a consequence of the increased processing difficulty experienced by child readers compared to skilled adult readers. The cognitive demands associated with processing linguistic stimuli are far greater for younger children (in particular those who have recently learnt to read), compared to older children and adult skilled readers who have years of reading experience (e.g. Rayner, 1986). Hence any differences in binocular coordination between beginning and skilled readers could be due to three possible factors: the development of binocular coordination control in general; the development of binocular coordination specifically in relation to reading; or greater language processing difficulties for beginning compared to skilled readers.

The data from several studies have shown that children tend to have a greater magnitude of disparity between the two points of fixation than adults; furthermore, where adults tend to show a predominance of uncrossed fixation disparities, children tend to show a higher proportion of crossed fixation disparities than adults. This pattern of differences between adults and children has been found on both reading (Blythe et al., 2006) and non-reading tasks (Bucci and Kapoula, 2006; Fioravanti et al., 1995; Yang and Kapoula, 2003). Given that children and adults show differences in binocular coordination for non-reading based tasks, the observed developmental changes in binocular coordination during reading cannot be attributed solely to high-level cognitive processing of linguistic stimuli. Rather, these differences between adults and children appear to be more low-level in nature and perhaps improvements in binocular coordination during reading reflect age-related improvements in oculomotor control more generally.

Overall, it is clear that developmental changes in binocular coordination during reading occur, but the differences between adults and children whilst reading cannot necessarily be attributed to children's increased processing difficulty as beginning readers as they also occur during non-reading tasks. What remains uncertain as yet is why these age-related changes in binocular coordination occur (see Kirkby et al., 2008 for a discussion of this issue). However several studies have described a general development of eye movement control maturing at around adolescence, perhaps linked to the maturation of the brain via synaptic pruning and myelination (see Luna and Velanova, Chapter 35, this volume).

Is there a link between binocular coordination and dyslexia?

The third of our three questions is currently something of a greater challenge to address, partly due to the lack of empirical studies specifically investigating which aspects of reading are affected by binocular coordination for those with dyslexia, and partly due to the conflicting evidence in the literature. We will, therefore, first provide an overview of the eye movement research associated with the argument that poor binocular coordination and reading difficulties may be causally related. Then, although there are only a few studies that have directly measured the binocular eye movements of individuals with reading difficulties, we will discuss the data (often based on non-reading tasks) supporting this claim.

The 1994 DSM-IV Criteria for Reading Disorder (dyslexia) are: a) reading achievement, as measured by an individually administered, standardized test of reading accuracy or comprehension, substantially below that expected given the person's chronological age, measured intelligence, and age-appropriate education; b) the disturbance interferes with academic achievement or activities of daily living that require reading skills; c) if a sensory deficit is present, the reading difficulties are in excess of those usually associated with the specific sensory deficit (APA, 1994). After several decades of research there is still considerable disagreement over the neurological and cognitive basis of dyslexia and this remains strongly debated. The most influential theory of dyslexia is the phonological-deficit hypothesis (Liberman, 1973; Snowling, 2000; Stanovich, 1988), where cognitive deficits in processing the relationships between printed letters and speech sounds cause the behavioural problems experienced by dyslexics (Ramus, 2003). A far more controversial approach to understanding the pattern of deficits associated with dyslexia is the magnocellular-deficit theory, where causation is attributed to sensory deficits as a result of impairments in the magnocellular pathway of the visual system (Stein, 2001). The magnocellular theory of dyslexia will be the main focus of this section, as the proponents of this theory have argued that poor binocular coordination can be causally linked to reading difficulty.

Stein (2001) suggests that visual deficits, such as unstable binocular coordination during fixation and poor vergence control, can lead to letter and word processing difficulties (Bigelow and McKenzie, 1985; Eden et al., 1994; Cornelissen et al., 1992, 1993; Evans and Drasdo, 1990; Kapoula et al., 2007; Stein and Fowler, 1993; Stein et al., 1986; 1988). Stein proposed that children with dyslexia make reading errors due to their inability to perform appropriate vergence movements during fixation (Kapoula et al., 2007; Stein et al., 1988). Recall that vergence movements (non-parallel movements of the two eyes) are made by adult and child readers during fixations, such that the residual disparity from the preceding saccade is reduced (Blythe et al., 2006; Liversedge et al., 2006a, 2006b). Stein argued that vergence movements are necessary in order to maintain a stable, fused visual percept of the words on a page, and that up to two thirds of the dyslexic population may be affected by the inability to perform appropriate vergence movements during fixations (Kapoula et al., 2007; Stein et al., 1988). Specifically, it was claimed that individuals with dyslexia fail to make appropriate vergence movements during fixations in reading and, thus, experience an unstable single percept from the two retinal inputs (there are often anecdotal reports that dyslexic readers experience blurring of letters, letters moving around in a word, and letters obscuring one another).

The magnocellular deficit theory postulates deficient functioning of the magnocellular stream of the visual system, and neurological problems are suggested to affect visual contrast sensitivity as well as reduced binocular stability (Stein, and Fowler, 1993; Cornelissen et al., 1993; see Boden and Giaschi, 2007, for a review). Both these deficits in magnocellular function would obviously negatively impact on a child's ability to learn to read; however, deficits in binocular coordination in dyslexia remain inadequately investigated to date (Kirkby et al., 2008). In particular, some intervention programs already focus on improving binocular coordination in dyslexic children (Stein et al., 2000), even though there has been little empirical evaluation of the extent to which such a deficit exists. Importantly, the present chapter highlights that binocular disparity is commonplace during reading and non-reading tasks for both skilled adult and child readers, hence binocular disparity is not unique to dyslexic readers. In addition to examining whether dyslexic readers do show poorer binocular coordination we must also ask, therefore, whether fixation disparity in dyslexic readers impacts on their reading performance.

Interestingly, there are also some eye movement experiments indicating that dyslexic children's fixations are largely adequate in reading-like, visual scanning tasks (De Luca et al., 1999, 2002; Hutzler et al., 2006; Hutzler and Wimmer, 2004). However, these studies only recorded the movements of one eye during the task and, therefore, they provide no information in relation to binocular coordination during reading.

If dyslexia is caused by poor binocular control then dyslexic individuals should exhibit different binocular coordination behaviour compared to skilled readers in general, and not only during reading. In order to support the claim that poor binocular coordination is a cause of children's reading difficulties, it would be necessary to demonstrate poor binocular coordination in such children both during tasks that require linguistic processing and during tasks that do not, compared to typically developing children. A difference between typically developing and dyslexic children on a reading task alone would leave the researcher unable to distinguish between whether poor binocular coordination is a cause, consequence, or correlate of reading difficulty. In contrast, if poor binocular coordination was found to occur for dyslexic children during non-reading tasks in the absence of any linguistic processing demands, at least it would then be shown that reading difficulty is not the cause of poor binocular coordination in dyslexic children. We will now briefly outline research that has attempted to examine whether reading difficulty is associated with poor binocular coordination in reading and non-reading tasks (e.g. Bucci et al., 2008; Jaschinski et al., 2004; Kapoula et al., 2007; Kirkby et al., submitted; Stein et al., 1988).

Stein and colleagues examined children's vergence eye movements in response to simulated movements of small targets in depth. Using both subjective reports and more objective eye movement recordings, the findings led Stein and colleagues to suggest that a number of children with dyslexia are unable to maintain stable binocular fixation (Stein and Fowler, 1981, 1982, 1993; Stein et al., 1988; Stein, 1989, 2001). Other studies have investigated binocular coordination in individuals with dyslexia by using dichoptic methodologies in which different images are presented to each of the eyes using a synoptophore.[3] In these studies, the images presented to the two eyes were gradually drawn apart in either a convergent or a divergent direction. The children were asked to report the moment at which they experienced double vision (i.e. the moment at which the magnitude of disparity between the two retinal inputs became too great for them to be successfully fused). Several studies

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[3] The Synoptophore is a haploscope that allows the experimenter to present separate slides to each eye in order to test various aspects of binocular vision.

were conducted using this method, reporting eye movement data in one instance whilst relying on the subjective self-report of children in other cases (Bigelow and McKenzie, 1985; Stein and Fowler, 1981, 1982, 1993; Stein, 1989). While typically developing children did make vergence movements up until the point at which fusion broke, Stein et al.'s (1988) data showed that children with dyslexia failed to make appropriate, stimulus-driven vergence movements (instead, they made parallel drift movements of the two eyes). Together, these results indicate that dyslexic children have poorer binocular coordination compared to non-dyslexic children, at least during certain non-reading tasks.

In addition to the studies by Stein and colleagues, two recent studies have demonstrated a reduced capacity to verge the eyes during fixation in children with dyslexia on both non-reading and single-word reading tasks (Kapoula et al., 2007; Bucci et al., 2008). Similarly, Jaschinski et al. (2004) used dichoptically presented nonius lines to determine a psychophysical measure of fixation disparity. In this test of disparity, the participant views dichoptically presented vertical lines, one above the other, and they are required to make small adjustments until the lines appear vertically aligned. The remaining disparity between the two lines following the participants' adjustment is taken as a measure of their fixation disparity. Jaschinski et al. found that the mean fixation disparity for dyslexic children was larger in magnitude than that of typically developing children. Thus, several studies examining fixation disparity on non-reading tasks have found evidence of relatively poor binocular coordination in dyslexic children compared to their typically developing peers. Note, however, that the non-reading tasks used in these studies have not required oculomotor behaviour analogous to that observed during reading. This raises the question of whether the results would generalize to reading or to scanning tasks that demand similar eye movement behaviour to reading.

There are, however, studies which have not found differences between groups of typically developing children and children with dyslexia in their capacity to verge the eyes. Lennerstrand and colleagues conducted a longitudinal study employing a number of different methods for examining binocular coordination (Lennerstrand et al., 1993, 1994). A synoptophore test was used to examine vergence capacity when viewing small, simple pictures. In addition, participants completed other orthoptic tests, and their binocular eye movements were recorded during a sentence reading task. Vergence control was found to be comparable for children with and without dyslexia during the synoptophore test. Interestingly, however, for the sentence reading task, the children with dyslexia were found to have greater binocular asymmetry during saccades compared to the typically developing children. Given that there were no differences in binocular coordination between the dyslexic and typically developing children in the non-reading task, but a difference in the reading task, these data indicate that a cognitive modulation of binocular coordination may be present for children with dyslexia.

Recently Kirkby et al. (submitted) conducted a study that measured binocular coordination in adults, typically developing children, and children with dyslexia during both a reading and a non-linguistic dot scanning task. Participants were required to either scan (from left to right) horizontal arrays of dot strings or to silently read sentences as their binocular eye movements were recorded. The dot stimuli were carefully designed to appear visually similar to horizontal arrays of words (sentences), without requiring any linguistic processing. The resulting oculomotor behaviour observed during the dot scanning task were similar to that observed during reading (highly stylized patterns of fixations and saccades). With respect to binocular coordination, Kirkby et al. found that fixation disparity was significantly greater for dyslexic children compared to both adults and typically developing children during reading, but not during the non-reading task. Kirkby et al. concluded that observation of poorer binocular coordination in dyslexic readers exclusively when reading (in both Kirkby et al. and Lennerstrand et al.'s studies) casts serious doubt on the claims of the magnocellular theory. Given the lack of a difference in binocular coordination between dyslexic and typically developing children on non-reading tasks, it seems highly unlikely that a low-level dysfunction in binocular coordination causes the reading difficulties associated with dyslexia. Rather, Kirkby et al. propose that increased fixation disparity during reading in children with dyslexia may result either from inadequate attentional or cognitive resource allocation in the reading process, or from suboptimal linguistic processing.

It could also be argued that the differences in binocular coordination during reading for dyslexic children might arise due to the greater linguistic processing difficulty that dyslexic children experience in the reading task compared to their typically developing peers. Such a suggestion contrasts, however, with the research with skilled adult readers, discussed above, showing little direct evidence for a link between processing difficulty and binocular coordination (e.g. Heller and Radach, 1999; Hendriks, 1996; Juhasz et al., 2006). We suggest that the manipulations of processing difficulty used with adults (such as word frequency) do not approximate the difference in cognitive effort required for reading in children with dyslexia compared to that in skilled (adult or child) readers.

In summary, a number of studies (Bigelow and McKenzie, 1985; Bucci et al., 2008; Cornelissen et al., 1992, 1993; Eden et al., 1994; Evans and Drasdo, 1990; Jaschinski et al., 2004; Kapoula et al., 2007; Stein and Fowler, 1993; Stein et al., 1986, 1988) have shown differences in binocular coordination between readers with dyslexia and matched controls. To date, however, only one study has recorded binocular eye movements from the same group of dyslexic children during both a reading and a non-reading task (Kirkby et al., submitted). Kirkby et al.'s results indicate that dyslexia is associated with increased fixation disparity exclusively during reading and, hence, poor binocular coordination is unlikely to cause reading difficulties. Overall, it is clear that there are conflicting findings in the literature on binocular coordination and dyslexia, and it is evident that much more research is needed. First, further studies must confirm whether or not poor binocular coordination occurs exclusively during reading for children with dyslexia. Second, if differences in binocular coordination are specific to reading, then further studies must be conducted to distinguish between two possible explanations: 1) poor binocular coordination is a consequence of severe processing difficulty and, hence, is seen in children with dyslexia but is not necessarily specific to that group (stronger manipulations with adults could result in an effect on their binocular coordination); 2) poor binocular coordination during reading is an inherent characteristic of dyslexia and reflects the particular attentional/linguistic abnormalities associated with that pheneotype.

Conclusions

The chapter has provided an overview of the current topical issues surrounding binocular coordination during reading. A number of studies now illustrate that precise coordination of the eyes is not necessary for fluent reading. In fact the two points of fixation are frequently disparate, with the two eyes often fixating different letters within a word (though disparity rarely exceeds two character spaces). Vergence movements occur during fixations and tend to be in a corrective direction for the residual binocular disparity from the preceding saccade. Nevertheless, disparity remains until the end of fixation albeit reduced in magnitude. Readers can fuse up to 0.37° of retinal disparity during reading, and no age-related changes for fusional limits have been found. Furthermore, evidence from a range of studies indicates that saccades are programmed on the basis of a single fused percept.

The chapter focused on three critical issues. Our review of whether visual/cognitive factors impact on binocular coordination in skilled readers concluded that disparity during reading is, at most, minimally affected by the processing demands of the task. Further research is necessary, though, to confirm whether processing difficulty, or mediating variables such as saccade amplitude or fixation duration, can in some circumstances impact on binocular coordination. Second, our review indicated that binocular coordination develops with age; at around 12 years of age children display a pattern of binocular coordination similar to that for adults. Importantly, comparisons of reading and non-reading data indicate that these changes are not associated with changes in reading skill but rather reflect a low-level development in oculomotor control. Finally, we considered whether variability in binocular coordination is linked to dyslexia. Although there is some evidence that dyslexia in children is associated with poor binocular coordination, a recent direct comparison of binocular coordination in reading and a non-reading task indicates that increased fixation disparity for dyslexic children during reading may in fact be a consequence of reading difficulties. Further research is needed to clarify the extent to which increased fixation disparity in dyslexic readers might be attributable to reading material itself, or the cognitive/linguistic processing demands associated with reading and comprehending text.

The research outlined in this chapter not only has important implications for our understanding of binocular coordination in general, but is also critical for our understanding of eye movement control during reading. In terms of methodology, the finding of disparate fixations has implications for inferring the precise location of overt attention (as determined by where the eyes are fixating). That is, the two eyes are frequently disparate during fixations and yet the two retinal inputs are fused; even if the positions of both eyes are recorded, it is unclear where overt attention should be considered to be located (especially if the two eyes are fixating different letters). Research based on the recording of just one eye produces particular uncertainty about the precise location of overt attention in the text. In some cases, it may even be that the non-recorded eye is fixating a different word to the recorded eye.

The fixation disparities that occur during reading raise questions about the interpretation of some existing findings based on the recordings of just one eye. For example, some studies have shown that the characteristics of a word can influence eye movement behaviour on the prior word (parafoveal-on-foveal effects) (Kennedy, 2000). Such findings are central to determining whether attention can be allocated to more than one word at any one time. However, a contributing factor to such effects may be a subset of fixations in which the non-recorded eye is actually fixating the next word in the sentence (and affecting fixation durations which are associated with the prior word in the sentence that is being fixated by the recorded eye). Thus, it is possible that 'parafoveal-on-foveal' effects in such circumstances may not be driven by parafoveal processing (for a thorough discussion of parafoveal-on-foveal effects, see Drieghe, Chapter 46, this volume). Similarly, words that are thought to have been skipped might actually have been fixated by the non-recorded eye. Importantly, given that the two eyes occasionally fixate on different words, a fully comprehensive model of eye movement control in reading will need to account for the position of the two eyes separately, rather than assuming that the two eyes fixate in precisely the same location as is currently the case (e.g. Engbert et al., 2005; Reichle et al., 1998).

One recent model does take into account the relative positions of the two eyes (Shillcock et al., 2010). Shillcock et al. (2010) simulated the effect of a range of both crossed and uncrossed fixation disparities in their model. The results indicated that fixation disparity would impact on lexical identification, as disparity increases the width of the foveal window (thereby increasing the range of information that falls within high-acuity vision). The results also indicated that crossed disparities would facilitate lexical identification more than uncrossed fixation disparities. In addition to binocular disparity, their model also incorporates foveal splitting, whereby the left half of a fixated word is initially projected to the right hemisphere and the right half of a word is initially projected to the left hemisphere of the brain via contralateral projections (e.g. Lavidor et al., 2001). Model simulations indicated that the processing advantage associated with crossed fixation disparities was increased by precise foveal splitting, such that the greater the simulated overlap between hemifoveas the smaller the difference between crossed and uncrossed fixation disparities. Note, however, that the assumption of precise foveal splitting is controversial and strongly debated (see Jordan and Paterson, 2009, 2010).

Finally, the issues outlined here have particular implications for our understanding of the role of binocular coordination in dyslexia. As emphasized above, much more research is needed to clarify the nature of any difference in binocular coordination in dyslexic compared to typical populations, and to identify whether any differences are specific to reading. The issue is of particular importance due to the potential implications of this research for intervention programmes.

Acknowledgements

J.A. Kirkby was supported by the Leverhulme Trust. Portions of this work were completed while S.J. White was on Study Leave granted by the University of Leicester. H.I. Blythe was supported by an ESRC Postdoctoral Fellowship. We would like to thank Kevin Paterson and Denis Drieghe for their helpful comments on an earlier version of this chapter.

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