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The binocular coordination of eye movements during reading in children and adults

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Abstract

Recent evidence indicates that each eye does not always fixate the same letter during reading and there has been some suggestion that processing difficulty may influence binocular coordination. We recorded binocular eye movements from children and adults reading sentences containing a word frequency manipulation. We found disparities of significant magnitude between the two eyes for all participants, with greater disparity magnitudes in children than adults. All participants made fewer crossed than uncrossed fixations. However, children made a higher proportion of crossed fixations than adults. We found no influence of word frequency on children's fixations and on binocular coordination in adults.

Keywords: Reading; Binocular coordination; Adults; Children

1. Introduction

The purpose of this study is to examine coordination of the two eyes in children and adults when reading. There is a wide literature concerning the control of eye movements during reading (Liversedge & Findlay, 2000; Rayner, 1998), and within this there are several well-developed and competing models which can account for many phenomena that are observed, e.g. the E-Z Reader Model (Pollatsek, Reichle, & Rayner, 2006; Rayner, Reichle, & Pollatsek, 1998; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 1999, 2003), the SWIFT Model (Engbert, Longtin, & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl, 2006), and the Glenmore Model (Reilly & Radach, 2003, 2006). Almost all of this research has been based on recordings of the movements of just one of the two eyes, as there has been an implicit assumption that the two eyes move together and fixate the same letter of a word when we read (Liversedge, White, Findlay, & Rayner, 2006a). However, recent evidence suggests that this assumption may be incorrect (Heller & Radach, 1999; Juhasz, Liversedge, White, & Rayner, 2006; Liversedge et al., 2006a; Liversedge, Rayner, White, Findlay, & McSorley, 2006b).

1.1. Adults' binocular coordination in reading

Heller and Radach (1999) reported that the two eyes make asymmetrical saccades during reading, such that one eye makes a larger saccade than the other. They found that the magnitude of this asymmetry was around 5% of the amplitude of long saccades (10–12 letters), and 15% of the amplitude of short saccades (2–3 letters). This suggests that the eyes are landing apart, possibly even on different characters within the word. Heller and Radach's data are, however, largely descriptive and no formal statistical analyses were provided.

More recently, Liversedge et al. (2006a) recorded the binocular eye movements of normal adult readers as they read single sentences. They found that across all fixations,

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the fixation positions of the two eyes were on average 1.1 character spaces apart during reading. On 53% of fixations the eyes were aligned to within one character space, but on 47% of fixations the positions of the two eyes were more than one character space apart (disparate fixations). Within the 47% of disparate fixations, the majority were uncrossed with the left eye fixating to the left of the right eye. Only 8% of fixations were crossed, such that the fixation position of the right eye was to the left of the left eye. These data are consistent with Heller and Radach's (1999) finding of disparity between the two eyes when reading.

Juhasz et al. (2006) also examined normal adult readers with single sentence stimuli and found a very similar pattern of results with a mean disparity between the positions of the two eyes of 1.1 character spaces, and 45% of fixations being unaligned by more than one character space. They also found that the majority of unaligned fixations were uncrossed, with a smaller proportion of crossed fixations. Within their experiment, Juhasz et al. also manipulated case (normal vs. mIxEd), as well as word frequency, a linguistic manipulation of processing difficulty. Both manipulations of reading difficulty produced reliable effects on fixation durations, but did not affect the nature of disparity between the two eyes. These findings suggest that the cognitive demands of reading do not influence binocular coordination.

1.2. Children's binocular coordination

Clear developmental trends have been observed in many basic eye movement parameters (see Rayner, 1998 for a review). For example children make, on average, longer fixations and shorter saccades when reading than do adults McConkie et al. (1991). However, coordination of the two eyes during reading is a less researched issue in both children and adults. As yet, it is not known how the characteristics of binocular coordination might develop with age. To date, there have not been any studies that have systematically examined the binocular coordination of typically developing children during normal reading to allow comparison with adult data. Therefore the principal aim of this study was to examine binocular coordination in children.

Cornelissen, Munro, Fowler, and Stein (1993) monitored the eye movements of three groups of children as they read word lists. The three groups were comprised of typically developing children, children with reading difficulties who passed the Dunlop test, and children with reading difficulties who failed the Dunlop test. The Dunlop test is a self report procedure that is argued to provide an index of the stability of ocular dominance. Cornelissen et al. found no reliable difference in the average fixation disparity between the three groups of children. However, and perhaps more interestingly for our purposes, in a separate analysis the typically developing children were found to have significantly greater fixation disparities than adult participants. It is important to note, however, that these eye movement data were recorded during a relatively unnatural reading task and consequently, the extent to which these data generalise to performance during normal reading has yet to be established.

Bassou, Pugh, Granié, and Morucci (1993) examined binocular coordination during reading of text passages in 10-year-old children, with and without heterophoria (latent muscle imbalance). They found that in all children, saccades of the two eyes were well-coordinated temporally but not spatially, with greater disparities between the two eyes in children with heterophoria than in children without heterophoria. Whether the disparities were crossed or uncrossed was not reported. In addition to the analyses of fixation disparity, Bassou et al. also examined vergence movements made during fixations and found that such movements served to reduce the disparity that occurs during a fixation.

Several other recent studies have provided more thorough examinations of binocular coordination in typically developing children, although none of these have employed a reading task. Fioravanti, Inchingolo, Pensiero, and Spanios (1995) conducted an experiment to replicate and extend a finding first reported by Collewijn, Erkelens, and Steinman (1988). In their experiment Fioravanti et al. measured the binocular saccades of adult participants as they looked from one light emitting diode to another and found that during saccades, the abducting eye (the eye moving in an outward direction) typically moves with a larger amplitude, higher velocity, shorter duration, and greater skewness than the adducting eye (the eye moving in the nasal direction). This larger, faster movement in one eye than the other leads to disparity at the end of the saccade whereby the abducting eye typically has a landing site further in the direction of the saccade than the adducting eye. While this divergence is transient and is usually followed by convergent movements which largely correct the disparity, a difference in the positions of the two eyes typically remains by the end of the saccade. Thus, the saccadic effect they reported would result in an uncrossed fixation. Fioravanti et al. also extended these findings to examine binocular coordination in children. The pattern of results was very similar for older children (11–13 years) and adults, but they obtained the opposite pattern for younger children (5–10 years). For this latter group, saccades of the adducting eye showed larger amplitudes, higher velocities, shorter durations, and greater skewness. Thus, Fioravanti et al.'s data clearly show a tendency for the eyes of younger children to become crossed during a saccade. Specifically, they reported that the spatial saccadic disconjugacy for younger children was 1.97°, compared to 0.63° for older children and 0.48° in adults. Therefore, in addition to the reversed direction of saccadic disconjugacy, the magnitude of resulting disparity is also greater in younger children than in older children and adults.

More recently, Yang and Kapoula (2003) used the same task and also reported saccadic disconjugacy of over 2° for children, a significantly greater effect than obtained for adults. Further, they broke down their child participant group into different age ranges and also found that saccadic disconjugacy reached adult values around the age of 10–12 years, in keeping with previous findings. Yang and Kapoula also reported an effect of viewing distance in children, such that binocular disparity in children was greater at close viewing distances than at far viewing distances. This difference was not observed in adults. Consequently, Yang and Kapoula argued that the modulation of fixation disparity by viewing distance in children was likely to be due to immature cortical control of vergence.

One study has examined the effect of task on binocular coordination in children. Bucci and Kapoula (2006) compared the binocular saccades of children aged 7 to those of adults, when reading either single words, or when making saccades to LEDs. They found no difference in the absolute disparity of saccades made to either LED or single word targets in children or adults. However, a significant difference between the two participant groups was reported, with larger disparities in children than adults, though the direction of these disparities is not reported. Bucci and Kapoula also reported that children make larger post-saccadic vergence movements than do adults, although again the direction of this vergence is not reported. While the results of this study may not generalise to normal reading due to the tasks employed, these data do suggest that processing difficulty does not affect binocular coordination in either children or adults. The findings of this study do agree with those of Fioravanti et al. (1995), and of Yang and Kapoula (2003), however, in showing that children's saccades in non-reading tasks and single word reading are more poorly binocularly coordinated than those of adults.

Our secondary aim in the present study was to examine whether processing difficulty systematically influenced binocular coordination in children. To this end, our study included a manipulation of word frequency in order to induce processing difficulty and assess its influence on binocular coordination. Specifically, we generated three hypotheses each concerning a different aspect of binocular coordination for which we anticipated differences in behaviour between children and adults. First, given the findings of Juhasz et al. (2006) and Liversedge et al. (2006a) who showed that fixation disparity was prevalent even at the end of a fixation, we anticipated similar fixation disparity effects both for adults and for children where disparity remains between the positions of the two eyes at the end of fixations. Furthermore, given Fioravanti et al.'s (1995) finding that children's binocular eye movements are disparate to a greater degree than those of adults, we might also predict that the magnitude of disparity at the end of fixations will be of greater magnitude in children than in adults.

Second, the present experiment also allowed us to test the prediction that children will exhibit a higher proportion of crossed than uncrossed fixations (i.e., the pattern of fixation alignments will be reversed from that seen in adults). Fioravanti et al. (1995) showed that the direction of the disparity effect observed in children is reversed relative to that observed in adults. To be clear, children's points of fixation are more likely to be crossed, whereas adults' are more likely to be uncrossed. The present experiment enabled us to examine this prediction.

Third, the inclusion of a critical high and low frequency target word within our sentences provided an opportunity to further investigate the influence of processing difficulty on binocular disparity. In particular, we were interested to know whether increased processing difficulty would affect binocular disparity during normal reading or not (as per Juhasz et al., 2006). Specifically, we wished to examine whether any such modulatory influence occurred in children when reading sentences.

2. Methods

2.1. Participants

The 12 adult participants were all members of the University of Durham community. The age range of adult participants was 18–21 years. All participants were native English speakers with normal, uncorrected vision who participated voluntarily in the study. They were paid for their participation. All subjects were naïve regarding the purpose of the study.

The 12 child participants were contacted through local schools, with permission from parents and headteachers who were informed about the nature of the study and its purpose. All child participants were native English speakers with normal uncorrected vision and no known reading difficulties. The age range of child participants was 7–11 years (mean 9 years and 11 months). All were volunteers, and naïve regarding the purpose of the study.

Due to the difficult and tiring nature of binocular eye tracking, we found that we were able to track approximately 1 out of 2 adults and 1 out of 4 children who volunteered to take part in this experiment.

2.2. Apparatus

Binocular eye movement recordings were made using 2 Fourward Technologies Dual Purkinje eye trackers (Generation 5.5 and Generation 6 for the right and left eyes, respectively). Eye positions were recorded every millisecond. The eye trackers were interfaced with a Pentium 4 computer, with all sentences presented on a Philips 21B582BH 24″ monitor. Sentences were presented in white, Courier New font size 11, on a black background. The room was dimly illuminated. Sentences were presented at a viewing distance of 100 cm; each character covered 0.19° of horizontal visual angle. Subjects were asked to bite on a bar with a wax dental impression and to lean against forehead rests during the experiment, to minimise head movements.

2.3. Materials and design

2.3.1. Children's stimuli

Fifty-six experimental items were constructed, 28 of which contained a high or low frequency target word (the remaining 28 contained a different manipulation that will not be discussed in this paper). Simple syntactic structures were used to maximise children's comprehension. The high and low frequency target words were always 6 letters long. The median frequency for high frequency target words was 93 counts per million (range: 19 to 1480 per million) and the median frequency for low frequency target words was 7 counts per million (range: 1 to 14 per million). Inter-quartile ranges were 7 for the low frequency words, and 128 for the high frequency words. All word frequencies were taken from the CELEX English word form corpus (Baayen, Piepenbrock, & Gulikers, 1995). In addition to manipulating the frequency of target words, we ensured that the target words in the children's stimuli would be acquired between the ages of 6 and 8 years of age (MRC Database, Coltheart, 1981). All sentences were between 50 and 60 characters long and all target words were at least 20

Table 1
Examples of the experimental sentences for adults and children

Group	Condition	Sentence
Adults	High frequency	Once he saw the retired *worker* in the local pool looking very sad indeed.
	Low frequency	Once he saw the retired *healer* in the local pool looking very sad indeed.
Children	High frequency	The bitter *coffee* that you gave me tasted really unpleasant.
	Low frequency	The bitter *cherry* that you gave me tasted really unpleasant.

characters from the start/end of the sentence. Examples of the children's stimuli with the frequency manipulation are given in Table 1.

In addition to the 56 items, 5 practice items were presented at the beginning of the experiment. After 20 of the sentences, distributed randomly throughout the experiment, participants used a button box to respond yes/no to comprehension questions.

2.3.2. Adult stimuli

Forty experimental items consisting of a single sentence were constructed, each containing a target word that was either high or low frequency. The high and low frequency target words were always 6 letters long. The median frequency for high frequency target words was 145 counts per million (range: 74 to 356 per million) and the median frequency for low frequency target words was two counts per million (range: 1 to 2 per million). Inter-quartile ranges were 1 for the low frequency words, and 115 for the high frequency words. Again, all word frequencies were taken from the CELEX English word form corpus (Baayen et al., 1995).

All sentences were between 70 and 80 characters long, and were presented from left to right with the first character of each sentence appearing in the same position on the left of the screen. All target words were positioned at least 20 characters from the start/end of the sentence.

In addition to the 40 experimental items, 5 practice items were presented at the beginning of the experiment. After 15 of the sentences, distributed randomly throughout the experiment, participants used a button box to respond yes/no to comprehension questions.

2.4. Procedure

Participants were instructed to read the sentences normally, and to answer the questions as accurately as possible by pressing a button box. For child participants, information sheets were sent to parents in advance in order that the procedure could be explained prior to arrival. Also, all instructions were given verbally to the children at the start of the experiment and children were given lots of encouragement throughout the experiment.

The left and right eye trackers were calibrated for each eye monocularly in turn (i.e., during calibration of the right eye, the left eye was occluded and vice-versa). The participant was instructed to look at each of three fixation points in turn presented horizontally on the left, centre, and right of the screen. The fixation position was recorded for each calibration point. This calibration was then checked for accuracy, after which it was repeated for the other eye. Once both eyes had been calibrated accurately, the practice and experimental sentences were then presented. Following each sentence for the adults, and every four sentences for the children, the calibration was checked for accuracy, and the eye trackers were recalibrated if necessary. All participants were given a break half way through the experiment, and additional breaks were given if required. The entire experiment lasted approximately one hour for children and 40 min for adults.

2.5. Analyses

Custom-designed software was used for the data analyses. Fixations were manually identified in order to avoid contamination by dynamic overshoots (Deubel & Bridgeman, 1995; see also Liversedge et al., 2006a).

3. Results

3.1. Global measures

First, we report the mean fixation durations, saccade lengths, and regression frequencies for children and adults (presented in Table 2). These data are based on every valid fixation made during the experiment. While all adult participants completed the entire experiment, some of the children were unable to do this as they became tired. Three of the 12 children completed 50–74% of the experiment, 4 of the children completed 75–99% of the experiment, and 5 o f the children completed the entire experiment. Fixations of less than 80 ms or more than 1200 ms were deleted (4.5% of data). Of these, 1.7% were made by adults and 2.8% were made by children. A further 4.1% of fixations were excluded from the analysis due to an absolute disparity at the end of fixation more than 2 standard deviations from the mean for any given participant (1.6% of these fixations were made by adults, 2.5% were made by children). Finally, a further 3.5% of fixations were excluded from the analysis due to a start of fixation absolute disparity more than 2 standard deviations from the mean for any given participant (1.7% of these fixations were from adults, 1.8% were from children).

Throughout Section 3, where appropriate, we conducted analyses of variance and *t*-tests treating participants (F_1, t_1) and items (F_2, t_2) as random variables consistent with Clark (1973; though see Raaijmakers, Schrijnemakers, & Gremmen, 1999). When effects were reliable at the alpha level of .05, we consistently refer to them as reliable, and when effects approached this alpha level we consistently refer to them as marginal.

As can be seen from Table 2, the children made, on average, longer fixations, shorter saccades, and more regressions than adults during reading. The developmental trends observed in these data are very similar to those reported by McConkie et al. (1991), who compared three different studies that had examined children's oculomotor behaviour during reading (see also Rayner, 1998).

Second, the accuracy scores from the comprehension questions are reported to further demonstrate that our participants did not experience any difficulty in reading the experimental sentences. The mean adult score was 78%

Table 2
Mean fixation duration, saccade length, and regression frequency for adults and children

	Adults	Children
Fixation duration		
M	240 ms	279 ms
SD	88 ms	135 ms
Mean saccade length		
M	8.2 chars	7.1 chars
SD	6.2 chars	5.6 chars
Mean regression frequency		
M	20.5%	27.8%
SD	9.3%	3.6%

correct, whilst the mean score for children was 91%. On first inspection, it may appear that the eye movement data and comprehension data are contradictory. The general pattern of eye movements shows that children were slower at reading the sentences than adults. However, the level of comprehension for the two groups was, if anything, better for children than adults. These aspects of the data are entirely compatible on the assumption that the less fluent pattern of eye movements observed in children does not necessarily imply a lack of comprehension. To be clear, these data suggest that while children may be slower to read a sentence, they do still ultimately fully comprehend that sentence. Most importantly, taken together, the global eye movement data and the comprehension scores are strong evidence that all participants were reading and comprehending the sentences normally in our experiment.

3.2. End of fixation disparity analysis

Following Liversedge et al. (2006a), fixations were categorised as aligned or unaligned. A fixation was considered to be aligned when the points of fixation of each eye were within one character space of each other (0.19°). An unaligned fixation occurred when the points of fixation of the two eyes were more than one character space apart. Within those fixations that were categorised as unaligned, we further categorised fixations as either uncrossed or crossed. We defined an uncrossed fixation as the left eye fixating to the left of the right eye. We defined a crossed fixation as one where the fixation position of the right eye was to the left of the left eye.

Table 3 shows the mean absolute disparity between the points of fixation of the two eyes at the end of fixations, that is, after any vergence movements have been completed. These analyses represent a conservative measure of fixation disparity during reading and are based on every valid fixation made during the experiment.

Our data showed that, for children, the mean end-of-fixation disparity magnitude was 1.58 character spaces. For adults, the end-of-fixation disparity between the positions of the two eyes had a mean magnitude of 1.26 character spaces. One-sample t-tests were used to compare the mean absolute disparity to one character space (0.19° visual angle), to determine whether the eyes always fixate within one character space of each other (as has been assumed). These t-tests showed that both for children ($t_1(11) = 4.95$, $p < 0.001$; $t_2(55) = 14.99$, $p < 0.001$), and for adults ($t_1(11) = 3.13$, $p = 0.01$; $t_2(39) = 10.63$, $p < 0.001$), the mean disparity between the two eyes was significantly larger than one character space.

An independent samples t-test comparing mean absolute disparity in children and adults showed that children's disparity magnitude was greater than that of adults. This effect was reliable by items and marginal by participants ($t_1(22) = 1.96$, $p = 0.06$; $t_2(94) = 5.88$, $p < 0.001$). The mean proportions of aligned, crossed and uncrossed fixations in children and adults at the end of fixations are shown in Table 4.

Due to the dependent nature of the three categories of fixation alignment, the analysis comparing their relative likelihood of occurrence in children and adults must necessarily be broken down into several stages (as per Liversedge et al., 2006a). First, we considered the likelihood of making an aligned (as opposed to an unaligned) fixation. In this first stage, we did not break down the unaligned fixations into further categories. In support of the claim that the two eyes do not always fixate the same character space when reading, these data showed that, numerically, the majority of fixations made by both children and adults were unaligned. Further, an independent samples t-test comparing the proportion of aligned fixations in children and adults found that children made fewer aligned fixations than adults (significant by items and marginal by participants, $t_1(22) = 1.93$, $p = 0.07$; $t_2(94) = 4.42$, $p < 0.001$). Thus, at the end of fixation children had greater disparity magnitudes than adults, and they also had a higher proportion of unaligned fixations than adults (though note that both effects were marginal in the participants analyses).

Fixations categorised as unaligned were further categorised as either crossed or uncrossed. As these two categories are still dependent, we made a comparison of the proportion of crossed fixation against a chance baseline of 50%. Importantly, no counterpart analysis was necessary for the alternative category of unaligned fixations (i.e., uncrossed fixations) since the two are entirely dependent and therefore what holds for one must also hold for the other. A one-

Table 3
Absolute disparity magnitudes in character spaces at the start and the end of fixation

	Adults	Children
End of fixation		
M	1.26	1.58
SD	0.95	1.22
Start of fixation		
M	1.26	1.53
SD	0.89	1.11

One character space is equal to 0.19° visual angle.

Table 4
Mean alignment proportions at the start and end of fixation (note that percentages have been rounded to the nearest whole number)

	All start data (%)	End aligned (%)	End crossed (%)	End uncrossed (%)
Adults				
All end data		48	13	39
Start aligned	48	86	6	8
Start crossed	12	19	81	0
Start uncrossed	40	16	0	84
Children				
All end data		39	24	37
Start aligned	39	84	8	9
Start crossed	24	14	86	0
Start uncrossed	37	11	0	89

sample t-test comparing the proportion of crossed fixations to 50% (i.e., chance) showed that both children and adults made fewer than 50% crossed fixations. This effect was reliable across participants and items for adults ($t_1(11) = 3.26$, $p < 0.01$; $t_2(39) = 16.50$, $p < 0.001$) and we observed a similar effect that was reliable by items but not participants for children ($t_1(11) = 1.30$, $p = 0.22$; $t_2(55) = 5.99$, $p < 0.001$). Indeed, an independent samples t-test showed that children make a higher proportion of crossed fixations than adults, though again, while this effect was significant by items it was not reliable by participants ($t_1(22) = 1.29$, $p = 0.21$; $t_2(94) = 4.54$, $p < 0.001$).

To summarise, all participants had, on average, disparity magnitudes between the positions of the two eyes that were significantly greater than one character space at the end of the fixation. Children's disparity magnitudes at the end of fixations were greater than those of adults. Furthermore, children made a higher proportion of unaligned fixations than adults. Within these unaligned fixations, all participants were more likely to make uncrossed than crossed fixations. However, children made a higher proportion of crossed fixations than did adults.

3.3. Start of fixation disparity analyses

We also examined disparity magnitudes and the proportions of different types of fixation disparity at the beginnings of fixations to investigate first, whether disparity characteristics are similar at fixation onset and fixation offset, and second, if they are not, then to examine the nature of vergence movements that occurred during fixations. The start of fixation data were taken immediately after saccade offset, at the earliest point during fixation when the eyes are first stable. As with the end of fixation disparity analyses, fixations were categorised as aligned, crossed or uncrossed.

Table 3 shows the mean absolute disparity magnitudes at fixation onset. These means are calculated from the fixation points of the two eyes on every valid fixation made during the experiment. The start-of-fixation disparity magnitude was, for children, 1.53 character spaces compared to 1.26 character spaces in adults. One-sample t-tests for children and adults, comparing mean disparities to one character space (0.19° visual angle) showed disparities between the two eyes that were significantly greater than one character space for both the child participants ($t_1(11) = 4.87$, $p < 0.001$; $t_2(55) = 15.26$, $p < 0.001$) and the adult participants ($t_1(11) = 3.00$, $p < 0.05$; $t_2(39) = 9.60$, $p < 0.001$).

We also conducted an independent samples t-test to compare the mean disparity magnitudes observed in children and adults at fixation onset. This analysis showed that fixation disparities were reliably greater in children than in adults, ($t_1(22) = 2.06$, $p = 0.05$; $t_2(94) = 5.88$, $p < 0.001$). Thus, consistent with the findings for end of fixation disparity, the analyses described above indicate that both children and adults exhibited fixation disparity of greater than one character space during reading at the beginning of fixations. Furthermore, the magnitude of binocular disparity at fixation onset was greater in children than in adults.

The mean proportions of aligned, crossed and uncrossed fixations at the start of fixation are shown in Table 4. As with the data from the end of fixation, numerically, the majority of fixations were unaligned. Again, we used an independent samples t-test to directly compare the proportion of aligned fixations observed in both participant populations. As anticipated, our results showed that children made fewer aligned fixations than adults with the effect reliable by items and marginal by participants ($t_1(22) = 1.78$, $p = 0.09$; $t_2(94) = 4.24$, $p < 0.001$).

Finally, within those fixations categorised as unaligned at fixation onset, we conducted one sample t-tests to compare the proportions of crossed fixations to 50% (chance). We again found that adults made significantly fewer than 50% crossed fixations ($t_1(11) = 3.79$, $p < 0.05$; $t_2(39) = 18.83$, $p < 0.001$). Children also made fewer than 50% crossed fixations (though this effect was reliable by items but not participants, $t_1(11) = 1.32$, $p = 0.21$; $t_2(55) = 6.63$, $p < 0.001$). Further, an independent samples t-test showed that children made a higher proportion of crossed fixations than did adults; again this effect was reliable by items but not by participants ($t_1(22) = 1.59$, $p = 0.13$; $t_2(94) = 5.45$, $p < 0.001$).

To summarise, the patterns of disparities observed at the start and at the end of fixation were very similar. Numerically, there was greater disparity between the points of fixation in children than in adults at both the beginning and end of fixation, and on average the disparity was more than one character space for all participants. Furthermore, children made fewer aligned fixations than adults both at the beginning and at the end of fixations. For the unaligned fixations, both children and adults made crossed fixations less often than chance. However, the proportion of crossed fixations was greater in children than in adults, and this increased proportion of crossed fixations occurred at fixation onset as well as at fixation offset. Once again, we note that some of these effects were not reliable in the participants analyses.

3.4. Comparison of start and end of fixation disparity

By comparing the data from the beginnings and ends of fixations, we can begin to examine whether there are movements of the eyes during fixations, and whether any movements during fixations differ between children and adults. Table 3 shows the mean disparity magnitudes for children and adults both at the start and the end of fixations.

A 2 (Participant Group: adults vs. children) × 2 (Sample Point in Fixation: beginning vs. end) repeated measures ANOVA showed a main effect of group, where children's disparity magnitudes were significantly greater than those of adults throughout fixations. This effect was marginal by participants and significant by items ($F_1(1,22) = 4.12$, $p = 0.06$; $F_2(1,94) = 35.32$, $p < 0.001$). However, the analysis showed no reliable effect of sample point in fixation ($F_1(1,22) = 1.62$, $p = 0.22$; $F_2(1,94) = 18.93$, $p < 0.001$) and no reliable interaction between the two ($F_1 < 1$; $F_2(1,94) = 1.61$, $p = 0.21$).

Table 4 shows the overall alignment patterns both at the start and at the end of fixations, and also the proportions of fixations that are aligned, crossed or uncrossed at the end of fixation, as a function of their alignment at fixation onset. We again conducted repeated measures ANOVAs to investigate differences in the proportion of aligned fixations. These analyses showed a main effect of group that was marginal by participants and reliable by items where children made fewer aligned fixations than did adults ($F_1(1,22) = 3.50$, $p = 0.08$; $F_2(1,94) = 19.19$, $p < 0.001$). Again, no reliable difference between the proportions of aligned fixations at the start and end of fixations was observed ($F_s < 1$). The interaction between participant group and sample point in fixation was also non-significant ($F_s < 1$).

Finally, we conducted repeated measures ANOVAs to compare the proportion of crossed fixations in children and adults at the beginnings and ends of fixations. While there was a numerical difference such that children made more crossed fixations than adults, this effect was not reliable ($F_1(1,22) = 2.10$, $p = 0.16$; $F_2(1,94) = 25.43$, $p < 0.001$). There was also no reliable effect of sample point in fixation ($F_1(1,22) = 1.20$, $p = 0.29$; $F_2(1,94) = 6.63$, $p = 0.01$), or interaction between the two ($F_1(1,22) = 1.20$, $p = 0.29$; $F_2(1,94) = 3.06$, $p = 0.08$).

In summary, we found group differences in both the mean disparity magnitude and the proportion of aligned fixations both at the beginning and at the end of fixations that were either reliable or marginal. However, we observed no significant differences in either the disparity magnitudes or the fixation alignment proportions between the start and the end of fixations.[1]

3.5. Movements during fixations

Four categories of movement (or non-movement) were defined, following Liversedge et al. (2006a). For each of the categories of movement, we conducted an independent samples *t*-test to determine whether there were reliable differences between children and adults. First, stable fixations were categorised as those fixations where both eyes move less than or equal to 0.1 character. Only 10% of children's fixations and 9% of adults' fixations were stable using this criterion. There was no reliable difference between children and adults in the proportion of stable fixations that occurred ($t_s < 2.9$).

The second category of movement is drift, where the eyes moved an equal amount in the same direction (and the difference in movement between the eyes was less than or equal to 0.1 characters). Once again, children and adults were very similar, with drift movements occurring for 14% of fixations in which there was a movement, in both children and adults ($t_s < 1$).

Of all the fixations during which a movement occurred in both children and adults, 86% showed a difference in movement between the two eyes of more than 0.1 character spaces. We defined such fixations as those during which vergence had occurred. Within this category of fixation, we further discriminated between two different types of vergence movement which we took to form our final two categories. We defined our third category of movement as convergence, whereby one or both eyes move more than 0.1 characters and the points of fixation were, in the majority of cases, closer together at the end of the fixation than at the beginning of the fixation. By contrast, we defined our fourth category of movement during a fixation as divergence, whereby one or both eyes move more than 0.1 characters and the points of fixation were, in the majority of cases, further apart at the end of the fixation than at the beginning of the fixation. In children, the probability of vergence movements being divergent was 46%, and of being convergent was 54%. In adults, the probability of vergence movements being divergent was 41%, and therefore the probability of vergence movements being convergent was 59%. These data, along with the proportions of divergent and convergent movements observed for both crossed and uncrossed fixations, are shown in Fig. 1.

An independent samples *t*-test showed that adults made a higher proportion of convergent movements than did children, though the effect was only reliable by items ($t_1(22) = 1.01$, $p = 0.32$; $t_2(94) = 3.66$, $p < 0.001$). These data demonstrate that when the eyes are making non-parallel

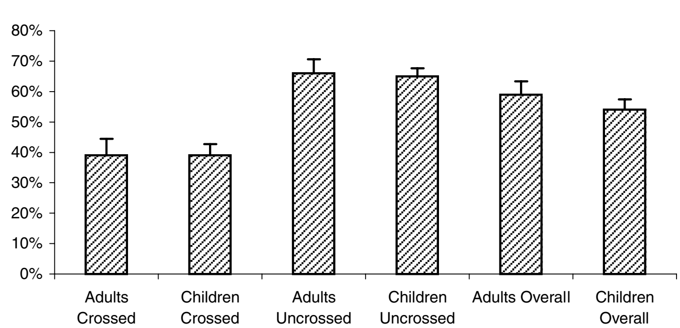

Fig. 1. The likelihood of vergence movements during a fixation being convergent (as opposed to divergent) for crossed and uncrossed fixations in children and adults.

[1] These data differ from those of Liversedge et al. (2006a), who do report systematic changes in the nature of disparities between the two eyes from the beginning to the end of fixation. The difference in findings between the present data and those of Liversedge et al. (2006a) are likely due to the procedure by which we manually identified saccades. In the present data, saccade selection was consistently more conservative than was the case in the Liversedge et al. study. That is to say, that the start point and end point of a fixation were marked as occurring later and earlier with respect to the end of the preceding saccade, and the start of the subsequent saccade respectively for any single fixation. We undertook this selection procedure to be especially careful about avoiding contamination of fixations by dynamic overshoots. In line with this explanation, the mean fixation duration for adults in this paper is 240 ms, compared to 287 ms reported in Liversedge et al. (2006a). The overall effect of this categorisation procedure would be to reduce the amount of vergence movement that could occur during a fixation.

vergence movements, they are more likely to be converging than diverging in both participant groups.

In summary, both the children's and the adults' data show that the eyes are more likely to move during a fixation than not, that this movement is more likely to be vergence than drift, and that convergence is more likely than divergence. The only difference we obtained between children and adults in movements during a fixation was that adults made a higher proportion of convergent movements and fewer divergent movements than did children.

3.6. Effects of word frequency

Recall that we included a critical word in our sentences that was either high or low frequency. This word was included in order to determine whether linguistic processing difficulty modulated any binocular disparity effects that we observed during reading.

First fixations on the critical target word of less than 80 ms or more than 1200 ms were deleted (16% of data). Of these, 7% were made by children and 9% were made by adults. A further 5% of fixations were excluded from the analysis due to an absolute disparity at the end of fixation more than 2 standard deviations from the mean for any given participant (2% were made by children, 3% of these fixations were made by adults).

To examine whether the frequency manipulation did induce processing difficulty as we anticipated, we computed the first fixation duration (the duration of the first fixation on the word, regardless of whether it was or was not refixated), and gaze duration (the sum of all fixations on the word prior to a fixation on another word). Consistent with a great deal of prior research on the frequency effect (Rayner, 1998), there was a significant and reliable effect of word frequency on first fixation durations for adults ($t_1(11) = 3.52$, $p < 0.01$; $t_2(39) = 2.22$, $p = 0.03$) where the mean fixation duration on high frequency words was 251 ms compared to 280 ms on low frequency words. Further, a similar effect was found in the gaze duration data where gaze durations were 280 ms on high frequency words compared to 334 ms on low frequency words ($t_1(11) = 3.98$, $p < 0.01$; $t_2(39) = 5.11$, $p < 0.001$) for the adult participants. However, no reliable frequency effects occurred for the children. There was no hint of a frequency effect in their first fixation duration data. However, perhaps the best measure for examining frequency effects in children is the gaze duration measure (since they refixate a high proportion of words). Although the mean gaze duration for high frequency words was 412 ms compared to 432 ms for low frequency words, the effect was not significant ($t_s < 1$). Given that there were no reliable frequency effects for the child participants, we were forced to restrict our analysis of whether processing difficulty modulated disparity effects to the data for our adult population alone. Consistent with the findings of Juhasz et al. (2006), we found no evidence of a frequency effect on either disparity magnitude or on the proportions of different fixation alignments for adults (all $F_s < 2$, all $p_s > 0.1$).

4. Discussion

4.1. Summary of main findings

At both the start and at the end of fixation: (1) All participants had, on average, disparities between the positions of the two eyes with magnitudes significantly greater than 1 character space. (2) Children's fixation disparity magnitudes were significantly greater than those of adults. (3) Within the unaligned fixations, all participants were more likely to make uncrossed than crossed fixations. However, children made a significantly higher proportion of crossed fixations than do adults. (4) When the eyes made vergence movements during a fixation, convergence was more likely than divergence for all participants. Adults made a higher proportion of convergence and less divergence than children.

4.2. Binocular coordination during reading

Overall, the patterns found in the adult data are very similar to those found by Liversedge et al. (2006a) and Juhasz et al. (2006) in terms of both the magnitude of disparity, and the proportions of different fixation alignments. Generally, during reading, the positions of the two eyes are more than one character apart, and the eyes are aligned to within one character space on a numerical minority of fixations. Within unaligned fixations, for adults it is relatively uncommon for the positions of the two eyes to be crossed. However, on around 40% of fixations, adults' eyes are uncrossed by more than one character space. These data show that the visual system can, under normal circumstances at least, tolerate a certain amount of disparity between two differing patterns of retinal stimulation during reading. Readers do not normally experience diplopia when they read, and indeed, none of our participants reported this experience. Thus, it appears that despite two disparate retinal signals a unified perceptual representation of the text is achieved.

Furthermore, our data also showed that small movements of the eyes did occur during fixation. Typically, such movements in the present study were non-parallel vergence movements. The pattern emerges, in adults more clearly than in children, that convergence is more likely than divergence. Additionally, the very low proportion of crossed fixations at the start of fixation is consistent with data reported by Collewijn et al. (1988) who showed that adults' eyes typically become uncrossed during a saccade. Therefore, it seems that often, an adult reader's eyes become uncrossed during a saccade, and that this disparity is maintained until fixation offset despite convergence movements during the fixation. The assumption that has existed within the literature on eye movements in reading, that the two eyes fixate the same letter during a fixation, does seem to be incorrect on a substantial proportion of fixations.

While these characteristics of adult binocular coordination in reading are now quite well-established (Liversedge et al., 2006a; Liversedge et al., 2006b; Juhasz et al., 2006), our understanding of children's binocular coordination in reading is less well-developed. While Fioravanti et al. (1995) and Yang and Kapoula (2003) have examined children's saccadic binocular coordination during eye orienting tasks, previous research had not examined whether or not the disparity that is known to occur during saccades also existed during fixations during reading.

4.3. Differences between adults' and children's binocular coordination during reading

As predicted, children were found to show significantly greater disparity magnitudes than adults, both at the start and at the end of fixation. Clearly, in addition to children's eyes becoming more disparate than adults' during saccades (Fioravanti et al., 1995; Yang & Kapoula, 2003), this increased disparity in children persists throughout the fixation, that is to say, it is not entirely corrected as the reader extracts visual information from the text. As with adult readers, children do not normally experience diplopia as they read. Indeed, none of our child participants reported having any difficulties at all with reading from the screen. In addition, our comprehension data indicate that our child participants' understanding of the text was good and the eye movement data indicate that they were reading and comprehending the sentences normally. It seems reasonable, therefore, to conclude that the visual system somehow copes with the retinal disparities produced by unaligned fixations in order to construct a unified visual percept. Thus, when children read they appear to tolerate an average disparity equating to at least 1.5 character space differential between the two retinal signals. We will return to the possible mechanisms by which perceptual unification is achieved later.

The second hypothesis concerning differences between children and adults was based on the data from Fioravanti et al. (1995), who showed that children's eyes were more likely to become crossed during a saccade than were those of adults. We therefore anticipated that children would exhibit a greater proportion of crossed than uncrossed fixations, the opposite pattern to that observed in adults. Our data did not fully support this hypothesis. While children did show a significantly higher proportion of crossed fixations than adults, the proportion of crossed fixations was still smaller relative to the proportion of uncrossed fixations that we observed.

A likely explanation for the difference in the predicted and observed proportion of crossed fixations is the relatively broad age range of the children that we tested in the present study. Our children were aged between 7 and 11 years, and the mean age of the child participants was 9 years and 11 months. In contrast, Fioravanti et al. (1995) tested a group of younger children (aged 5–9 years) and a group of older children (aged 11–13 years). They found that while younger children's eyes became crossed during saccades, older children's data was more similar to that of the adults, with the eyes more frequently becoming uncrossed during saccades. Thus, these data are actually suggestive of a developmental difference in the frequency of crossed fixation disparity. To explore this possibility in more detail, we examined the proportion of unaligned fixations which were crossed in relation to each participant's age. Consistent with this possibility, we found that for our three youngest participants (aged 7, 8, and 9 years) crossed fixations occurred on 42.7% of fixations. However, for the remainder of the children (aged 10 or 11 years) crossed fixations occurred on 35.9% of fixations. Thus, our data are at least suggestive of a developmental trend such that the proportion of crossed fixations children make during reading is reduced with age. Recall also that although Fioravanti et al. showed a reversal of the direction of disconjugacy in children compared to adults during saccades, the present data extend these findings illustrating that these characteristics not only occur during a saccade, but also persist throughout subsequent fixation.

The current findings and those of Fioravanti et al. (1995) raise the question of why the proportion of crossed disconjugate saccades and the proportion of crossed fixations change with age. Fioravanti et al. argued that this particular pattern is perhaps a consequence of inaccurate neural control of the musculature required for binocular saccadic movements. An alternative explanation is that the bias for crossed over uncrossed fixations in younger children exists as a consequence of a different muscular balance. Such an imbalance may arise due to younger children performing the majority of their visual work at distances closer to them than older children and adults. Previous research has demonstrated that the oculomotor system does adapt as a consequence of distance, such that the lateral phoria can be altered by depth cues in the environment (Ebenholtz & Fisher, 1982; Ebenholtz, 1986). Consequently, it is possible that the eyes of younger children will be converged to a greater degree than those of older children and adults. Thus, when adults and younger and older children view stimuli at the same viewing distance (as was the case in both the Fioravanti et al.'s study, and our study), then we might anticipate a greater proportion of crossed fixations and saccades in younger children compared to older children and adults.

Regardless of the particular explanation for the effects, we can also form one other important conclusion on the basis of the current data and those of Fioravanti et al. (1995). The present data were obtained in a reading task, whereas the data from Fioravanti et al. were obtained in a non-reading saccadic orienting task in which LEDs were saccade targets. Given that the data from both studies are very similar, this suggests that differences between the adult and child participants are not a consequence of developmental differences in the nature of higher-level cognitive processes associated specifically with reading. Rather, it seems likely that differences in binocular coordination that exist across ages are due to some low-level visual/ocular immaturity in children compared to adults.

The final aspect of our data in which we find differences between children and adults is in the movement that occurs during fixations. Across all participants, convergence during fixation was more common than divergence. Considering adult data alone, then given that the most common disparity was for the eyes to be uncrossed, then assuming vergence to be corrective, we might expect vergence movements to be convergent. This was the case, both here and in previous data (e.g., Liversedge et al., 2006a).

By contrast, the proportion of fixations that were crossed in our child participants was far larger than was the case for adults. Consequently, while we still observe a tendency for a prevalence of convergent vergence movements, this is reduced relative to that observed in adults. Presumably, this in turn may be related to children's increased likelihood of making crossed fixations, consistent with which divergence would be the necessary corrective movement. Numerical differences in the data (see Fig. 1), support this argument. From Fig. 1 it is clear that vergence movements during a fixation tend to be in a corrective direction relative to the disparity which occurs during that fixation. Given that children make a higher proportion of crossed fixations than adults, this accounts for why they make an overall higher proportion of divergent movements than adults during fixations.

4.4. The mechanism underlying the formation of a unified perceptual representation?

Clearly, there now exists a substantial amount of data that demonstrates that both children's and adults' eyes are disparate on a substantial proportion of fixations during reading. Also, it is clear that neither children nor adults experience diplopia when they read. Consequently, there must be some psychological mechanism by which two disparate patterns of retinal stimulation are unified into a single perceptual representation (both during reading, and presumably, more generally during other visual tasks). In our view, there are two possible mechanisms by which such a unified visual representation may be achieved: suppression or fusion. According to the suppression hypothesis, the visual information received by one of the two eyes is suppressed and the visual system delivers a single signal on the basis of one of the two disparate patterns of retinal stimulation. In contrast, the fusion hypothesis posits that a single representation is constructed through the fusion of the two disparate retinal signals. The present data do not permit us to discriminate between these two theoretical possibilities. However, a recent experiment by Liversedge et al. (2006b) is at least suggestive that the latter account is the more plausible explanation. Liversedge et al. (2006b) presented sentences within which a target compound noun was presented dichoptically. Their results showed that there was no difference in landing positions on the target words, regardless of whether they were presented under dichoptic or control conditions, providing evidence in favour of the fusion hypothesis. Thus, on the basis of those data it seems reasonable to conclude that the psychological mechanism underlying the perception of a single unified visual representation during reading is one of fusion, not suppression. The data from Liversedge et al. (2006b) are particularly striking in relation to the data reported here in that the present data show increased disparity for children compared to adults. Thus, the question of how the visual system handles disparate retinal signals is not only of significance to adults, but also to children, and future research is required to address this.

4.5. Effects of processing difficulty on binocular coordination

Despite a reliable effect of word frequency on first fixation duration in our adult data, the effect of frequency did not modulate either fixation disparity magnitude or alignment proportions. In this respect our data are consistent with the data reported by Juhasz et al. (2006), who also showed that processing difficulty does not affect binocular coordination during reading, and inconsistent with data reported by Heller and Radach (1999).

We did not obtain a reliable frequency effect in the first fixation or gaze duration data for children. Previous research has found that children do show an effect of word frequency on their first fixation durations and gaze durations (Hyönä & Olson, 1995). There may be several reasons why the present data do not show this effect. First, it may simply be a lack of power in the current data set. Although the overall analyses were based on data from every valid fixation made, the word frequency analyses were based only on fixations made on one target word per sentence, and therefore, there was necessarily a reduced data set. Also, several of the children did not complete the entire experiment due to the tiring and time-consuming nature of taking binocular recordings. Consequently, the children's data set was smaller overall than the adults' data set despite containing data from the same number of participants, again offering an explanation for the failure to obtain reliable frequency effects for the child participants.

Another possible explanation concerns our particular manipulation of word frequency. Word frequency is commonly confounded with age of acquisition (Juhasz & Rayner, 2003, 2006). Here, we were very careful to control the age-of-acquisition metrics associated with our target words in order to ensure that the children would be entirely familiar with them. A consequence of such control was that the range of word frequencies that we used was constrained by our control of age-of-acquisition and therefore our frequency manipulation may not have been as strong as possible.

4.6. Summary

In summary, the data reported here clearly show the basic differences between children's and adults' binocular coordination during normal reading. All readers have disparity between the positions of their two eyes as they read, and this disparity is greater in magnitude for children than adults. In addition to this, children make a higher proportion of crossed fixations than adults, both at the start and at the end of fixation. Comparison with previous research suggests that these differences are driven by a low-level immaturity in children's oculomotor control rather than being due to differences in high-level cognitive function associated with reading development.

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