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FACULTY OF MEDICINE, HEALTH AND LIFE SCIENCES

School of Psychology

Children's Development of Oculomotor Control during Reading

by

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ABSTRACT

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Data are presented from five experiments examining the characteristics of children's and adults' eye movement behaviour during reading. In Experiments One and Two, participants' eye movements were measured when reading text where every word disappeared at a certain moment after fixation onset. In Experiment One, the words disappeared 60 ms after fixation onset. For children, there were differences in their eye movement behaviour across the two conditions, while adults were able to read the disappearing text normally. In Experiment Two, the presentation duration was manipulated. The differences between adults and children across the conditions suggested that age-related changes when reading disappearing text were not a consequence of a developmental change in the speed of visual processing. Rather, the differences were related to the reader's cognitive processing of the text.

In Experiment Three, children's and adults' eye movements were measured as they read text in which the word to the right of fixation disappeared 60 ms after onset of fixation on word N. Children's reading was more disrupted by the manipulation than adults', and this was attributed to a developmental change in the timing of the initiation of parafoveal pre-processing.

Experiment Four measured children's and adults' binocular coordination during reading. Children showed a greater magnitude of disparity between the two eyes than adults, and also made a higher proportion of crossed fixations than adults. It was argued that developmental changes in binocular coordination were due to either neural or muscular maturation.

In Experiment Five, children's and adults' binocular eye movements were recorded as they read single words that did or did not contain a single-letter misspelling, and made a decision as to whether they were correctly spelled. The words were presented dichoptically, so the word presented to one eye could be varied in its horizontal position on the screen relative to that presented to the other eye. The results showed that children, as well as adults, achieved a single percept through a mechanism of fusion rather than suppression. While the range of disparities that could be fused was greater than that which typically occurs with normal binocular coordination, the limits of Panum's fusional area for linguistic stimuli are suggested to lie between 0.37° and 0.74°. There was no evidence to support the hypothesis of a developmental change in the size of Panum's fusional area.

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Chapter One

Introduction to children's monocular eye movement control

There has been relatively little research carried out to examine the development of oculomotor control in children in either reading or non-reading tasks. The following sections of this literature review will discuss the limited work that has been conducted in these areas, and summarise the main findings in order to provide a context for the experimental work reported in the first section of this thesis.

All the studies discussed in this brief review have taken monocular eye movement recordings and compared those of children across varying ages with those of adults. The eye movements themselves show some developmental change, in addition to reflecting the changes in cognitive processing of the stimulus which occur with age. There is a separate, relatively broad literature on eye movements in both reading and non-reading tasks with dyslexic participants. Although in many cases the participants in these studies are children, as they are a special population, the literature covering this research is beyond the scope of this thesis. However, there are some studies included in this literature review which have included both typically developing and dyslexic children, and for these studies the data from the typically developing children will be discussed.

1.1 Basic characteristics of eye movements in reading

When reading, the eyes make a highly characteristic pattern of movements as the reader progresses through a sentence. Extremely fast movements from one location in the text to another, saccades, are interspersed with periods where the eyes are relatively still upon a given word – fixations. For an adult reader, fixations typically have durations in the range of 200-250 ms (Rayner, 1998).

It is during these fixations that visual information is extracted from the page in order to allow perceptual and cognitive processing of the stimulus, this being, in reading, the printed text. Saccades serve the purpose of moving the eyes so that new information falls onto the fovea – the area of the retina with high acuity – and typically have amplitudes of seven to nine character spaces in adult readers (Rayner, 1998). Saccades in reading can either move the eyes onto a new word in the sentence, or they can move the eyes backwards through the sentence onto a previously fixated word (a regression), or they can make a small, within-word movement (a refixation). Not all words are fixated when reading a sentence; some words are skipped, and the frequency of word skipping can be determined by both visual characteristics (e.g. word length) and linguistic characteristics (e.g. word frequency) (for reviews, see Drieghe, Rayner & Pollatsek, 2005; Rayner, 1998; Rayner & Pollatsek, 1989).

From this characteristic pattern of eye movements, several standard measures of oculomotor behaviour during sentence reading can be calculated as an index of the reader's visual and cognitive processing associated with the comprehension of the text. A brief explanation of these measures will now be given, as they will be the dependent variables for the experimental work reported in this thesis.

There are multiple measures of the time taken to recognise and process a word within the context of a sentence. Single fixation duration is the duration of the fixation where only one fixation was made on it as the reader progressed through the sentence. The first fixation duration is the duration of the initial fixation on a word, irrespective of whether or not that word was refixated. Any effects that are observed for either single fixation durations or first fixation durations are generally taken to reflect very early visual and linguistic processing. For example, effects of word frequency are typically seen on these measures (e.g. Henderson & Ferreira, 1990).

The gaze duration for a word is the sum of all fixations on that word until the point where the eyes leave the word. If an effect is observed in gaze durations that has not affected single or first fixation durations, then this is taken to reflect a slightly later stage of processing associated with refixations on a word before leaving it. The sum of all fixations on made on a word in a sentence is the total reading time. Effects which are seen in total reading times, but not upon the earlier measures, are typically assumed to be due to higher order cognitive processing such as semantic or syntactic processing.

In addition to the durations of fixations, there are three further measures that will be used which also reflect the reader's processing of the word. These measures are refixation frequencies, regression frequencies, and word skipping probabilities.

Refixations are the instances in which the reader makes additional fixations on the same word following the first fixation, before the eyes leave the word and are reported as probabilities. Refixations within a word are also reflected temporally in the measure of gaze duration, where differences between first fixation duration and gaze duration show that the word has been refixated. Regression frequencies are the number of leftward eye movements that are made during the reading of a sentence, i.e. the number of times that a reader goes back to re-inspect earlier parts of the sentence. Word skipping probability is the probability that the reader will not directly fixate the word during first pass. The more difficult the text, the greater the need for the reader to fixate each word individually.

Many of these measures of eye movement behaviour during reading can be considered in relation to each other in terms of both the temporal and spatial contiguity of the summed fixations on which each measure is based. Temporal contiguity refers to the serial order of fixations as the reader moves their eyes through the sentence, typically with respect to a particular word or region of interest; thus, in the case of two sequential fixations, those two fixations can be referred to as being temporally contiguous. For example, effects in the measure of gaze duration may be driven by the occurrence of two, temporally contiguous fixations. Spatial contiguity refers to the spatial proximity of fixations in relation to each other, such that two fixations which land on the same word or region of interest may be referred to as spatially contiguous. For example, effects in the measure of total word reading times may be driven by a combination of first pass fixations and fixations after regressions which were all on the same critical word. All eye movement measures which are computed by the summing of multiple fixations on a particular region of interest may be affected by either the temporal or spatial contiguity of the fixations, or both of those characteristics. The particular measures of eye movement behaviour on which an effect is observed can therefore be informative not only with respect to the occurrence and the size of the effect, but also to some degree the mechanism underlying that effect by considering whether that measure is based on fixations which are temporally or spatially contiguous, or both.

All the discussed measures will be reported in order to draw a comparison between the speed and fluency of adults' and children's reading.

1.2 Children's oculomotor control on non-reading tasks

The research which has examined children's oculomotor control on non-reading tasks has documented developmental trajectories in some parameters but not others – some aspects of basic oculomotor control are skills that, in themselves, improve with age. A complete summary and discussion of this literature is beyond the scope of this review; however, some key studies will be described covering a range of oculomotor parameters that do or do not change with age. Briefly, a body of research has shown that latencies of both visually-guided and voluntary saccades (Cohen & Ross, 1978; Groll & Ross, 1982), and fixation stability (Kowler & Martin, 1982) change with age. Specifically, saccadic latencies decrease with age, whether to a visible target or in an anti-saccade task, where the participant is required to make an eye movement in the opposite direction to the stimulus that appears.

This has been observed in both single-step and double-step paradigms (a single target, or two sequential targets, respectively), and it is argued that although there are developmental changes in saccadic latency, these changes suggest quantitative change in saccade programming as opposed to more qualitative differences in processing capacity between adults and children (i.e. that children have reduced processing resources compared to adults, as opposed to them having different strategies in saccadic programming). In addition to age-related decreases in saccadic latencies, fixation stability also improves with age - although adults are known to make small saccades during long fixations in order to avoid retinal adaptation (microsaccades; see Engbert & Kliegl, 2004), the amplitude of these microsaccades is much larger in children.

While saccadic latencies and fixation stability are shown to improve with age, other parameters of eye movement control do not show developmental change. Saccadic accuracy, peak saccadic velocity, and saccadic overshoot have all been observed to be the same in children as in adults (Cohen & Ross, 1987; Fukushima, Hatta & Fukushima, 2000; Salman, Sharpe, Eizenman, Lillakas, Westall, To, Dennis & Steinbach, 2006).

From this research it is clear that a very basic aspect of eye movement behaviour, saccade programming as reflected by saccadic latencies, shows a developmental change such that saccadic latencies decrease with age. However other key eye movement parameters, such as saccadic accuracy, peak velocity and overshoot, do not show age-related change. These conclusions have been drawn from research that has used very simple visual stimuli. To make comparisons between eye movement data from this research and that from reading experiments, it must be considered that there are several key differences between the two types of stimuli. Therefore, in comparing the data from reading and non-reading experiments, any conclusions concerning developmental change must be considered carefully as there are several potential causes of developmental change that may be confounded.

First, there are very different cognitive demands associated with the processing of linguistic and non-linguistic stimuli. Any differential patterns of effects between reading and non-reading studies which show age-related changes may reflect the high-level semantic and syntactic processing associated with text comprehension. Specifically, children are less skilled readers than adults and typically require simpler material in order to successfully read and comprehend the text. This issue can be addressed by giving participants age-appropriate materials in order minimise the confound of reading skill, and to allow examination of age-related changes in eye movements. However, despite this, it is still possible that developmental differences in eye movement data from reading tasks may reflect the children's increased difficulty in text processing and comprehension compared to skilled adult readers.

Second, differences in the patterns of results between non-reading and reading research may still reflect differences in low-level oculomotor control where the different types of stimuli have very different visual characteristics. For example, text is visually more complex than individual dots or lines. The non-reading studies discussed here all used very simple stimuli with minimal oculomotor demands, i.e. Light Emitting Diodes (LEDs) with basic saccadic orienting tasks. In order to read successfully, a rapid series of fixations and saccades must be made across a relatively small and detailed stimulus. The timing of these fixations must allow the reader to extract the necessary visual information from the page, and to plan subsequent eye movements. Further, saccades must be planned and executed with high accuracy. Each fixation must bring useful information onto the fovea, minimising duplication of information across fixations, yet allowing subsequent fixations to be integrated meaningfully. The visual requirements of moving the eyes fluently and accurately through a sentence are, therefore, vastly more complex than simply making a saccade to a single visual target. The visual complexity of the stimuli, and the demands upon the oculomotor system to efficiently extract information from that complex stimulus, may well evoke differences between adults and children that are not observed on more simple oculomotor tasks.

The final section of this literature review will focus on children's eye movements when reading. A brief review will be given of research which has examined children's within-word eye movement behaviour in reading.

1.3 Children's within-word oculomotor control

There have been very few studies which have examined children's eye movements in reading. A subset of these studies has looked at eye movement behaviour when reading individual words, or words presented as lists, rather than normal sentences. These tasks will have minimal oculomotor demands in comparison to sentence reading. Given the scarcity of data on children's eye movements during reading, these studies still provide valuable information concerning children's visual processing of linguistic stimuli despite their use of a relatively unnatural reading task. One such study examined the optimal viewing position within words for children (Aghababian & Nazir, 2000). The optimal viewing position (OVP) is the location within a word where, if fixated, word recognition is most accurate (O'Regan & Lévy-Schoen, 1987). For adults, the OVP is just to the left of the centre of a word. This study examined the OVP in children.

It should be noted that eye movements were not recorded as part of the Aghababian and Nazir study. Children were presented with fixation dots for one second, and then a word was presented for a given duration at a manipulated horizontal offset relative to the fixation dots. The authors argued that in this way they were able to control the children's fixation positions on the words. Further, by briefly presenting words, the authors aimed to restrict the reader to a single fixation per word. They manipulated the presentation duration of the words in relation to each child's response accuracy in order to determine the minimum presentation duration for each individual at which a stable baseline performance level was achieved. They showed that as age increased, shorter presentation durations were required to establish the baseline performance level (approximately 60%) of word recognition. These presentation durations were, by a matter of hundreds of milliseconds (ms), shorter than the mean fixation durations for children of those ages reported by McConkie, Zola, Grimes, Kerr, Bryant & Wolff (1991; see discussion in section 1.4). They found that children aged 6- to 7-years required presentation durations of, on average, 125 ms. As age increased the presentation duration necessary for the baseline level of word recognition accuracy decreased, so that children aged 10- to 11-years required, on average, 60 ms presentation durations (note that these values were estimated from a graph). However, in this task the presentation durations reflect the time necessary for a task which has much lower cognitive demands than sentence reading. There is no requirement for higher, sentence-level processing, nor for saccade programming.

They demonstrated that, in this single-word recognition task, the OVP effect was manifest by the age of 6-years (first grade). However, given that they did not record eye movements, it is entirely possible that children moved their eyes away from the location of the fixation dots throughout the trial, or that they did not follow the instructions and fixate the dots at all on certain trials.

The occurrence of the OVP effect in young children's reading was argued to show that word recognition strategies are the same in adults and children. Previous work was reported to assume that the development of word recognition passes through several, qualitatively different stages. For example, children begin by visually recognising words in a relatively idiosyncratic manner, gradually progressing to a left-to-right, letter-by-letter strategy where grapheme-phoneme correspondences are being learned.

Children begin by recognising only the visual appearance of words and later learn letter-sound correspondence; finally, familiar clusters of letters such as morphemes are recognised, speeding up word recognition from the prior letter-by-letter strategy. If this were the case, very different patterns of preferred viewing positions would be observed in children, reflecting either their idiosyncratic visual recognition of the entire word form, or their left-to-right, letter-by-letter strategy. However, the lack of differences between skilled adult readers and children in their preferred viewing positions in this data set is strong evidence for their having the same word recognition strategy. Aghababian and Nazir went on to examine the number of letters correctly reported from different locations within the word, thereby including those trials where the child was unable to identify the entire word. Again, there were no developmental trends observed in the location of correctly recognised letters, further supporting the view that that there is no categorical shift in reading strategy with age.

The viewing position effect was mediated by word length in children aged 6- to 11-years, an effect which does not typically occur in skilled adult readers. In the children's data, word recognition accuracy was much poorer with non-central fixations on long words compared to short words. It was suggested that this effect is linked to the shorter perceptual span in younger, less skilled readers (see discussion in section 1.4). Given that younger readers are able to extract information from a smaller area around the point of fixation than are skilled readers (Rayner, 1986), it is likely that fixations on the ends of longer words will leave younger readers unable to access information from the more distant letters in the word. Therefore, it becomes more crucial for younger readers to fixate close to the centre of long words, so maximising the number of letters within the fixated word from which useful information can be extracted. In contrast the larger perceptual span in adult readers eliminates this difficulty with non-central fixations on long words, by allowing them to extract information from the more distant letters.

In addition to this word length effect in children, the overall level of word recognition accuracy changed with word frequency/familiarity for all participants, showing that word recognition was better for more frequent words than less frequent words. Thus, a word frequency effect occurs in lexical processing by at least 7-years of age (they were unable to examine this effect in 6-year-old children, as these children were not familiar with a sufficiently wide range of words from the selected database to examine familiarity effects). Further, the frequency effect did not interact with the reader's age. This study, therefore, provides some insight into children's visual processing of linguistic stimuli, and the influence of some characteristics of that text upon children's visual processing. Although this study effectively eliminated eye movements, by use of very brief presentations which restricted participants to a single fixation per word, it demonstrated the occurrence in child readers of some highly reliable effects known to occur in skilled adult readers.

The observation of preferred viewing effects in children as young as 6-years-old, alongside the lack of letter-position effects in the letter-identifying task, is strong evidence that children's strategy in word identification is not qualitatively different to that of adults. Further, this study also found effects of word frequency on lexical processing in children by the age of 7-years-old, which Hyönä and Olson (1995) had previously observed in children by the age of 8-years (see later discussion).

While this study investigated aspects of children's visual processing during single-word reading, a different study has directly examined children's eye movement behaviour through recording eye movements on a more natural reading task (Vitu, McConkie & Zola, 1998).

However, once again the focus was not upon the eye movements across the entire sentences. The analysis focussed upon single words within the sentence to which regressions were made, to examine lexical characteristics that affected the probability of making a regression to that word. It should be noted that the children in this study were aged 12-years-old, at which age previous studies have suggested that most sentence-level characteristics of eye movement behaviour are approaching, or have already reached, adult levels (Buswell, 1922; Taylor, 1965; McConkie *et al.*, 1991). The authors argue that while 12-year-old children's eye movements during reading are largely similar to those of adults, the one characteristic in which they differ from adults is the frequency of regressions. Given the authors' interest in regressive eye movements for the present study, the relatively high frequency of regressions in 12-year-old children who are otherwise argued to show adult-like eye movement behaviour is argued to make them an ideal sample. The children's eye movements were monitored as they read passages of text that were age-appropriate.

The results showed that 28% of eye movements within a line of text were regressions, and that the probability of making a regression was linked to the length of the preceding saccade – long saccades were more likely to be followed by a regression than short saccades were. The probability of making a regression was also related to the probability of having skipped a word in the preceding saccade – long saccades were more likely to have skipped a word, and so were more likely to be followed by a regression to that word. Long saccades that did not skip a word were less likely to lead to a regression.

Further, several variables relating to the visual processing of the skipped word also affected regression probabilities. Long words that were skipped were more often fixated with a regression than were short words that were skipped. The authors argued that this was due to the ease with which different words within a sentence could be perceived in high-acuity vision during a given fixation. Due to the drop-off in visual acuity with increasing eccentricity around the point of fixation, shorter words can be more readily identified from fixations on the previous word than can long words. In line with this, the launch site of the saccade which skipped a word also affected regression probabilities – when overall saccade length was controlled, regressions were more likely to be made to words that were skipped from a distant launch site than from a relatively closer launch site. However, the length of the skipping saccade still influenced regression probabilities, independent of the proximity of the launch site to the skipped word.

The authors argued that the position of the eyes both at the beginning and at the end of a word-skipping saccade determines whether or not a regression is made to that word. Critically, the acuity with which that word is perceived in parafoveal vision, as a consequence of the distance between the position of the fixation on the preceding word and the position of the fixation on the critical word, is argued to determine whether that word is identified without a direct fixation.

In addition to the physical limitations of visual acuity drop-off, there are cognitive limitations on the area of useful information around the point of fixations from which a reader can usefully extract information – the perceptual span. By the age of 11-years-old, the perceptual span is thought to be close in size to, if not equal to, that of skilled adult readers (see discussion in section 1.4, Rayner, 1986). Therefore, it seems highly likely that the data from this study can be generalised to adult readers, where the probability of skipping (and subsequently regressing to) a word is shown to be at least partially dependent upon the quality of preview of that word from prior fixations.

In addition to these visual factors, word frequency was also shown to affect regression probabilities. Regressions were made more often to low-frequency words that were skipped than to high-frequency words that were skipped, and it was argued that lexical identification of low-frequency words is less likely to be completed on the preceding fixation than is identification of high-frequency words. Therefore, when skipped, regressions are more often necessary to low- than to high-frequency words.

When considering regressions that do not follow a word having been skipped, it was predicted that the characteristics of the origin word – that from which the initial, progressive saccade was launched – would affect regression probability. However, neither the fixation position on the origin word, the refixation probability on the origin word, nor the frequency of the origin word reliably affected regression probabilities to that origin word. It therefore seems that while the level of processing associated with a word affected the probability of making a regression to that word (in the case of words that are skipped), this was not always the case (in the case of words that were not skipped). While the authors suggested that this is evidence against purely lexical models of regression probabilities, they did not offer an alternative hypothesis. However, it was acknowledged that their analyses did not distinguish between alternative regression destinations – many of the regressions in this data set were within-word regressions and not, for example, regressions back to the origin word.

Further analyses of the same data set alongside additional data from adult readers looked at the effects of fixation location on fixation durations (Vitu, McConkie, Kerr and O'Regan, 2001). In line with Aghababian and Nazir (2000), a highly similar distribution of landing positions on the words occurred for both adults and children with the most frequent landing position being just to the left of the centre of the word. It was shown that refixation probabilities increased for all participants when the first fixation location was further from the centre of the word. However, this effect was stronger in children than in adults, reflecting overall increased refixation probabilities in children while adults made very few refixations, particularly for shorter words.

The data showed, counter-intuitively, that both single fixation durations and first fixation durations (in the cases where two fixations were made on a word) were longest when the fixation was in the centre of the word. Further, there was a fixation duration trade-off effect in all participants, where first fixations were longest and second fixations were shortest when the first fixation was located toward the centre of the word. Conversely, the further away from the word centre that first fixations were, the shorter first fixations tended to and the longer second fixations tended to be. The optimal viewing position (OVP), where words are most likely to be correctly identified and have been previously shown to be most quickly identified (albeit in non-natural reading tasks), is the centre of the word. Therefore, the authors argued that one might assume that fixation durations would be shortest here, reflecting the relative ease of processing that should occur if the centre of the word is fixated.

Explanations of this effect on single, first, and second fixation durations by both oculomotor and cognitive control models of eye movements in reading are discussed and rejected by Vitu *et al.* However, critically, for the purpose of this review, no differences were observed between children and adults. The results showed that the same patterns of within-word eye movement behaviour occurred for both adults and 12-year-old children, in relation to fixation durations and refixation probabilities as functions of the first fixation position on a word.

1.4 Children's oculomotor control in sentence reading

Section 1.2 discussed how, on very simple tasks with minimal cognitive demands, some aspects of oculomotor control develop with age. However, in addition to these relatively low-level effects, there can also be changes in eye movements which reflect developmental trends in the underlying cognitive processes which are driving those eye movements.

A small number of studies have examined children's eye movement behaviour when reading sentences. By and large, their findings follow a similar pattern. The data tend to show that when reading, children make more, longer fixations, more regressions, and shorter saccades than do adults. Some studies have matched the reading material difficulty to the readers' ages, while others have not. The observation of highly similar trends in results for both types of stimuli suggests that the differences in eye movement behaviour between adults and children do not purely reflect increased reading difficulty in children. Control of eye movements when proceeding through a sentence in itself must also improve with age, as children's eye movements when reading are still less fluent than those of adults even when reading material that is not linguistically difficult for them.

One of the earliest studies to examine children's eye movements in reading, Buswell (1922) monitored the eye movements of a large sample of students across all grades (ages 6- to 18-years-old) and also a group of adults in college, deliberately excluding particularly good or poor readers. He used the same stimuli for all readers (except the 6-year-olds, who read very simple passages), with the aim of excluding the material as a confounding source of variance. However, this meant that the stimuli were not generally matched to the readers in terms of difficulty. The stimuli were short stories, presented as passages of text, which the participants read both silently and aloud; only data from the former condition are discussed here, as reading aloud may well induce different patterns of eye movements than the more normal silent reading does. He measured the number of fixations per line of text, the mean fixation duration, and the number of regressive movements per line of text to assess the fluency of the readers' eye movements. It was found overall that 9- to 10-years-old was the age at which the developmental changes in most of these parameters reached their asymptote, i.e. adult levels. After this age, minimal changes were observed.

For the mean number of fixations, Buswell found an overall decrease in their frequency per line of text as age increased. As age and reading skill increased, fewer fixations were made. This change with age was most rapid between the ages of 6- and 10-years, but continued to decrease across the range of ages tested (i.e. up to adult readers). Similarly, the mean fixation duration decreased overall with age, with the change occurring most rapidly up to the age of 10-years. Older, more skilled readers made fewer, shorter fixations than beginner readers. The number of regressions per line also decreased with age; again, the change was most marked between the ages of 6- and 10-years but continued to change across the range of ages tested. However, as a consequence of using the same materials for all ages, it is unclear whether these changes in oculomotor control were developmental changes in their own right, or simply a consequence of the increased difficulty experienced by less skilled readers.

Buswell went on to consider the influence of reading comprehension on these eye movement parameters, in a subgroup of participants aged 8- to 12-years-old. The mean number of fixations per line was shown to decrease as comprehension increased. Further, the mean duration of fixations also decreased as comprehension increased. Readers made fewer, briefer fixations as their reading comprehension improved. Finally, the number of regressions made during reading also decreased as reading comprehension increased. Buswell summarised that the eye movement parameters of number of fixations per line, durations of fixations, and number of regressive movements all decreased across both the age of the reader, and as reading comprehension improved. This suggested that it is the difficulty in cognitive processing of text which caused the changes in eye movement behaviour seen across age groups. The time period in which the most rapid improvement within these parameters occurred was during the first four grades – approximately between the ages of 6- and 10-years-old. This pattern of results fits well with those of McConkie *et al.* (1991), and of Taylor (1965), which will also be discussed.

In another study that examined developmental trends in eye movements during reading, Taylor (1965) described the results from a large study which recorded the eye movements of 12,143 participants from 6-years-old to college students (Taylor, Frackenphol & Pettee, 1960). Using photographic recordings, it was observed that, as age increased, the mean number of fixations, number of regressions, and fixation durations decreased, while the mean recognition span and reading rate increased. These data therefore clearly showed the development of basic oculomotor control during reading with age, but differences in these parameters cannot be considered in relation to reading ability, as the difficulty and age-appropriateness of the text given to readers was not reported.

One study has examined the changes in eye movement patterns during reading that occurred between two testing sessions, one year apart, in children of different ages in comparison to adults (Lefton, Nagle, Johnson & Fisher, 1979). Children of normal reading ability aged 8- and 10-years were compared with adults and poor readers aged 11-years as they read paragraphs of text and had their eye movements monitored. The paragraphs were matched to the reader's age in difficulty. The focus here will be upon the age-related changes observed, rather than the comparison between good and poor readers which the authors discuss in the context of reading disorders. The results showed that for the durations of forward and regressive fixations, and for the numbers of forward and regressive fixations, there were significant decreases with age. While this overall effect is consistent with the data from Buswell (1922) and Taylor (1965), no t-tests are reported to determine where between the three groups these significant differences lie.

Given that the participants were tested on two sessions, one year apart, further changes on these measures can be examined with relation to age, although it should be noted that the same materials were used on both occasions and so any effects here may be confounded by participants' familiarity with the stimuli. Here, changes are between the ages of 8- and 9-years, and 10- and 11-years for the two children's groups (the mean age of adult participants is not reported). A main effect of testing session, reflecting these changes in age, was found for the number of forward fixations only. No change between these ages was found for the durations of forward or regressive fixations, or the frequency of regressions.

Finally, Lefton *et al.* reported that significant interactions were found between the age group and the testing session for durations of forward and regressive fixations, and the number of regressive fixations. No t-tests are reported to explore these interactions; however, the authors report some observations for the durations of forward fixations, based on descriptive data. They report that adults' forward fixation durations decrease across the two testing sessions, but that over this year both 8- and 10-year-olds' forward fixation durations increase. This seems contrary to what might be expected, where adults might not show any change in eye movement fluency across a year given that they were already skilled readers at the first testing session, but that children between the ages of 8- and 10-years-old might show strong improvements over the course of a year during which they had presumably received normal reading instruction.

However, no description or explanation is offered for the significant interactions observed on the number of forward fixations or the durations of regressive fixations. From the descriptive data, it can be seen that all participants showed a decrease across testing sessions in the number of forward fixations that they made, but that the magnitude of this decrease reduced with age. This is consistent with the idea that younger children might make the strongest improvement in reading skill throughout the course of a year, with adults showing a minimal change. Finally, the descriptive data for the durations of regressive fixations showed that while adults' durations decreased across testing sessions, both groups of children's durations increased. As with the forward fixation durations, this pattern of results is contradictory to that which might be expected based on changes in reading skill with age.

A final set of results is reported which compares the variability in eye movement measures across the age groups. Lefton *et al.* found that, for both the number of forward fixations and the number of regressions, there was a significant effect of participant group where the amount of variability decreased with age. Again, no t-tests are reported to explore this main effect across the three groups. A significant decrease in variability from one testing session to the next was observed for the number of forward fixations, with a significant interaction between participant group and testing session. Although no t-tests were conducted, the descriptive data are reported to find that 8-year-old children showed the greatest decrease in variability across testing sessions.

The patterns in these data are unclear, and for main effects across three participant groups and interactions no t-tests are reported to investigate the effects fully. In places, the data seem to pattern in an unexpected direction to those which might be predicted by the usual improvements in reading skill with age. However, the use of the same stimuli across both testing sessions may have created a confound in the data. Overall, however, despite the limitations of this study, it does seem reasonable to safely conclude that forward and regressive fixations decrease in both duration and frequency with age.

A more recent study by McConkie *et al.* has examined children's eye movement control in reading, and presented new data alongside a review of previous work in this area (McConkie *et al.*, 1991). The findings across the studies were quite consistent. It was reported that as age and reading ability increased, the mean fixation duration decreased. While Buswell (1922) and Taylor *et al.* (1960) were reported to have found that the number of fixations decreased with reading skill, McConkie *et al.* (1991) found this to be relatively constant across ages. This difference in findings was attributed to the difficulty of stimuli. McConkie *et al.* argued that when reading material was matched to the reader's age, there was no developmental decrease in the number of fixations.

The authors also reported that all three studies showed no developmental effect on the number of regressions made (children 6- to 11-years-old) but that all ages within this range showed a higher frequency of regressions than adults. However, although their own data showed no developmental change in the frequency of regressions, the data from Buswell (1922) and from Taylor (1960) can be considered to show an effect of age. The raw data from Buswell showed a decrease from four regressions per line of text in 6- to 7-year-olds to 1.3 regressions per line of text in 10- to 11-year-olds. The raw data from Taylor showed a decrease from 52 regressions per 100 words in 6- to 7-year-olds to 28 regressions per 100 words in 10- to 11-year-olds. When these data were converted into the percentage of regressions per line of text, in order to make them comparable across studies, the data still showed a gradual decrease in the number of regressions between the ages of 6- to 7-years and 10- to 11-years, from 26% to 19% (Buswell, 1922), and from 23% to 21% (Taylor, 1960). Although the effect appears small, with the lack of statistical analyses it seems premature to conclude that there is a constant number of regressions in reading across ages, as the descriptive data suggest otherwise.

They also reported that, in their data, saccade length increased with age, although if this were the case, one might have anticipated a corresponding decrease in the number of fixations reported. This was not the case, as previously discussed. It was suggested that the equipment used may have underestimated the number of refixations (and subsequently overestimated fixation durations) by failing to detect small saccades. Further data from McConkie *et al.* (1991) indicated that younger children made a higher proportion of short saccades than older children or adults, as well as having showed a higher proportion of refixations. In summary, the data reported in this chapter indicated that as reading skill increased with age, first fixation durations decreased, fewer fixations were made, saccade lengths increased, and the proportion of refixations decreased. The frequency of regressions showed a weaker developmental trend; however, children still seemed to have made more regressions than adults.

A further set of studies has used children's eye movements when reading as an index of cognitive processing difficulty, where psycholinguistic manipulations within the text and their influence on eye movement were the focus of the research, as opposed to the eye movement behaviour itself. Hyönä and Olson (1995) examined the eye movements of children aged between 8- and 12-years-old, as they read aloud sentences containing target words which were manipulated for length and frequency. They also included a sample of dyslexic children, but data from these participants will not be discussed here.

The two chosen lexical characteristics - word frequency and word length – both have an impact upon adult readers' eye movement behaviour, that being an on-line index of the reader's moment-to-moment cognitive processes associated with the text. This study examined whether these lexical characteristics have a similar impact upon children's cognitive processing, as indexed by their eye movement behaviour. In this study, an eye movement measure is reported that is additional to those measures defined earlier in section 1.1 – re-inspection frequency. Re-inspections are return fixations that are made on a word, after the eyes have moved away from their initial fixation(s) on that word. This measure includes return fixations from both earlier and later portions of the sentence.

With regard to word length, adult readers typically make more refixations on long than short words, subsequently leading to longer gaze durations on long words than short words. They are also more likely to skip short words than long words. The analyses showed that an effect of word length also occurred in the eye movements of children aged 8- to 12-years-old. The children made more refixations, more first pass fixations, and more re-inspections to long words than to short words. They also had longer gaze durations on long words than short words. As is typical with adult readers, there was no effect of word length upon first fixation durations. These data therefore showed that the word length manipulation had the same effect upon children's eye movement behaviour as is typically seen for adult readers.

For a word frequency manipulation, adult readers typically make longer first fixations on low frequency than on high frequency words, and refixate high frequency words less often than low frequency words. For the children in this study, a significant effect of word frequency was found upon first fixation durations, gaze durations, the number of first pass fixations, and the frequency of re-inspections to the word, such that the children made more, longer fixations on low frequency than high frequency words. Again, this pattern of effects from the word frequency manipulation is the same as that which typically occurs with skilled adult readers.

Finally, interactions between the manipulations of word length and word frequency occurred on all of the measures discussed. First, the effect of word frequency was significant in first fixation durations on short (five to six letter) and long (nine to 11 letter) words, but not in medium length (seven to eight letter) words. The authors did not provide an explanation of this interaction. Second, the effect of word frequency was significant across all word lengths for both the number of first pass fixations and for gaze durations, but the effect was stronger for long words than for short or medium length words. This interaction reflected the children's increased need for multiple fixations upon long words that were difficult to identify, as opposed to shorter or more familiar words. Third, the effect of word length upon the frequency of re-inspections was significant for low frequency words but not for medium or high frequency words. This interaction again demonstrated the children's need for multiple inspections of long words that were difficult to identify, as opposed to shorter or more familiar words.

Overall, the data from this study provide very clear evidence that the two manipulated lexical characteristics – word length and word frequency – have a very similar impact upon children's eye movement behaviour during reading as they do upon the eye movement behaviour of skilled adult readers. The results from this study provide the most comprehensive eye movement data overall for children during reading.

A second line of research concerning children's reading, which has used eye movements as a tool for examining higher-level processing, has examined the size of the perceptual span in children compared to adults. The perceptual span is defined as "the area of effective vision, or the region from which useful information can be obtained during a fixation in reading" (Rayner, 1986). Given that children make more fixations and shorter saccades when they read than adults (Buswell, 1922; Taylor, 1965), it seems likely that the perceptual span is smaller in children than in skilled adult readers. This study used the moving window technique, in which a "window" of unaltered letters is visible to the reader about the point of fixation, and which moves with the reader's eyes as they proceed through the sentence. All letters and spaces outside the window were replaced by Xs, thus also obscuring word boundaries. In this way, the amount of information available to the reader was strictly controlled on a fixation-by-fixation basis. Here, children aged 7-, 9-, 11-years, and adults, read sentences which were presented with window sizes ranging between five and 29 character spaces, as well as a control condition in which the full sentence was available. All participants read the same materials, which were appropriate in difficulty for the youngest participants. The windows were symmetrical around the fixation position.

The results showed significant developmental changes in the window size with which the reading rate reached its maximum. Children aged 7- and 9-years-old reached their maximum reading rate with 11 character spaces' of information available to the right of fixation, while the 11-year-olds and adults reached their maximum rate with 14 character spaces' of information to the right of fixation. It was also observed that, across the age range tested, older readers were relatively more disrupted by small window sizes than were younger readers. This indicates that there is variation in the use of information within the window according to the age of the reader. Younger readers do make some use of information to the right of fixation but are minimally disrupted if this is unavailable and so apparently devote less of their processing capacity to words to the right of fixation than older readers. However, older readers are more disrupted by information within their maximum span being unavailable and this suggests that they make greater use of information to the right of fixation than younger readers do. Therefore, in addition to the size of the perceptual span changing with age, the use of information within the perceptual span also appeared to change with age. Beginning readers made more use of foveal information, while more skilled readers could also devote some of their processing capacity to parafoveal text. This pattern of results was also clearly indicated in the eye movement measures (fixation durations, number of fixations, and saccade lengths).

Subsequent experiments also used the moving window technique, but preserved word boundaries in the masking outside the window, and the window size was determined by the number of words rather than the number of letters. Whether or not words to the left of fixation were available was also varied. The reading rate of 7-year-olds reached its maximum when just one word was available to the right of fixation, while for all other age groups the maximum rate was reached when two words were available to the right of fixation. On average, defining the window in terms of words rather than characters meant that there were 7.2 fewer characters available when maximum reading rate was reached. This suggested that readers made use of word boundary information further to the right of fixation than they could process useful letter-level information. All readers' maximum rate was disrupted by the presence of a boundary to the left of fixation. Again, these effects were observed in the eye movement measures as well as the maximum reading rate. A final experiment looked at reading of material that was matched in difficulty to the readers' ages. Overall the size of the perceptual span, as measured by the smallest window size with which the maximum reading rate was reached, was smaller when reading more difficult texts. This is a clear demonstration that the level of processing difficulty for the fixated text reduces the amount of information which we can extract from text to the right of fixation (see also Henderson & Ferreira, 1990; White, Rayner & Liversedge, 2005). It was observed that, when reading age-matched text, the eye movement patterns of 9-year-olds became much more like those of 7-year-olds. The results show very clearly that eye movements reflect the processing difficulty experienced by the reader.

Other experimental work examining the perceptual span during reading in children has looked at cross-linguistic differences (Häikiö, Bertram, Hyönä & Niemi, under submission). Specifically, they looked at the letter-span – a sub-component of the perceptual span which shows the spatial range over which letter identity information (as opposed to letter feature information, word identity information, etc.) is available during a given fixation in reading. This work was carried out with Finnish children, and aimed to compare the letter-identity span in Finnish children compared to English children. Finnish words are, on average, longer than English words. The authors suggest, therefore, that Finnish readers might have a larger perceptual span than English readers due to their increased dependence on parafoveal information to recognise words during fixations. They monitored the eye movements of adults and children aged 8- to 12-years-old as they read passages that were presented using the moving window technique. The four different (symmetrical) window sizes were seven, 11, 15 and 19 character spaces, and letters outside this window were replaced with visually-similar letters so that letter feature, but not identity information was preserved.

They found significant interactions between the reader's age and the text window size on the number of words read per minute, on the length of progressive saccades, on gaze durations, on the number of fixations made, on total fixation time, and on word skipping probability, but not on the probability of making a regression. Overall, 8-year-olds' letter identity span was found to extend five to seven character spaces to the right of fixation, 10-year-olds' extended seven character spaces to the right of fixation, while 12-year olds' and adults' extended beyond the maximum that was presented in this experiment (nine character spaces). The results also showed that, surprisingly, younger readers were more disrupted by smaller window sizes than adults were. This is in contrast to the results of Rayner (1986), who found that children were relatively less disrupted than adults by decreases in window size.

The authors suggest that this difference in results is due to cross-linguistic differences in typical word length. In Finnish, in the smallest window size, most words would not fall within the boundary and so would be partially obscured. They claim that not being able to see the entire word is detrimental to less skilled readers who may use a whole-word recognition strategy, compared to skilled readers who may be better able to integrate information across subsequent fixations. They carried out analyses, within data from the smallest window size only, which compared words which did or did not fall entirely within the window. This analysis confirmed that younger readers were more disrupted when the entire word was not available during a given fixation than were older, more skilled readers. These data emphasise that the reader's skill as well as their age is reflected in their eye movements as they read, and that the span across which letter-identity is available is not purely a visual factor.

A final set of experiments monitoring children's eye movements during sentence reading have manipulated the spatial characteristics of the text through both text spacing and text case. Spragins, Lefton and Fisher (1976) measured the eye movements of 8- and 9-year-olds, and adults, as they read paragraphs which were either in normal text or in AlTeRnAtInG cAsE, and which were either normally spaced, had the spaces between words filled with meaningless symbols, or the spaces deleted altogether. They found, on the measures of reading speed and perceptual span (the number of words per minute, and the number of words in the paragraph divided by the number of fixations made, respectively), that alternating case was much more difficult for the participants to read than the normal text, and that when spacing was disrupted, reading was also less fluent. So when reading alternating case, and when reading text where the spacing is disrupted, reading was both slower and less efficient in terms of the perceptual span. Unfortunately, no t-tests are reported to investigate the main effect of spacing, where the main effect occurs across three conditions – normal text, filled spaces, or deleted spaces. The descriptive results suggest that reading is less fluent in both disrupted spacing conditions compared to the normal text. However, there do not appear to be differences in the eye movement measures between the two conditions where the spacing is disrupted.

The results from fixation durations and frequency of regressions are less clear, with very few significant effects in the frequency of regressions. For the fixation duration measure, the authors did not report whether these were single or first fixations, or simply every fixation that occurred as the readers progressed through the sentences. There was no significant difference between normal and alternating case for fixation durations or regression frequencies, surprisingly, but no explanation is offered for this lack of effects. It would seem likely that the increased reading times are therefore due to participants making more fixations on text presented as alternating case, though the durations of these fixations were not significantly increased.

The most interesting result is the interaction between all three variables, observed in both reading speed and measures of perceptual span, where readers of all ages are reduced to the same low performance levels by combinations of disrupted word shape and word boundaries. Within each of these manipulations separately, group differences are maintained despite any overall influences of the disruption. The overall group differences reflected the smaller perceptual span, longer fixations and higher frequency of regressions in younger compared to older readers. However, when both aspects of the text were disrupted simultaneously, the authors argue that both adults and children are reduced to a "letter-by-letter" strategy in reading.

It can therefore be seen, across all of these studies, that eye movement patterns reflect the age-related changes in processing difficulty associated with learning to read, as well as showing some developmental trends in their own right.

1.5 Summary

Overall, the research described here has described a range of measures of reading fluency and lexical processing, and their variation with the reader's age. As younger readers move their eyes through a sentence, they make more, longer fixations, shorter saccades, and more regressions than adult readers. These differences occur even when the readers are given material that is matched to their age in terms of difficulty. Therefore, there must be some element of these developmental trends in eye movement fluency that is not simply a consequence of processing difficulty. The first section of this review discussed some eye movement parameters that show developmental change in their own right, in the absence of the processing requirements associated with reading. However, it seems likely that the increased difficulty of children compared to skilled adult readers in processing and comprehending written text plays a causative role in the differences in eye movement patterns. For example, the size of the perceptual span has been shown to decrease when readers are given more difficult text.

There are two clear conclusions that can therefore be drawn from this body of research. First, that eye movements in reading clearly do reflect, to a large degree, the processing difficulty of the reader as a consequence of the written stimulus. However, second, there are some aspects of oculomotor control which, within themselves, develop with age. The visual demands of making a rapid sequence of fixations and saccades across a relatively small visual stimulus are high, and therefore it seems entirely possible that oculomotor control in sentence reading is a skill that must develop with age in addition to reflecting the reader's cognitive processes.

Chapter Two

Children's reading of disappearing text

2.1 Introduction

The aim of Experiments One to Three was to examine the characteristics of children's visual processing during fixations in reading in comparison to skilled adult readers. The uptake of visual information from the printed page is necessary in order for the reader to initiate the higher-level, linguistic processing of the text. Processing of text is distributed across multiple fixations in reading, and words are processed both foveally and parafoveally. Consequently, Experiments One to Three will examine visual processing of both the fixated word (word N) and the word to the right of fixation (word N+1).

In Experiment One, the focus was on the visual processing of the fixated word. Previous research has already investigated this issue in skilled adult readers. These experiments have restricted the temporal availability of text as the reader progressed through sentences, and examined its impact on the fluency of their eye movements. When adults read text where each word in turn either is masked 50 ms after it is fixated (Isheda & Ikeda, 1989; Rayner, Inhoff, Morrison, Slowiaczek & Bertera, 1981), or literally disappears 60 ms after it is fixated (Rayner, Liversedge, White & Vergilino-Perez, 2003; Liversedge, Rayner, White, Vergilino-Perez, Findlay & Kentridge, 2004), adults' reading proceeds as normal. These experiments restricted the initial stage of processing, where visual information must be extracted from the page, to durations that were far shorter than typical fixations in reading. Rayner *et al.* (1981) reported that reading rate was the same when the fixated word was masked after 50 ms as when reading normal text. Further, the number of fixations per sentence, the duration of fixations, and the mean saccade length were all the same in the masked condition as when readers were presented with normal text. These data showed that when useful visual information for any given word was available for only 50 ms, reading could proceed in an apparently unimpaired manner.

Further evidence came from studies in which, rather than being masked after a given duration, the word literally disappeared 60 ms after fixation onset (Rayner *et al.*, 2003; Liversedge *et al.*, 2004). When the reader's eyes moved to a different word in the sentence, the previously fixated word re-appeared and the newly fixated word in turn disappeared 60 ms after fixation onset. Again, this methodology restricts the period for which useful input is available to the visual system. They found that, as when text is masked after very short presentation durations, total sentence reading time was not affected, i.e. that reading appeared to proceed normally.

Importantly there was an effect of word frequency on first fixation durations, such that low frequency words received longer first fixations than high frequency words, under both normal and disappearing text conditions. So, even when the fixated word had disappeared after 60 ms, readers looked longer at the blank space that had replaced a low frequency word than if it had replaced a high frequency word. The authors argued that the visual system extracts from the printed page all the information necessary for linguistic processing of a word within the first 60 ms of a fixation. This is not to say that the linguistic processing itself is completed within 60 ms; simply that 60 ms is an adequate duration for the visual system to take up information sufficient to initiate normal linguistic processing. Further, it was concluded that the decision of when to move the eyes during reading is largely under cognitive control as opposed to visual control. If the latter were the case then all fixation durations would have been constant, as the fixated word disappeared each time after the same, fixed period. However, the frequency of the fixated word was shown to affect when readers moved their eyes from the fixated location to a new word, independent of the fact that the visual stimulus was no longer present. Therefore the linguistic rather than the visual properties of the fixated word were shown to be primarily responsible for determining fixation durations.

The overall analysis showed normal sentence reading times with the disappearing text presentation. However, Liversedge *et al.* (2004) also reported some strategic differences between the two conditions (normal vs. disappearing text). When reading disappearing text, readers made fewer but longer first fixations, and fewer refixations than when reading normal text. Rayner *et al.* (2003) also found a trend for longer fixations and fewer refixations when reading disappearing text. So although reading can proceed at an overall normal rate when the words disappear 60 ms after they are fixated, there are small differences in eye movement control that may reflect changes in reading strategy to cope with the unusual text presentation. When skilled adult readers might typically require a second first-pass fixation on a word but this is not possible, they are not particularly disrupted. They do not move on from the word and then return to it via a regression – regression probabilities were not different between the normal and disappearing text conditions. Somehow, their visual system has received sufficient input that they can progress through sentences without the usual refixations. The only consequence of doing so appears to be longer fixation durations, which was argued to be a strategy for the compensation of the reduced refixation probability. The reader may require a given amount of time to complete certain aspects of visual and linguistic processing before they can move their eyes on to the next word, and under disappearing text conditions this processing time is met through longer fixations rather than through refixations.

There has been no previous research that has examined the rate at which the uptake of visual information occurs during fixations in children's sentence reading. As previously discussed in section 1.4, children's mean fixation durations decrease with age (i.e. McConkie *et al.*, 1991). What is not known, however, is the speed and timing of visual processing during those fixations in comparison to skilled adult readers.

There has been one study which has begun to examine this issue in child readers, although it used a single word task which has very different processing demands from normal sentence reading. Aghababian and Nazir (2000) found that children could achieve a baseline of 60% correct word recognition when the stimuli were presented for durations much shorter than the mean fixation durations in reading for those ages (see section 1.3 in Chapter One for a fuller discussion of their study). Children aged 6- to 7-years required a mean presentation duration of 125 ms, and the required durations decreased steadily until children aged 10-11 years required a mean duration of 60 ms (note that these values are estimated from a graph). However, there were large standard errors for these mean values indicating large inter-individual differences. Further, these mean presentation durations relate to word recognition on a single word task, with no sentential context. When reading sentences, we know that readers typically make use of information from words to the right of fixation, and that this preview can decrease fixation durations when the word is directly fixated. Although it seems likely that parafoveal pre-processing is reduced in children relative to adults, the fact that their perceptual span extends beyond the fixated word clearly shows that they do pre-process text to the right of fixation. It is therefore possible that, when reading sentences normally, children might not need such long presentation durations as those lower limits found by Aghababian and Nazir in order to extract the necessary visual information.

The present study aims to investigate children's sentence reading performance under disappearing text conditions. Specifically, is a 60 ms presentation sufficient for children to extract the necessary visual information from any given word such that linguistic processing can proceed unimpaired? Previous research has shown that this presentation duration is sufficient for adult readers (Rayner *et al.*, 2003; Liversedge *et al.*, 2004), but the rapid uptake of visual information from the page when reading is an ability that develops with age (Aghababian & Nazir, 2000). This study directly investigates children's ability to extract visual information when reading sentences, an exercise that provides both preview and context for the processing of any given word, but also has much higher task demands than single word reading.

A number of predictions were made for the current experiment. First, it was predicted that there would be an interaction between participant group and text presentation condition for total sentence reading times, such that adults would not show any significant differences, but children would show increased total sentence reading times in the disappearing text condition compared to the normal condition. Second, it was predicted that adults would show a word frequency effect in their first fixation durations under both normal and disappearing text conditions. Both these predictions for the adult data were based on the findings of Rayner *et al.* (2003) and Liversedge *et al.* (2004), where adult participants' eye movements were largely normal when reading disappearing text, reflecting the relative ease with which they did so.

The research by Aghababian and Nazir (2000) showed that children required up to 126 ms for successful word recognition. Based on these findings, the third hypothesis was that children would be highly disrupted when reading disappearing text compared to normally presented text. It seems likely that 60 ms will be insufficient for children's visual systems to extract the necessary information from the page for normal linguistic processing to occur. This is predicted to be reflected by increased numbers of fixations, increased fixation durations, increased regression frequencies, as well as the increased total sentence reading times previously mentioned. Therefore, the final prediction was that children would show a word frequency effect on their fixation durations when reading normal text, but that this effect would not occur under disappearing text conditions. If, as predicted, 60 ms is an insufficient presentation duration to permit children to successfully read the sentences then it will also be too brief a presentation duration to permit lexical processing to the level where word frequency is influential.

2.2 Methods

Participants. The 12 adult participants were all members of Durham University, with an age range of 18- to 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 volunteers from local schools in the Durham and Southampton areas. All child participants were native English speakers with normal, uncorrected vision and no known reading difficulties. The age range of child participants was 7- to 11-years. Child participants were volunteers, and were naïve regarding the purpose of the study.

Apparatus. Monocular eye movement recordings were taken using a Generation 5 Fourward Technologies Dual Purkinje eye tracker. The position of participants' right eye was recorded every millisecond. The eye tracker was interfaced with a Pentium 4 computer, with all sentences presented on a 40 cm x 30 cm monitor. Sentences were presented in white, Courier New font size 14, on a black background, at a low contrast. The room was dimly illuminated. Sentences were presented at a viewing distance of 100 cm. Subjects were asked to bite on a bar with a wax dental impression and to lean against forehead rests during the experiment, to eliminate head movements.

Materials and Design. 40 experimental sentences were constructed, each containing a target word which was manipulated for word frequency. The high and low frequency target words were always six letters long. The median frequency for high frequency target words was 93 counts per million (range: 19 to 1,480 per million) and the median frequency for low frequency target words was nine counts per million (range: one to 57 per million). Inter-quartile ranges were 15 for the low frequency words, and 131 for the high frequency words. All word frequencies were taken from the CELEX English word form corpus (Baayen, Piepenbrock & Gulikers, 1995). Further, it was ensured that all target words would be acquired between the ages of 6- and 8-years of age (MRC Database, Coltheart, 1981).

All sentences were between 70 and 80 characters long, extending from the left side of the screen. Within each sentence, the target word was presented either in the first third of the sentence or in the final third of the sentence. All target words were positioned at least 20 characters from the start/end of the sentence. Examples of the stimuli with the two manipulations are given in Table 2.1. The full stimulus set is given in Appendix A.

In addition to the 40 experimental items, five practise items were presented at the beginning of the experiment. After 11 of the sentences, participants were required to answer a simple comprehension question, making a "yes/no" response using a button box.

Condition	Sentence
High Frequency	I tripped and had an accident in the dark forest last night.
Low Frequency	I tripped and had an accident in the dark cavern last night.

Table 2.1. Sample experimental sentences containing a word frequency manipulation.

Procedure. Participants were instructed to read the sentences normally, and to answer the questions as accurately as possible by pressing a button box to indicate "yes/no" responses. For child participants, information sheets were sent to parents in advance, and all instructions were given verbally to the children both at the start and throughout the experiment as required. Children were given lots of encouragement throughout the experiment.

An initial calibration of the eye tracker was carried out. Viewing was binocular, but only the right eye was recorded. The participant was instructed to look at each of three fixation points, extending in a horizontal line across the centre of the screen, while their fixation position was recorded for each point. This calibration was then checked for accuracy. Once the right eye had been calibrated with satisfactory accuracy, the sentences were presented. Following every four sentences, the calibration was checked for accuracy, and the eye tracker was recalibrated if necessary. The design ensured that the calibration check could not occur between a sentence and its related comprehension question. All participants were given a break half way through the experiment, and additional breaks were given if required. The entire experiment lasted approximately 20 minutes for adults, and half an hour for children.

Analyses. Custom-designed software was used for the data analyses. All fixations were manually identified. Fixations of less than 80 ms or more than 1200 ms were deleted (3.9% of data). Of these deleted fixations, 1.8% were made by adults and 2.1% were made by children. Throughout the analyses, there were cases where there were missing cells of data (typically items analyses). In these cases, where less than 5% of the cells were missing, they were filled with a global mean taken across groups and conditions. In cases where more than 5% of cells were missing, the analysis was not conducted.

Throughout the Results section, where appropriate, analyses of variance and t-tests were conducted treating participants (F_1, t_1) and items (F_2, t_2) as random variables consistent with Clark, (1973; though see Raaijmakers, Schrijnemakers & Gremen, 1999). In cases where both the participants and the items analysis give a p-value of < 0.05, the effect is referred to as significant. In cases where one of the two analyses is significant and the other is marginal, this is indicated in the text for the individual cases. In cases where only one of the two analyses is clearly reliable, or where both analyses give a p-value > 0.05, the effect is referred to as non-significant.

Post-hoc t-tests were conducted in order to examine reliable main effects and interaction terms from the ANOVAs in more detail. A Bonferroni correction was applied to these t-tests in order to reduce the likelihood of making a Type I error. For main effects of participant group, three t-tests were conducted in order to compare each of the three participant groups to each other. For the interaction terms, three t-tests were also conducted to compare the effect of the disappearing text manipulation in each participant group separately. Therefore, for all t-tests reported in Experiment One, a Bonferroni-corrected p-value of less than 0.016 was accepted as significant.

2.3 Results

Once the data had been collected for this experiment it was observed that, in the children's participant group, there were six older children (10- to 11-years) and six younger children (7- to 9-years). The original aim had simply been to compare adults and children in this experiment, as the collection of accurate eye movement recordings from children is relatively difficult. However given the opportunity to break down the children's participant group into two age groups, the following analyses are all presented with the variable of participant group having three levels – adults, older children, and younger children. Data was only analysed from participants who had scored at least 70% on the comprehension questions, in order to ensure that all participants were able to understand the sentences.

Global measures. Table 2.2 shows the mean total sentence reading time, number of fixations per sentence, mean fixation duration, mean refixation probability, mean word skipping probability, and mean number of regressions per sentence for adults, younger and older children. Each of the measures in Table 2.2 will be analysed individually to examine the developmental effects. For each measure, a 3 (Participant Group: adults vs. older children vs. younger children) x 2 (Text Presentation: normal vs. disappearing text) repeated-measures ANOVA was carried out. For all graphs, the error bars show the standard error for each group in each condition. The mean fixation durations are shown for all three participant groups, for both normal and disappearing text, in Fig. 2.1.

	Adults		Older children		Younger children	
	Normal	**DT**	**Normal**	**DT**	**Normal**	**DT**
Mean fixation duration (ms)	232 (97)	236 (104)	225 (99)	251 (130)	304 (153)	336 (164)
Mean total sentence reading time (ms)	2918 (756)	2858 (935)	3539 (1372)	3879 (1868)	6094 (2245)	6531 (2353)
Mean number of fixations per sentence	10.9 (2.5)	10.5 (3.0)	13.2 (4.1)	13.4 (4.8)	16.4 (5.0)	16.9 (5.2)
Mean number of regressions per sentence	2.3 (1.6)	2.5 (2.0)	3.8 (2.1)	4.0 (2.6)	4.9 (2.8)	5.1 (2.5)
Mean refixation probability (%)	12 (6)	11 (4)	18 (7)	15 (8)	31 (7)	17 (6)
Mean word skipping probability (%)	41 (11)	42 (7)	44 (14)	42 (9)	36 (5)	33 (6)

Table 2.2. Mean total sentence reading times, number of fixations per sentence, mean fixation duration, mean refixation probability, and mean number of regressions per sentence for adults, older and younger children. Standard deviations are shown in parentheses. DT refers to the disappearing text condition.

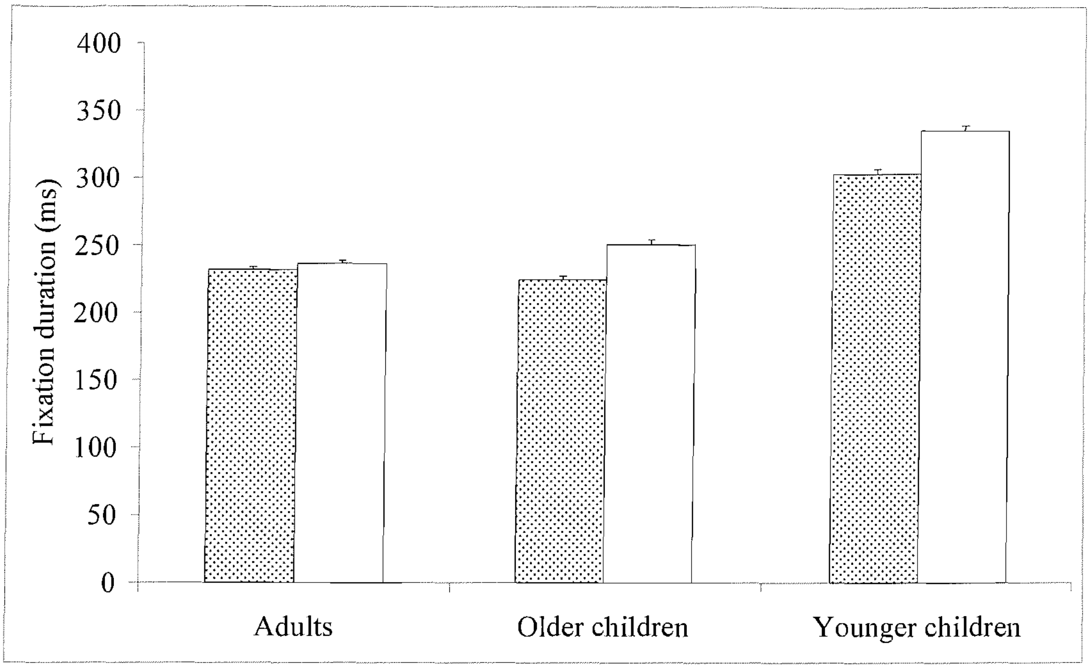

Fig. 2.1. Mean fixation durations of adults, older, and younger children for both normal and disappearing text. Spotted bars represent normal text, and plain bars represent disappearing text.

There was a significant main effect of participant group, where the mean fixation duration decreased with age (F_1 (2, 21) = 23.91, $p < 0.001$; F_2 (2, 78) = 498.73, $p < 0.001$). To further examine this effect, independent-samples t-tests were conducted. This subsequent analysis showed that younger children made significantly longer fixations than either older children or adults (all *t*s > 4, all *p*s < 0.01). However, there was no significant difference in the mean fixation duration between older children and adults (t_1 (16) = 0.12, $p = 0.19$; t_2 (39) = -0.65, $p = 0.52$).

There was also a significant effect of the text presentation, where longer fixations were made when participants were reading disappearing text than when they were reading normal text (F_1 (1, 21) = 12.30, $p < 0.01$; F_2 (1, 39) = 63.18, $p < 0.001$).

Finally, there was an interaction between participant group and text presentation that was reliable across items and marginal across participants (F_1 (2, 21) = 3.17, $p = 0.06$; F_2 (2, 78) = 7.16, $p < 0.01$). Paired-samples t-tests were conducted to examine the effect of text presentation in each participant group independently. These t-tests showed that for both older and younger children, longer fixations were made when reading disappearing text than when reading normal text (all *t*s > 3, all *p*s ≤ 0.016). However, no difference was observed on mean fixation durations between normal and disappearing text for the adult readers (t_1 (11) = -0.22, p = 0.83; t_2 (39) = -1.74, $p > 0.05$).

So, for fixation durations, child participants made longer fixations when reading disappearing text compared to normal text. This finding matches that reported by Liversedge *et al.* (2004) for adult participants, and will be considered in relation to the analysis of refixation probabilities in due course. The lack of an effect in the adult participants' data in these analyses will be discussed later.

The mean total sentence reading times for all participants, for both normal and disappearing text conditions, are shown in Fig. 2.2. As with the analysis of mean fixation durations, a significant main effect of participant group was found such that the time taken to read a sentence decreased with age (F_1 (2, 21) = 30.09, $p < 0.001$; F_2 (2, 78) = 247.29, $p < 0.001$). Again, independent-samples t-tests were conducted to examine where the significant differences were between the three participant groups. For total sentence reading times, the younger children were significantly slower than both older children and adults (all ts > 3, all ps < 0.016). While the older children did, on average, take longer than the adults to read the sentences, this effect was not reliable (t_1 (16) = -2.29, $p = 0.04$; t_2 (39) = -8.17, $p < 0.001$).

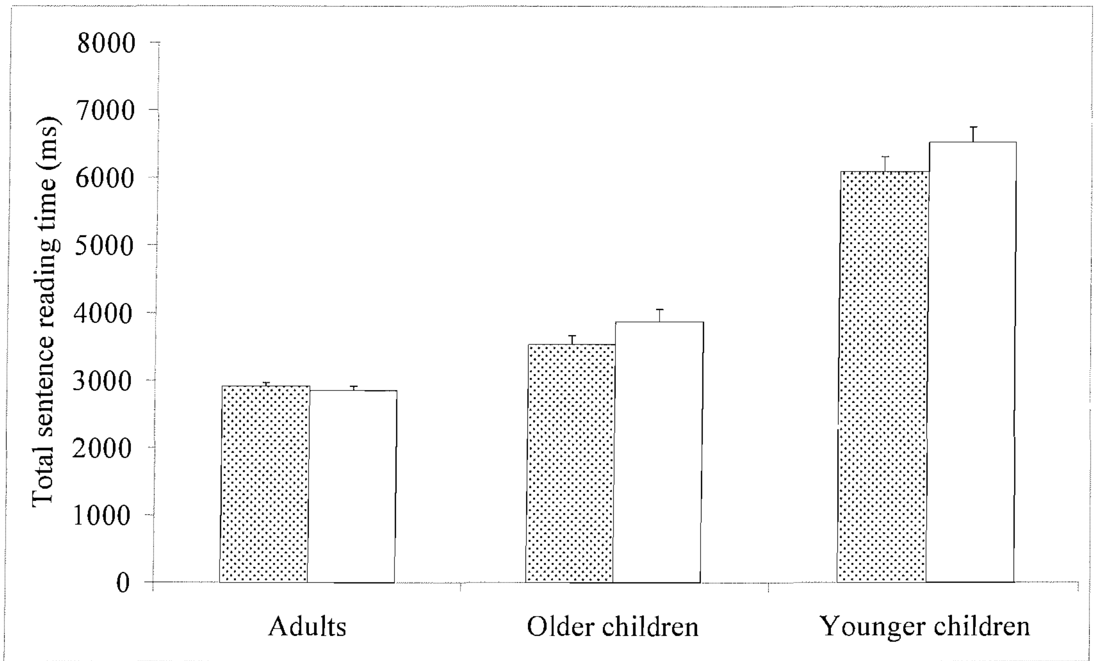

Fig. 2.2. Mean total sentence reading times of adults, older, and younger children for both normal and disappearing text. Spotted bars represent normal text, and plain bars represent disappearing text.

However, in contrast to the mean fixation duration data, the main effect of condition was not reliable (F_1 (1, 21) = 1.47, p = 0.24; F_2 (1, 39) = 6.23, p < 0.05), nor was the interaction between participant group and text presentation condition (F_1 (2, 21) = 0.86, p = 0.44; F_2 (2, 78) = 2.04, p = 0.14).

For the analysis of total sentence reading times, a slightly different pattern of results was found to that observed in the fixation duration data. There were longer sentence reading times for all participants when presented with disappearing text compared to normal text. Again, this finding is comparable to that reported by Liversedge *et al.* for adult readers.

The mean number of fixations made per sentence, under both normal and disappearing text presentation conditions, for adults, older, and younger children, is shown in Fig. 2.3.

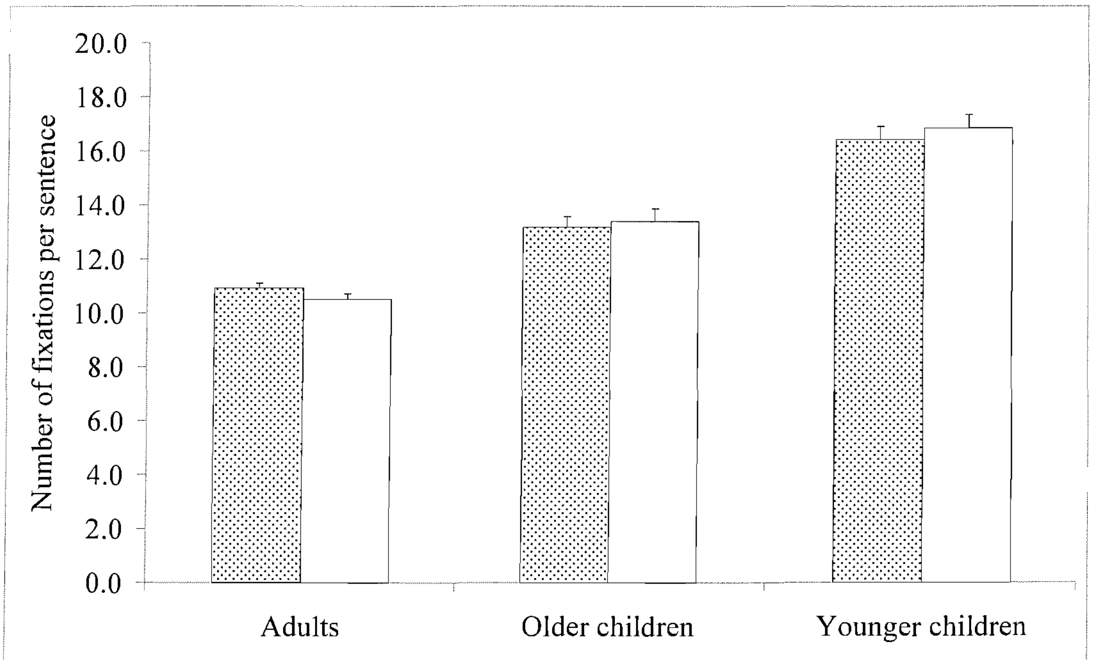

Fig. 2.3. Mean number of fixations made per sentence by adults, older, and younger children for both normal and disappearing text. Spotted bars represent normal text, and plain bars represent disappearing text.

Again, a significant main effect of participant group was found on the number of fixations made per sentence, decreasing with age (F_1 (2, 21) = 19.69, p < 0.001; F_2 (2, 78) = 127.79, p < 0.001). Independent-samples t-tests showed that the adult participants made significantly fewer fixations per sentence than either older or younger children (all ts > 2, all ps < 0.016). While older children did, on average, make fewer fixations per sentence than the younger children, this effect was not reliable (t_1 (10) = -2.57, p = 0.03; t_2 (39) = -8.39, p < 0.001).

The main effect of condition was not significant, nor was the interaction between participant group and condition (all Fs < 2, all ps > 0.2). These data therefore suggest that participants of all ages are making the same number of fixations when reading through a sentence irrespective of whether that sentence is presented normally or as disappearing text.

The mean number of regressions made per sentence by adults, older, and younger children under both normal and disappearing text conditions is shown in Fig. 2.4.

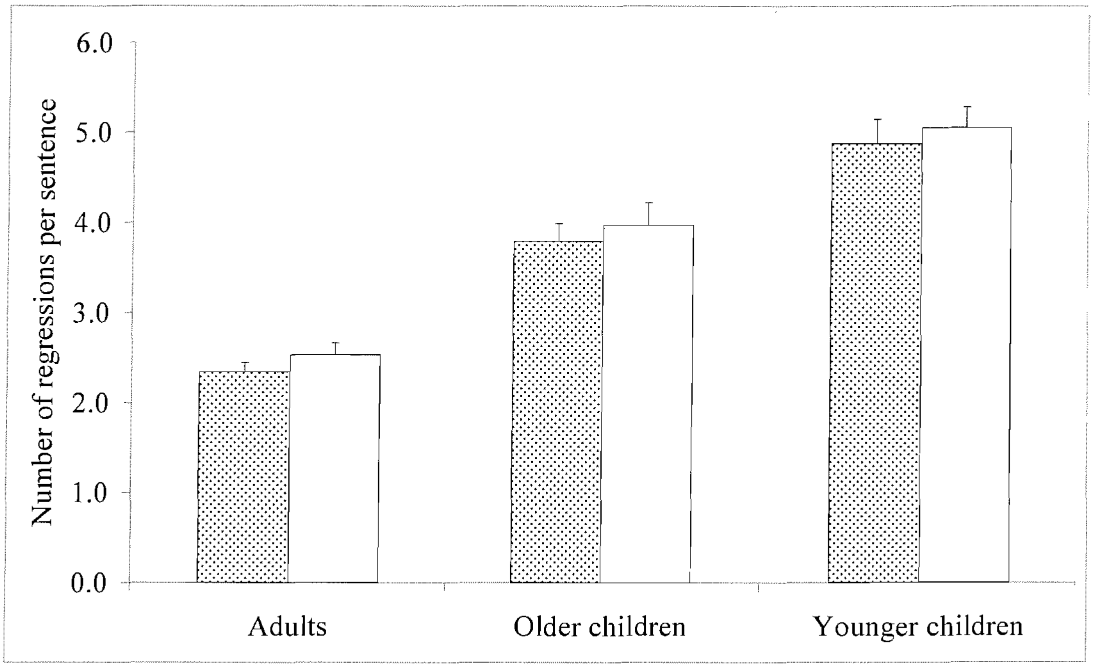

Fig. 2.4. Mean number of regressions made per sentence by adults, older, and younger children for both normal and disappearing text. Spotted bars represent normal text, and plain bars represent disappearing text.

A similar pattern of results was found for the number of regressions made per sentence as was found for the overall number of fixations made per sentence. A significant main effect of participant group showed that as age increased, the number of regressions made per sentence decreased (F_1 (2, 21) = 10.91, p = 0.001; F_2 (2, 78) = 82.94, p < 0.001). Adults made significantly fewer regressions per sentence than younger children (t_1 (16) = -4.559, p < 0.001; t_2 (39) = -15.267, p < 0.001). Further, adults made fewer regressions per sentence than older children although this effect was marginal in the participants analysis (t_1 (16) = -2.64, p = 0.018; t_2 (39) = -9.38, $p < 0.001$). The difference between older and younger children was not reliable (t_1 (10) = -1.82, p = 0.1; t_2 (39) = -5.22, $p < 0.001$).

There was no significant main effect of text presentation condition (F_1 (1, 21) = 0.63, p = 0.44; F_2 (1, 39) = 2.67, p = 0.11), nor was there a significant interaction (F_1 (2, 21) = 0.42, p = 0.96; F_2 (2, 78) = 0.13, p = 0.88).

So, for both the number of fixations made per sentence and the number of regressions made per sentence, there were the expected age-related changes but no effects of the disappearing text manipulation for any of the participant groups. All readers made the same number of fixations and regressions per sentence when the words were disappearing during fixations as when the text was presented normally. While this was predicted for the adult participants, it was predicted that the child readers would show considerable disruption to their eye movement behaviour as a consequence of reading disappearing text. This does not appear to be the case.

A key measure of reading difficulty in this experiment was refixation probability, as this is the measure in which Liversedge *et al.* did find differences for skilled adult readers when presented with disappearing text compared to normal text. This effect was suggested to be causal for the effect they observed on fixation durations. The effect of the disappearing text manipulation on fixation durations was observed in the present data set, but only for child participants. Therefore, it might be expected that in the following analysis of refixation probabilities, effects of the text presentation condition would only be observed for the child participants.

The mean refixation probability for adults, older, and younger children under both normal and disappearing text conditions is shown in Fig. 2.5. In the analysis of mean refixation probability, the main effect of participant group was found to be significant (F_1 (2, 21) = 15.91, $p < 0.001$; F_2 (2, 78) = 59.87, $p < 0.001$). Adults made significantly fewer refixations than younger children (t_1 (16) = -6.996, $p < 0.001$; t_2 (39) = -11.218, $p < 0.001$). However, the differences were not reliable between adults and older children (t_1 (16) = -1.89, p = 0.08; t_2 (39) = -5.33, $p < 0.001$), or between older and younger children (t_1 (10) = -2.20, p = 0.05; t_2 (39) = -6.26, $p < 0.001$).

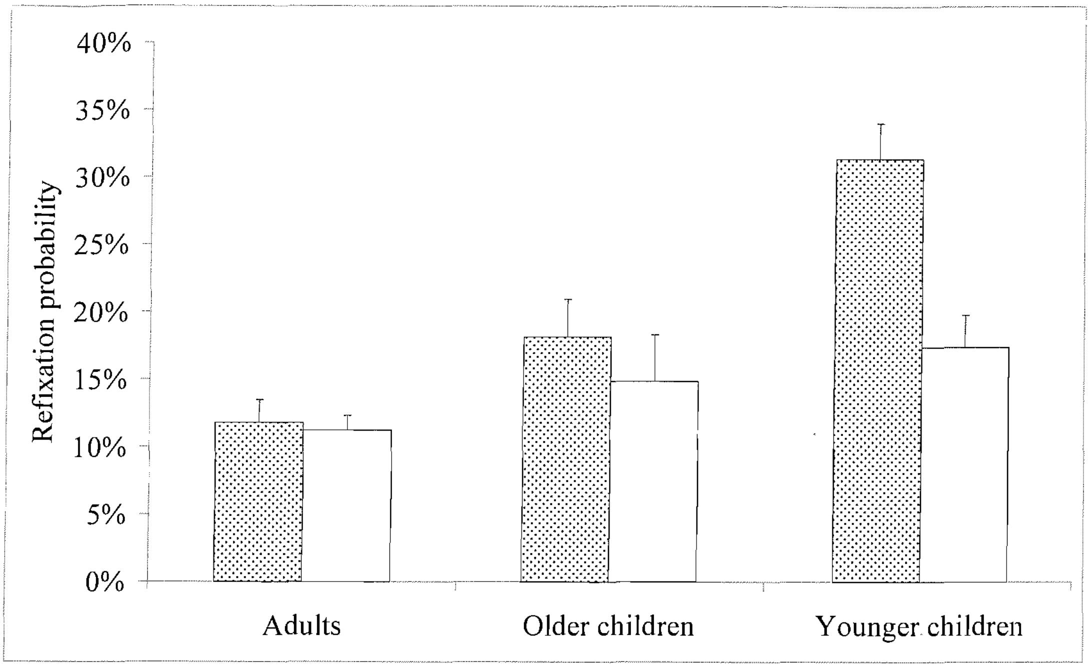

Fig. 2.5. Mean refixation probability for adults, older, and younger children for both normal and disappearing text. Spotted bars represent normal text, and plain bars represent disappearing text.

A significant main effect of text presentation condition was also found, where fewer refixations were made when reading disappearing text compared to normal text (F_1 (1, 21) = 9.37, $p < 0.01$; F_2 (1, 39) = 29.65, $p < 0.001$). Further, the interaction between participant group and text presentation condition was also found to be significant (F_1 (2, 21) = 6.91, $p < 0.01$; F_2 (2, 78) = 10.16, $p < 0.001$).

To further analyse the interaction, paired-samples t-tests were conducted for each participant group in order to examine the effect of the text condition for that group. These t-tests showed that younger children made fewer refixations when reading disappearing text compared to normal text, although this effect was not reliable (t_1 (5) = 3.11, $p = 0.03$; t_2 (39) = 5.77, $p < 0.001$). However, no difference in refixation probability was found across the two conditions for either adults or older children (all ts < 2, all ps > 0.1).

So, for refixation probabilities, a trend was found in the younger children's data in this analysis that was the same as the effect reported by Liversedge *et al.* for their adult participants. This would appear to be related to the effect on fixation durations, which again Liversedge *et al.* report for adult readers and here was found only for the child participants.

Finally, the mean word skipping probability for adults, older, and younger children under both normal and disappearing text conditions is shown in Fig. 2.6.

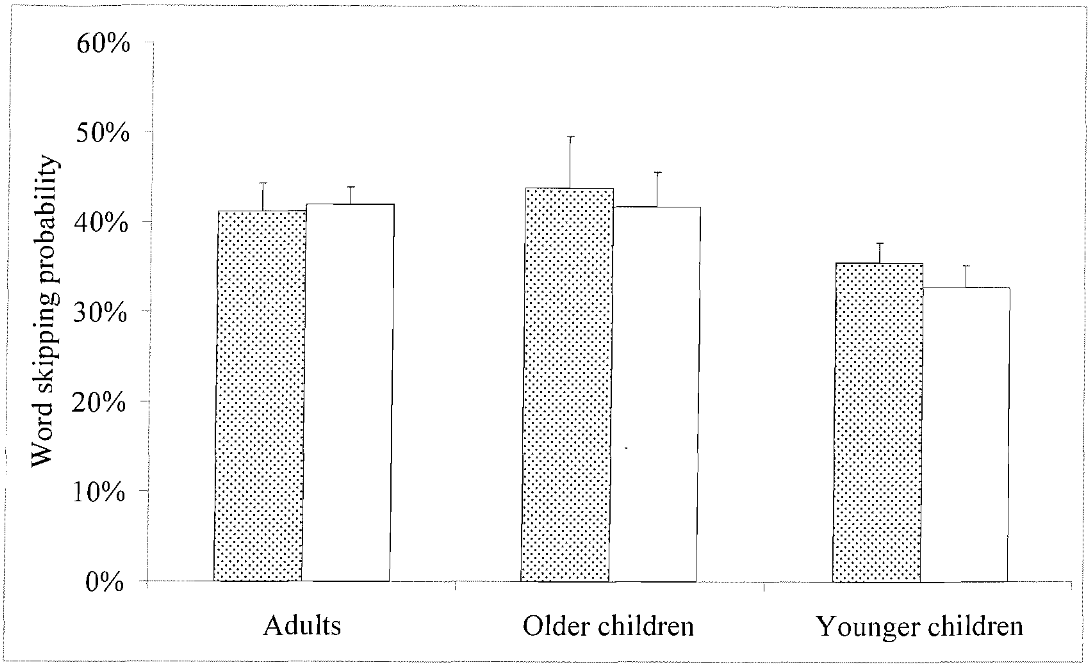

Fig. 2.6. Mean word skipping probability for adults, older, and younger children for both normal and disappearing text. Spotted bars represent normal text, and plain bars represent disappearing text.

There was no reliable effect of participant group, although the numerical trends clearly suggest that word skipping probability decreased with age (F_1 (2, 21) = 2.07, p = 0.15; F_2 (2, 78) = 19.30, p < 0.001). No significant effect of text presentation condition was found upon word skipping probability (F_1 (1, 21) = 0.66, p = 0.43; F_2 (1, 39) = 2.25, p = 0.14), nor was the interaction between participant group and condition significant (F_1 (2, 21) = 0.59, p = 0.57; F_2 (2, 78) = 1.25, p = 0.29).

Global measures – summary. Basic developmental trends between younger children, older children, and adults were observed on all measures – total sentence reading times, the number of fixations per sentence, regression, refixation, and word skipping frequencies, and fixation durations. Further, when reading disappearing text as opposed to normal text, participants made longer fixations but made fewer refixations. However, the disappearing text did not affect total sentence reading times, the number of fixations or regressions made by readers, nor did it affect the likelihood of word skipping.

Somewhat surprisingly, there were only two measures on which there was a significant interaction between participant group and text presentation condition – fixation durations and refixations. All children made longer fixations when reading disappearing text compared to normal text, whereas there was no difference in fixation durations across the two conditions for adult readers. Additionally, numerical trends showed that the younger children made fewer refixations when reading disappearing text than normal text, but there was no difference for either older children or adults. So while adults showed virtually no disruption when reading disappearing text, both older and younger children showed some disruption in their eye movement behaviour when reading disappearing text.

Local measures. In a second series of analyses, the word frequency manipulation was analysed with respect to both participant group and text presentation. Following Rayner *et al.* (2003), three key measures are reported – single fixation durations, first fixation durations and gaze durations. For each measure, a 3 (Participant Group: adults vs. older children vs. younger children) x 2 (Text Presentation: normal vs. disappearing text) x 2 (Word Frequency: high vs. low) repeated-measures ANOVA was carried out. Means and standard deviations for each of these three measures are reported in Table 2.3. The mean single fixation durations are given in Fig. 2.7.

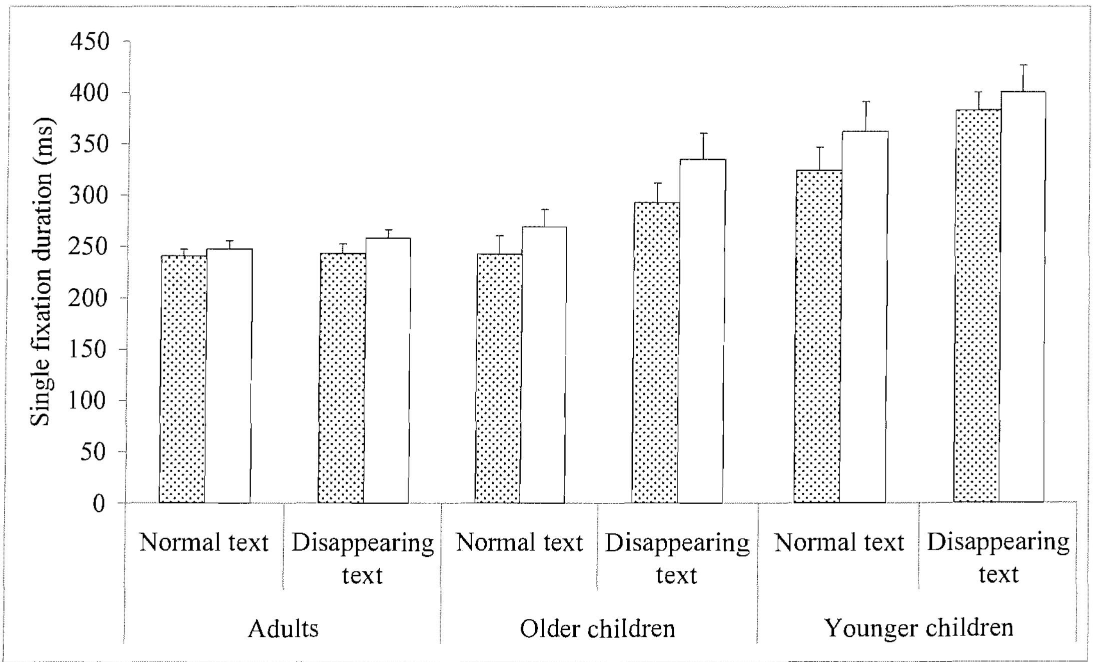

Fig. 2.7. Adults', younger children's, and older children's mean single fixation durations on high and low frequency words when presented as normal or disappearing text. Spotted bars represent high frequency target words and plain bars represent low frequency target words.

		Adults		10- to 11-years		7- to 9-years	
		Normal	**DT**	**Normal**	**DT**	**Normal**	**DT**
Single fixation duration (ms)	High	240 (66)	243 (81)	242 (100)	292 (111)	324 (111)	382 (122)
	Low	247 (75)	258 (76)	269 (106)	335 (161)	362 (140)	400 (164)
First fixation duration (ms)	High	235 (65)	233 (80)	231 (90)	286 (108)	331 (149)	371 (122)
	Low	243 (75)	253 (75)	280 (114)	316 (155)	335 (162)	372 (158)
Gaze duration (ms)	High	254 (73)	274 (103)	293 (131)	311 (127)	475 (289)	392 (119)
	Low	261 (80)	267 (79)	337 (227)	347 (154)	553 (375)	431 (209)

Table 2.3. Mean single fixation durations, first fixation durations, and gaze durations on high and low frequency words presented either normally or as disappearing text, for adults, older, and younger children. Standard deviations are shown in parentheses.

For single fixation durations, main effects of participant group, text presentation condition, and word frequency were all found to be significant (all Fs > 10, all ps < 0.01). Participants made longer fixations on low frequency than high frequency words, and longer fixations on disappearing text than normal text.

For the main effect of participant group, mean fixation durations decreased with age. Independent-samples t-tests showed that adult participants made significantly shorter single fixations than younger children (t_1 (16) = -5.74, $p < 0.001$; t_2 (39) = -8.26, $p < 0.001$). However, the differences between adults and older children (t_1 (16) = -1.62, $p = 0.13$; t_2 (39) = -3.59, $p = 0.001$) and between older and younger children were not reliable (t_1 (10) = -2.65, $p = 0.03$; t_2 (39) = -4.28, $p < 0.001$).

In addition to these main effects, the interaction between participant group and condition just reached significance (F_1 (2, 21) = 3.41, $p = 0.05$). Paired-samples t-tests were conducted to compare single fixation durations for normal and disappearing text for each of the three participant groups. These t-tests showed a significant effect of condition for older children where fixations were longer for disappearing text than for normal text (t_1 (5) = -4.32, $p < 0.01$; t_2 (39) = -2.61, p = 0.01), while the effect for the younger children was not reliable (t_1 (5) = -2.17, $p = 0.08$; t_2 (39) = -2.64, p < 0.016). There was also no significant difference between the conditions for the adult readers (t_1 (11) = -1.22, $p = 0.25$; t_2 (39) = -0.53, p = 0.60). None of the other interactions reached significance (all Fs < 2, all ps > 0.1).

A similar pattern of results was found for first fixation durations. Mean first fixations durations are given in Fig. 2.8. Again, there were significant main effects of participant group, text presentation condition and word frequency upon first fixation durations (all Fs > 9, all ps < 0.01). Adults made significantly shorter first fixations than younger children (t_1 (16) = -5.49, $p < 0.001$; t_2 (39) = -9.67, $p < 0.001$). However, the difference between adults and older children was not reliable (t_1 (16) = -1.60, $p = 0.13$; t_2 (39) = -4.03, $p < 0.001$), nor was the difference between older and younger children (t_1 (10) = -2.47, $p = 0.03$; t_2 (39) = -4.38, $p < 0.001$).

There was a significant interaction between participant group and condition (F_1 (2, 21) = 4.34, $p < 0.05$). Paired-samples t-tests showed that for older children, longer fixations were made when reading disappearing text compared to normal text, although this effect was marginal in the participants analysis (t_1 (5) = -3.39, $p = 0.019$; t_2 (39) = -2.88, $p = 0.01$). The same trend was observed in all participants, but the effect was not significant for the younger children or the adults (*t*s < 3, *p*s > 0.05).

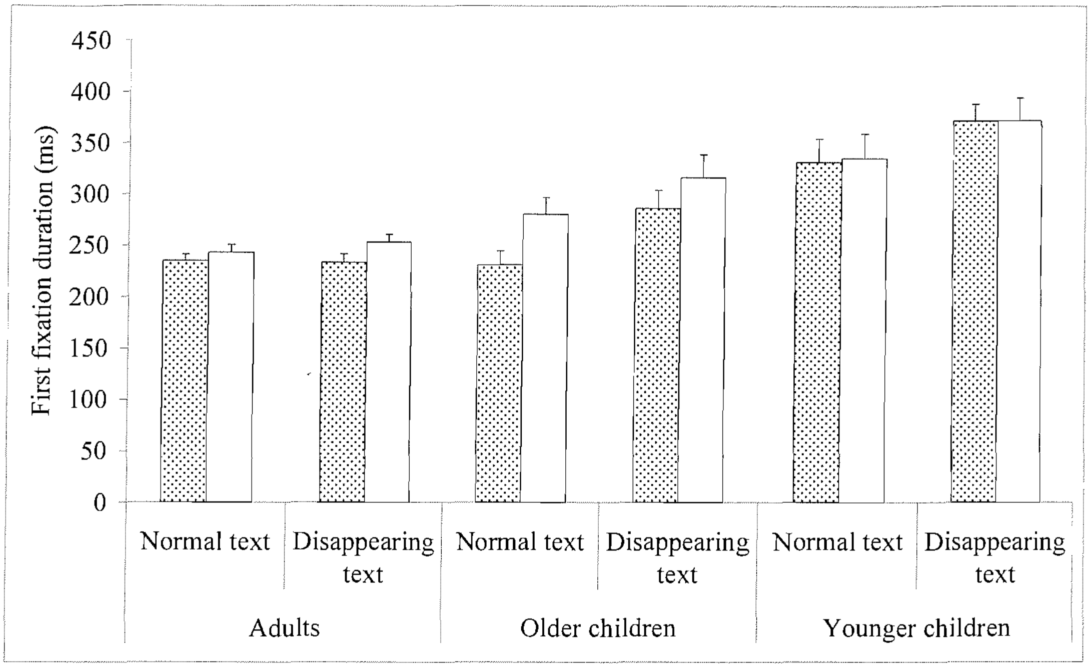

Fig. 2.8. Adults', older children's, and younger children's mean first fixation durations on high and low frequency words, under both normal and disappearing text conditions. Spotted bars represent high frequency target words and plain bars represent low frequency target words.

Further, the interaction between participant group and word frequency was significant (F_1 (2, 21) = 3.46, $p = 0.05$). Longer first fixations were made on low frequency words compared to high frequency words. Numerical trends in the data indicate that the effect of word frequency was larger for the older children than for the younger children or the adults. However, the t-tests revealed that this effect was not reliable for adults (t_1 (11) = -2.27, $p = 0.04$; t_2 (39) = -2.48, $p = 0.018$), older children (t_1 (11) = -5.37, $p < 0.01$; t_2 (39) = -2.23, $p = 0.03$), or younger children (t_1 (11) = -0.22, $p = 0.84$; t_2 (39) = 0.68, $p = 0.50$). Neither the interaction between condition and frequency nor the 3-way interaction was significant (all *F*s < 0.4, all *p*s > 0.5).

Finally, the mean gaze durations are shown in Fig. 2.9. Significant/ marginal main effects were found on gaze durations of participant group (F_1 (2, 21) = 18.91, $p < 0.001$), condition (F_1 (1, 21) = 3.78, $p = 0.07$), and frequency (F_1 (1, 21) = 17.52, $p < 0.001$). For the main effect of group, younger children's gaze durations were significantly lower than those of either older children or adults (*t*s > 2, *p*s <

0.016). However, the difference between older children and adults was not reliable (t_1 (16) = -2.13, p = 0.05; t_2 (39) = -4.78, p < 0.001).

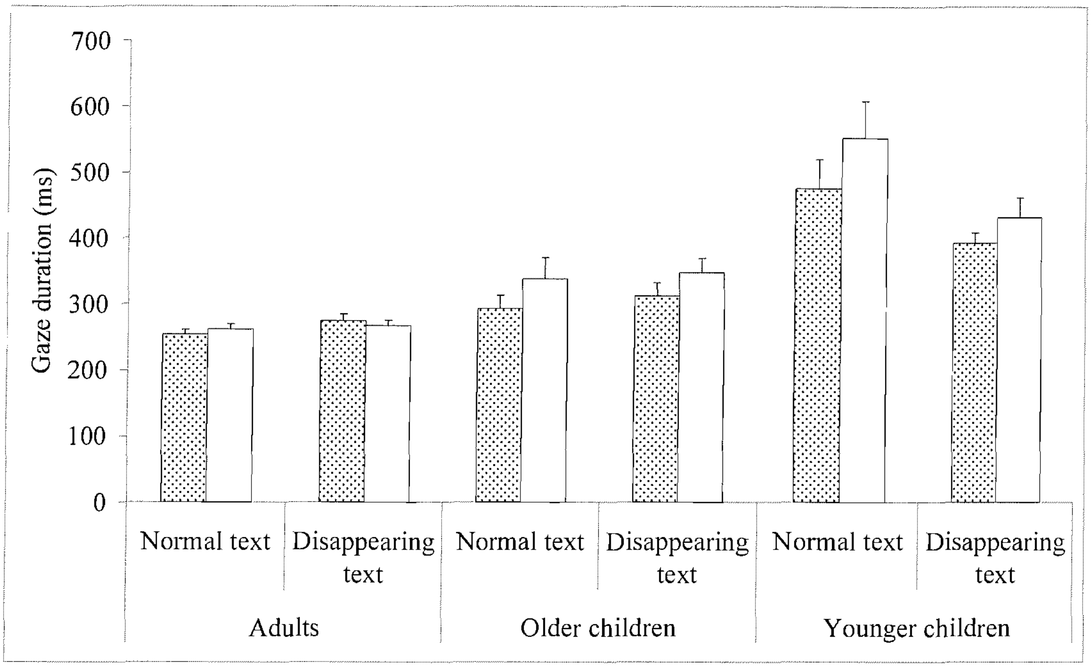

Fig. 2.9. Mean gaze durations for adults, older and younger children on high and low frequency words, under both normal and disappearing text conditions. Spotted bars represent high frequency target words and plain bars represent low frequency target words.

In addition to these main effects, reliable interactions occurred between participant group and condition, and between participant group and frequency (Fs > 6, ps < 0.01). For the interaction between group and condition, numerical trends suggest that there were longer gaze durations occurred for disappearing text than for normal text in younger children, but not in older children or in the adult group. However, the difference in gaze duration between the normal and disappearing text conditions was not reliable for any of the three groups (all ts < 3, all ps > 0.016).

In a similar manner, for the interaction between participant group and frequency, numerical trends in the data indicate that there was an effect of word frequency on gaze durations for both older and younger children, but not for the adults. However, the paired-samples t-tests show that there were no reliable differences in any of the three groups (all ts < 4, all ps > 0.016).

Local measures – summary. Effects of word frequency were found on single fixation durations, first fixation durations, and gaze durations. However there were no interactions between word frequency and text presentation condition. These data showed that the effect of word frequency was occurring for all participants, irrespective of whether the word was presented normally, or whether it had disappeared 60 ms after fixation onset. Therefore, even in younger children, whose eye movements across the sentences as a whole were disrupted when presented with disappearing text, word frequency was influencing fixation durations.

Response accuracy. The mean comprehension score of adults, older, and younger children when reading normal or disappearing text is shown in Fig. 2.10.

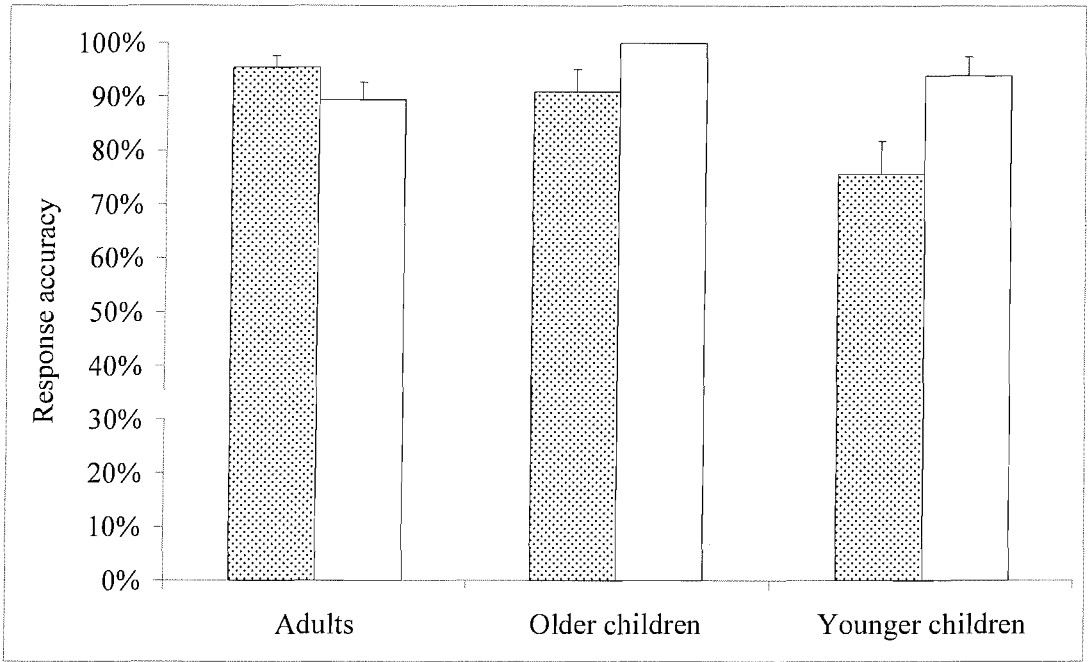

Fig. 2.10. Mean comprehension score of adults, older, and younger children for both normal and disappearing text. Spotted bars represent normal text, and plain bars represent disappearing text.

These data are reported in order to demonstrate that all participants, both adults and children, were able to read and understand the sentences equally well under both normal and disappearing text conditions. It should be noted that, overall, all participants had a mean comprehension score of at least 70%, and so were considered to have been reading and understanding the sentences normally. However, the overall calculation of response accuracy was averaged across conditions and so it may have been the case that a score of less than 100% reflected perfect comprehension in the normal condition and fairly poor comprehension in the disappearing text condition. Therefore, response accuracy was analysed in a 3

(Participant group: adults vs. older children vs. younger children) x 2 (Text presentation condition: normal vs. disappearing text) repeated-measures ANOVA, to examine whether participants' comprehension was affected by the disappearing text manipulation.

The analysis showed that while there was a numerical decrease in comprehension score with age, this effect was not reliable (F_1 (2, 21) = 6.23, $p <$ 0.01; F_2 (2, 20) = 2.29, p = 0.13). A main effect of text presentation condition was found where comprehension scores were actually higher when reading disappearing text than when reading normal text (F_1 (1, 21) = 5.20, $p < 0.05$; F_2 (1, 10) = 8.83, p = 0.01). Further, there was a reliable interaction between participant group and text presentation condition (F_1 (2, 21) = 5.24, $p = 0.01$; F_2 (2, 20) = 4.66, $p < 0.05$). However, paired-samples t-tests showed that there was no reliable difference in comprehension score between reading normal and disappearing text for any of the three groups when analysed separately (all *t*s < 4, all *p*s > 0.016).

The finding that comprehension of text does not decrease for adults when reading either normal or disappearing text replicates the data of Liversedge *et al.* (2004), where adults were able to read and comprehend text well, despite the fixated word disappearing 60 ms after fixation onset. For the children, the small improvement in comprehension score when reading disappearing text probably reflects their increased concentration when they realised that the text was presented in an unusual manner. Critically, these data demonstrate that the eye movement data from the disappearing text condition reflects normal reading behaviour rather than it being the case that readers were simply scanning text without actually comprehending it.

2.4 Discussion

Summary of overall results. The results from this experiment, in the context of previous research with adult participants, showed some age-related changes in the ability to rapidly take up information from the printed page during fixations in reading. There were three major findings. First, basic developmental trends were observed in all measures, as predicted. Younger readers made more fixations, longer fixations, more refixations, more regressions, and skipped fewer words than older readers. These main effects of participant group reflect the differences in processing difficulty associated with the age and reading skill of the participant, and are increasingly well-established in the literature (e.g. McConkie *et al.*, 1991; Rayner, 1986).

Second, a set of strategic differences were observed to occur between the different participant groups when reading normal or disappearing text. The first hypothesis of this experiment was that, based on Rayner *et al.* (2003) and Liversedge *et al.* (2004), adult readers would not show a difference between normal and disappearing text on their oculomotor measures. In the present experiment, this hypothesis was found to be largely supported. No differences were found between normal and disappearing text for adults in total sentence reading times, the number of fixations made per sentence, fixation durations, refixation probabilities, or number of regressions per sentence.

In contrast to the ease with which the adult participants read the disappearing text, the children showed differences between reading normal text and disappearing text on two of the eye movement measures – mean fixation durations and refixation probabilities. When examining mean fixation durations, the results showed that both older and younger children made longer fixations when reading disappearing text than when reading normal text. However, there was no related increase in the number of fixations made or the number of regressions made. Rather, all participants made fewer refixations when reading disappearing text. This in itself is expected, as refixations become redundant once the word has disappeared. However, the reduction in probability of making refixations was greater in younger children than in older children or adults.

For the child participants, it was predicted that they would show disruption in their eye movements when reading disappearing text. This hypothesis was found to be partially supported, with disruption caused by the disappearing text influencing the durations of fixations and the number of refixations made by children when reading. While there are clear differences in eye movement behaviour between reading normal and disappearing text, these differences were not as prevalent across different measures as might have been expected. Further, it is not entirely clear that the observed differences in oculomotor behaviour when reading disappearing text can be labelled as "disruption". This will be discussed in more detail shortly.

Summary of frequency manipulation results. A set of analyses showed that longer single fixation durations, first fixation durations, and gaze durations were observed on low frequency words than high frequency words for all participants under both text presentation conditions. These results are now the second demonstration of a word frequency effect on children's fixation durations in sentence reading, replicating the effect found by Hyönä and Olson (1995). It was predicted that while adults would show an effect of word frequency in both conditions, children's reading would be disrupted by the disappearing text presentation such that they would not show an effect of word frequency in this condition. It was argued that 60 ms would be an insufficient period for children to process the fixated word to a level where word frequency metrics are accessed and are influential on measures of linguistic processing such as fixation durations. However, all participants – adults, older children and younger children – showed an effect of word frequency, even when the fixated word had disappeared after 60 ms. Children as young as 7-years could process the word sufficiently within 60 ms such that fixation durations were significantly longer for low frequency words than high frequency words (or the gaps that had replaced these words).

Comparison with previous studies. The present data from the adult sample do differ slightly from those found by Liversedge *et al.* (2004), who observed longer fixations and fewer refixations when reading disappearing text. These differences between this and the Liversedge *et al.* study likely reflect the redundancy of refixations when reading disappearing text – once the word had disappeared, only moving the eyes to a different word in the sentence would cause the previously fixated word to re-appear. Therefore refixating within the gap of the disappeared, fixated word would bring no new information to the reader. Consequently, they found that readers made longer fixations but fewer refixations. In the present experiment, no differences were found on either of these measures in the adult sample. It seems likely that this difference between the results of the studies is due to the difficulty of the reading material. In order to make the between-group comparisons as meaningful as possible, all participants read the same set of sentences. These were constructed with simple syntactic structures, and target words controlled for age of acquisition, in order to be as appropriate as possible for 7-year-old children.

These materials would therefore have been easy for the adults to read, compared to the age-appropriate stimuli used in the experiments by Liversedge *et al.* Consequently, adult participants in the present experiment may not have needed to refixate words as often as they might normally do when reading less easy material, and so there would be no change in refixation frequencies across the two conditions due to a floor effect in the normal condition. In line with this argument, in the data reported by Liversedge *et al.*, adult readers refixated 20% of words in the normal condition, and just 10% of words in the disappearing text condition. In the present data, adult readers refixated 12% of words in the normal condition and 11% of words in the disappearing text condition.

The ease of the reading material for adults in this experiment is a probable cause of the lower probability of refixations, and subsequently the difference between findings of the studies when comparing normal and disappearing text conditions. In addition to the possibility that the increased fixation durations in the disappearing text condition observed by Liversedge *et al.* reflect the time taken to reach a given level of processing of the fixated word (that would normally be affected by refixations), it is also likely that the longer fixation durations simply reflect the difficulty of the materials compared to those used in the present experiment.

In summary, the main findings in the adult data from the present experiment were a clear replication of those from Rayner *et al.* (2003), showing that when fixated text disappeared after 60 ms reading could proceed quite normally, and that word frequency effects still occurred under disappearing text conditions. Rayner *et al.* argued that that the continuing occurrence of a word frequency effect, even after the fixated word has disappeared, is evidence for cognitive control models of eye movements in reading. Therefore the present data provide further support for that position, demonstrating that both adults' and children's eye movements when reading these sentences were largely under cognitive control.

Children's reading of disappearing text. The children's data showed that, firstly, children's oculomotor behaviour when reading sentences was affected by the fixated word disappearing after 60 ms. Second, children of all ages did show effects of word frequency within 60 ms of fixating a word. These patterns of data in the disappearing text conditions suggest that a 60 ms presentation duration permits quite detailed processing to occur in children as young as 7-years-old. As discussed in relation to the adult data, increased fixation durations were observed alongside a decrease in refixation probabilities when reading age-appropriate materials (Liversedge *et al.*, 2004).

In the present experiment, the sentences were easy for adult readers but were age-appropriate in difficulty for the children. Therefore, as can be seen from the data in the normal text presentation condition, a higher proportion of refixations was made by children than adults, and more so in the younger children than in the older children. Consequently, when the ability to make the normal proportion of refixations became redundant as the text disappeared, children's refixation probability decreased and fixation durations increased. This pattern of data for the children is similar to that observed by Liversedge *et al.* for adult readers when reading material of appropriate difficulty. Importantly, "disruption" to the eye movement behaviour caused by the disappearing text is minimal.

It might have been predicted that the younger, and hence less skilled, the reader is, the more disrupted their eye movement behaviour would be when reading disappearing text. Critically, Aghababian and Nazir (2000) showed that decreasing visual presentation durations of words are required as age increases, in order to allow successful word recognition. In that case, it ought to have been that in the present experiment the younger children showed far more disruption when reading disappearing text relative to older children or adults. However, the only significant interactions between participant group and text presentation condition were on fixation durations and refixation probabilities – clearly not the pronounced disruption that might have been expected.

For example, during normal text reading refixations offer the reader a second opportunity to sample the visual information from that word. The younger the reader, the more frequently refixations are made. When the text has disappeared during the initial fixation on a word, there is no opportunity to refixate that word. It might therefore be expected that a compensatory strategy such as increasing the number of regressions made would be employed in order to obtain a second fixation on that word, particularly by younger readers, in order to successfully read disappearing text. However, this was not the case in the present data. It seems that, despite the typically high frequency with which younger children make a second fixation on a word, they do not require this second fixation for successful reading.

When reading disappearing text, despite a significant reduction in the number of refixations and yet no corresponding increase in the overall number of fixations or the number of regressions made, comprehension did not decrease (in fact, there was a small but reliable increase). The present data therefore indicate that children between the ages of 7- and 11-years make refixations during normal reading which are not entirely necessary. While the frequency of refixations does decrease with age, and presumably with reading skill, by the age of 7-years it may be that the refixations are more habit than necessity. When reading text where there are strict temporal limits on the availability of text, the present data suggest that the children were forced into what seems an almost more efficient eye movement pattern. Overall, reading was slightly slower. However, within that slowing, the pattern of eye movement behaviour became more similar to that of older readers and comprehension increased.

The role that refixations play in reading must also be considered in relation to data from the studies with adult participants. As discussed, Liversedge *et al.* (2004) showed that adult readers made longer fixations but fewer refixations when reading age-appropriate text. While the 20% refixation probability for adults reading normal, age-appropriate text is lower than the 30% refixation probability for 7- to 9-year-olds reading normal, age-appropriate text, refixations are still a remarkably frequent occurrence. Despite this, data from several studies now clearly demonstrate that when a strategy of making refixations becomes redundant due to the word disappearing, readers learn very quickly not to make many refixations. This does not seem to affect the reader's ability to read and comprehend the text, and they do not appear to adopt any kind of compensatory strategy that would allow them to obtain a second fixation on the words, such as regressions. Therefore it would seem that the relatively high proportion of refixations that is typically made during normal reading may not be strictly necessary, and that when the reader is presented with text in such a manner that they cannot make useful refixations, abandoning refixations is minimally detrimental to them. However, it is noteworthy that despite the disappearance of the fixated word, even skilled adult readers continued to make a baseline proportion of refixations of about 10% – 12%.

One possible reason for this is that refixations serve a more critical purpose for beginning readers at a very early stage of reading, and that they persist into skilled reading in high proportions more as a habit than as serving a necessary function.

This habit then declines as reading skill increases, even though it is never entirely eliminated. Thus the proportion of refixations that is typically made may be higher than is strictly necessary in order for the reader to comprehend the text. In order to examine this issue in more detail, it will be necessary to study the eye movement behaviour of even younger children, at a more preliminary stage of learning to read, to examine how they are able to tolerate the redundancy of refixations that occurs under disappearing text presentation conditions.

The time course of visual information extraction during reading, and its developmental trajectory. The precise level of processing which is achieved within 60 ms by readers of different ages cannot be determined from these data. However, these data do show very clearly the advantage for lexical identification of reading words within a sentence context. Children as young as 7-years showed minimal disruption to their oculomotor behaviour when reading text where each word disappeared 60 ms after it was fixated. The data from Aghababian and Nazir showed that 6- to 7-year old children required, on average, 125 ms presentation durations in order to achieve a lexical identification baseline of 60% correct. This would predict that, under the present manipulation, the younger children ought to have found it very difficult to read the disappearing text, and this difficulty would have been reflected in their eye movement behaviour. However, in the present experiment readers had the benefit of the semantic and syntactic context of the sentence, as well as the preview and postview benefits associated with the distributed processing of words across multiple fixations. These benefits are not available to readers in a single word task, and will inevitably have facilitated lexical identification, as demonstrated by the children's successful reading of disappearing text in the present experiment.

As argued by Rayner *et al.*, although it is not claimed that adult readers can complete all processing associated with a word within 60 ms, this time period appears sufficient for the visual system to extract the necessary information from the page for linguistic processing to proceed unimpaired. The question then arises of how quickly the visual system can take up information from the page during reading, and whether this does decrease with age or whether it is more tightly linked to the ease with which the material can be read. The present data, in comparison with previous adult studies, suggest that the difficulty level of the reading material strongly affected the ease with which readers of different ages were able to tolerate the disappearing text conditions. Having said this, the materials used in the present experiment were appropriate in difficulty for the children, as reflected by their high comprehension scores. Therefore the present experiment compared easy reading for adults compared to normal reading for the children – it should be noted that the reading was not difficult for any of the participants and so processing difficulty alone may not entirely explain the disruption observed in children's eye movement behaviour when reading disappearing text.

The trend in the present data for effects to be significant by items but not participants suggests high inter-individual differences in eye movement behaviour when reading. This probably reflects the range of ages included within the two child participant groups. Further, the sample sizes in this experiment were quite small. Therefore Experiment Two was designed in order to examine in more detail the time course of visual information extraction during reading, and its development with age.

2.5 Conclusions

Experiment One examined adults', older children's, and younger children's reading performance when the visual availability of the fixated word was restricted to the initial 60 ms of fixation. While adults could read simple sentences entirely normally under these conditions, older and younger children showed some disruption in their eye movements. These results indicate that the time course of visual information extraction might be slower in children than in adults, and are also suggestive of an influence of reading difficulty on that process. When reading material which is difficult, a higher occurrence of within-word refixations is normal. With the disappearing text presentation, refixations are redundant and so strategic changes in the manner in which the eyes progress through the sentence are necessary. However, the exact role that refixations play in normal reading can be questioned based on data from several experiments which show that we can read well despite being deprived of the opportunity to make useful refixations.

Chapter Three

The speed of visual processing during fixations in reading

3.1 Introduction

In Experiment One, participants read sentences presented either normally, or as disappearing text where each word disappeared 60 ms after it was fixated. The aim was to investigate the visual processing of text by readers of different ages. Adults, older children aged 10- to 11-years, and younger children aged 7- to 9-years were compared on the disruption caused to their reading by the disappearing text. The results from Experiment One, when considered in relation to the data from previous adult studies, showed that, when reading age-appropriate text, some disruption is observed in the eye movement behaviour of the reader. Fewer refixations are made, but fixation durations become longer.

When reading very simple text, as was the case for the adult participants in Experiment One, there were virtually no differences between the normal and disappearing text conditions. While this suggests that there is an influence of cognitive processing difficulty upon the speed with which the reader can take up information from the printed page, i.e. text familiarity, predictability, etc., it is still possible that there is also an age-related change in the speed of visual information processing during reading. The primary aim of Experiment Two was therefore to more thoroughly examine the speed of visual processing of the fixated word during reading, and whether this systematically changes with the reader's age.

The data from Experiment One also raised a question over the role of refixations during reading. While, during normal reading, they serve the purpose of allowing the reader a second opportunity to take up information from the fixated word, this opportunity is denied to the reader when the text has disappeared. The data from Experiment One showed that although readers made longer fixations when reading disappearing text, they did not initiate any compensatory strategy in order to gain a second fixation on words when refixations became redundant. Despite the significant reduction in refixations and the apparent lack of compensation for this in terms of second fixations, there was no decrease in comprehension of the material being read.

These data suggest that when a reader is presented with text in such a way that does not allow them to progress through the text in their normal manner, they adopt a slightly different strategy of making longer first fixations rather than making second fixations on words. This does not appear to be detrimental to comprehension. In Experiment Two the disappearing text paradigm was again used, and the time for which the fixated word was available after fixation onset before it disappeared was manipulated – either 40 ms, 80 ms, or 120 ms in comparison to normal text.

The second aim of Experiment Two was therefore to examine whether manipulating the temporal availability of the fixated word would lead readers to adopt different strategies for reading, depending on the period of visual stimulation for any given, fixated word.

In Experiment One, all children showed some differences in their eye movement behaviour when reading disappearing text, compared to adults. There are two possible reasons for these age-related differences. First, as suggested by comparing the data from adult readers across several different studies, the difficulty of the text in relation to the reader's age seems to affect the strategic manner in which a reader moves their eyes through a sentence, and the disappearing text manipulation has varying effects depending upon the reader's normal eye movement pattern associated with text of a given level of difficulty. Therefore children, for whom all text will be more difficult to read in comparison to skilled adult readers, might be disrupted to a proportionally greater degree by disappearing text than adults.

Second, there may be a developmental change in the speed with which information can be extracted from the printed page that is independent of the cognitive processing associated with the text.

If children's difficulty in reading disappearing text is related more to their reading skill, then they should be affected by the decreasing presentation durations in this experiment in a manner that is equivalent to that observed with the adult readers. The adult data from Experiment One, in relation to other studies, showed clearly that a higher proportion of refixations are normally made when text is more difficult to read. In line with this, for children, when reading the same sentences as adults, we see a higher proportion of refixations being made in comparison to the adults. Further, refixation probability, and the subsequent effect on fixation durations, was the measure on which adults and children differed in their reading of normal compared to disappearing text in Experiment One.

In Experiment Two, all the presentation durations used would lead to the fixated word disappearing, on average, long before the participant made a refixation. For example, the mean durations of fixations preceding a refixation from Experiment One were 228 ms, 235 ms, and 293 ms for adults, older and younger children respectively. For the condition in which the words disappeared 120 ms after fixation onset, the longest presentation duration used in the present experiment, the fixated word would therefore have disappeared over 100 ms before the participant typically made a refixation.

To be clear, all the text presentation conditions used in Experiment Two would have prevented all participants from making useful refixations. This is pertinent in relation to the finding that the main difference in eye movement behaviour, when reading age-appropriate disappearing text, was the decrease in refixation probability compared to that which occurs during normal reading.

Therefore, when reading disappearing text, if the main cause of age-related differences is reading skill, then the pattern of disruption caused by the text disappearing after different presentation durations ought to be the same for both adults and children. While there may be significant main effects, where the disappearance of words after shorter durations causes more disruption than the longer presentation duration conditions, these ought to affect adults and children to a similar degree.

The alternate explanation for the disruption to children's reading caused by disappearing text is that there is a developmental change in the speed with which readers can take up visual information during fixations in reading. If this is the case, then a different pattern would be predicted for the results. There ought to be a more systematic progression in terms of the amount of disruption caused by the words disappearing after shorter durations.

More specifically, this hypothesis would predict significant interactions between the participant's age group and the presentation duration across all measures. At any given age, there would be a specific presentation duration at which normal processing of word N could be initiated from the given visual input, and so eye movement behaviour in this condition would be the same as that observed when reading normal text. For any presentation durations below that specific duration, disruption would be observed in the eye movement behaviour. The length of the given duration that allowed initiation of normal processing would be hypothesized to decrease as age increases and so the predicted interactions would show that younger children would experience difficulty with longer presentation durations than older children who, in turn, would experience difficulty with longer presentation durations than adults.

So, if the pattern of age-related differences in Experiment One is attributable to differences in reading skill then the results from Experiment Two are predicted to show a particular pattern of disruption to readers' eye movement behaviour, specifically on refixation probabilities, caused by all disappearing text presentation durations. For the adults, who typically make a low proportion of refixations on these easy sentences, all disappearing text conditions ought to cause minimal disruption. However, more generally, effects of the text presentation condition on eye movement behaviour ought to be equal across participant groups.

In contrast, if the pattern of results from Experiment One were a consequence of an age-related change in the speed with which readers can take up visual information then the data from Experiment Two ought to show interactions between participant age group and the presentation duration. In this case, there ought to be a categorical shift between conditions, varying with age in terms of its precise timing, in which readers are able to read normally, and this ought to be evident across several different eye movement measures.

3.2 Methods

Participants. The 16 adult participants were all members of the University of Southampton, with an age range of 18- to 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 32 child participants were volunteers from local schools, in the Southampton area. All child participants were native English speakers with normal, uncorrected vision and no known reading difficulties. The 16 younger children were aged 7- to 9-years old, and the 16 older children were aged 10- to 11-years. Child participants were volunteers, and were naïve regarding the purpose of the study.

Apparatus. The apparatus was the same as that used in Experiment One.

Materials and Design. The stimuli were identical to those used in Experiment One. Sentences were presented in each of four different presentation conditions. There were three disappearing text conditions, where the delay between fixation onset and the word disappearing was manipulated – either 40 ms, 80 ms, or 120 ms, as well as a normal condition. A Latin-square design was used such that each sentence was presented in every condition, but participants did not read each sentence more than once.

Procedure. The procedure was the same as in Experiment One.

Analyses. The analyses were carried out in the same manner as in Experiment One. Fixations of less than 80 ms or more than 1200 ms were deleted (4.4% of adults' data, 3.4% older children's data, and 3.6% of younger children's data).

In this experiment, to further examine significant main effects of both participant group and of text presentation condition, the following three post-hoc t-tests were conducted in each case; 40 ms disappearing text (DT) with 80 ms DT, 80 ms DT with 120 ms DT, and 120 ms DT with normal text. Specifically, adjacent levels of the manipulation were compared in order to examine the specific presentation duration at which disruption occurred. Therefore, for these main effects, a Bonferroni-corrected p-value of 0.016 was used to evaluate the significance of the t-tests. For significant interactions between participant group and text presentation condition, the adjacent levels of the condition were compared for each group separately, leading to nine t-tests being conducted. Therefore, for significant interactions, a Bonferroni-corrected p-value of 0.006 was used to evaluate the significance of post-hoc t-tests.

3.3 Results

Data were only analysed from participants who had scored at least 70% on the comprehension questions, in order to ensure that all participants were able to understand the sentences.

Global measures. Means and standard deviations for all global measures are shown in Table 3.1. Each of the measures in Table 3.1 will be analysed individually to examine the developmental effects. For each measure, a 3 (Participant Group: adults vs. older children vs. younger children) x 4 (Text Presentation: 40 ms DT vs. 80 ms DT vs. 120 ms DT vs. normal text) repeated-measures was ANOVA carried out. For all graphs, the error bars show the standard error for each group in each condition. Given the results from Experiment One, showing that the key measures were refixation probabilities and fixation durations, the analysis of these measures is reported first.

Fig. 3.1 shows the mean refixation probabilities for each of the three participant groups under all four text presentation conditions.

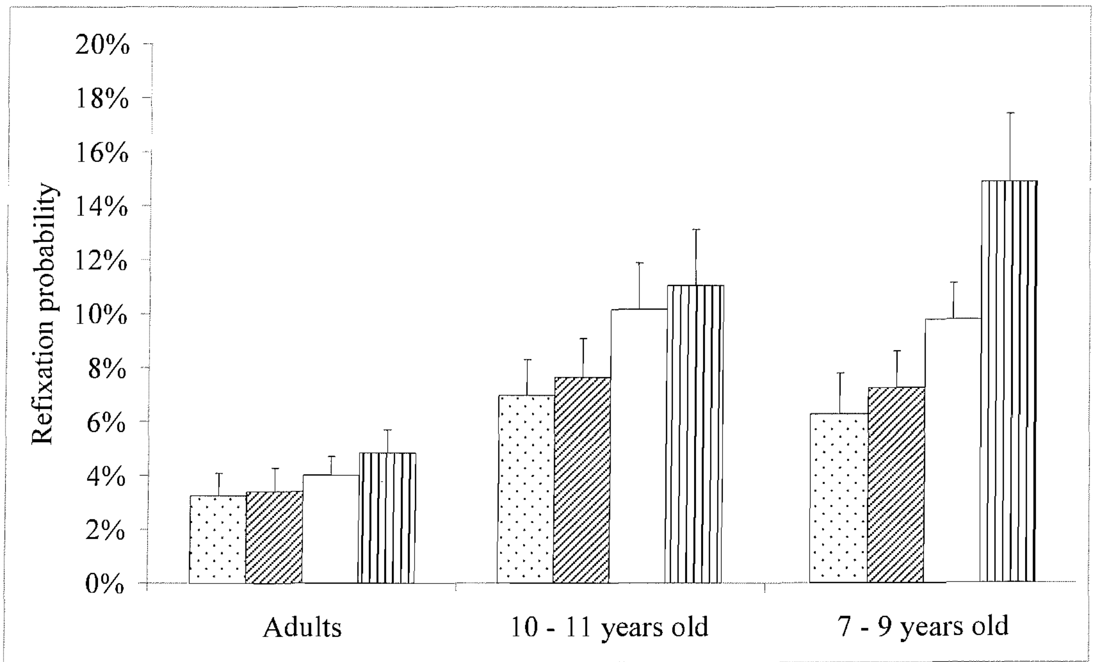

Fig. 3.1. Mean refixation probability for adults, older, and younger children for each of the four different text presentation conditions. Spotted bars represent data from the 40 ms DT condition, diagonal striped bars represent data from the 80 ms DT condition, plain bars represent data from the 120 ms condition, and vertical striped bars represent data from the normal text condition.

		Mean fixation duration (ms)	Mean sentence reading time (ms)	Mean number of fixations per sentence	Mean number of regressions per sentence	Mean refixation probability (%)	Mean skipping probability (%)
Adults	40 ms DT	264 (128)	2924 (815)	9.8 (2.5)	2.4 (1.5)	3 (3)	44 (7)
	80 ms DT	254 (113)	2738 (867)	9.4 (2.9)	2.2 (1.6)	3 (3)	44 (9)
	120 ms DT	254 (115)	2789 (774)	9.6 (2.3)	2.2 (1.4)	4 (3)	45 (8)
	Normal	249 (111)	2965 (760)	10.3 (2.4)	2.4 (1.4)	5 (3)	44 (9)
Older children	40 ms DT	280 (131)	5081 (2303)	15.8 (6.4)	5.3 (2.9)	7 (5)	41 (9)
	80 ms DT	271 (121)	5060 (2527)	16.2 (7.8)	5.4 (3.7)	8 (6)	40 (9)
	120 ms DT	271 (121)	4731 (2308)	15.3 (6.7)	4.9 (3.0)	10 (7)	39 (10)
	Normal	256 (113)	4666 (2120)	15.6 (6.6)	5.1 (3.1)	11 (8)	44 (11)
Younger children	40 ms DT	309 (134)	5809 (2352)	16.6 (5.9)	5.4 (2.9)	6 (6)	46 (11)
	80 ms DT	302 (131)	5522 (2168)	16.0 (5.4)	5.0 (2.9)	7 (5)	42 (12)
	120 ms DT	301 (138)	5838 (2311)	17.0 (5.6)	5.7 (3.0)	10 (5)	44 (10)
	Normal	285 (134)	5473 (1954)	16.8 (5.5)	5.2 (2.9)	15 (10)	39 (10)

Table 3.1. Means and standard deviations for fixation durations, total sentence reading times, the number of fixations and regressions made per sentence, and refixation and word skipping probabilities for adults, older, and younger children in each of the four text presentation conditions. Standard deviations are shown in parentheses.

There was a significant main effect of participant group, where younger readers made more refixations than older readers (F_1 (2, 45) = 5.71, p = 0.01; F_2 (2, 78) = 79.67, p < 0.001). Paired sample t-tests showed that while adults made fewer refixations than either older or younger children (all ts > 3, all ps < 0.01), the difference between older and younger children was not reliable (t_1 (30) = -0.21, p = 0.84; t_2 (39) = -0.91, p = 0.37).

There was also a main effect of text presentation condition, showing that fewer refixations were made with shorter presentation durations (F_1 (3, 135) = 22.47, p < 0.001; F_2 (3, 117) = 22.03, p < 0.001). This is unsurprising, given that refixations were redundant once the word had disappeared. Paired-samples t-tests showed that there were significant decreases in refixation probability between the 80 ms and 120 ms DT conditions, and between the 120 ms DT and normal conditions (all ts > 2, all ps < 0.016). However, there was no significant difference in refixation probability between the 40 ms and 80 ms DT conditions (t_1 (47) = -1.36, p = 0.18; t_2 (39) = -1.13, p = 0.27).

There was also a significant interaction between text presentation condition and participant group (F_1 (6, 135) = 4.44, p < 0.001; F_2 (6, 234) = 7.27, p < 0.001). When the three groups' data were analysed separately, the only difference in refixation probability was between the 120 ms DT condition and the normal condition for younger children, this being marginal by participants (t_1 (15) = -3.13, p = 0.007; t_2 (39) = -3.68, p = 0.001). For the younger children, the differences were not reliable between the 40 ms DT and the 80 ms DT conditions (t_1 (15) = -1.33, p = 0.20; t_2 (39) = -1.07, p = 0.29) or between the 80 ms DT and 120 ms DT conditions (t_1 (15) = --4.19, p = 0.001; t_2 (39) = -1.82, p = 0.08). All comparisons for the older children and adults failed to reach significance (all ts < 3, all ps ≥ 0.01).

These data show clearly that while readers of different ages had different baseline refixation probabilities under normal reading conditions, they were all reduced to a similar, low proportion when the fixated words were disappearing. The magnitude of the effect was largest in the younger children.

Fig. 3.2 shows the mean fixation durations for each participant group in each of the text presentation conditions. Significant main effects on fixation durations were found for both participant group and text presentation condition (all Fs > 9, all ps ≤ 0.001). For the effect of participant group, all three groups were found to be significantly different from each other (all *t*s > 2, all *p*s ≤ 0.01), with the exception of the difference between adults and older children across participants (t_1 (30) = -1.26, $p = 0.22$; t_2 (39) = -7.02, $p < 0.001$). Younger readers made significantly longer fixations than older readers.

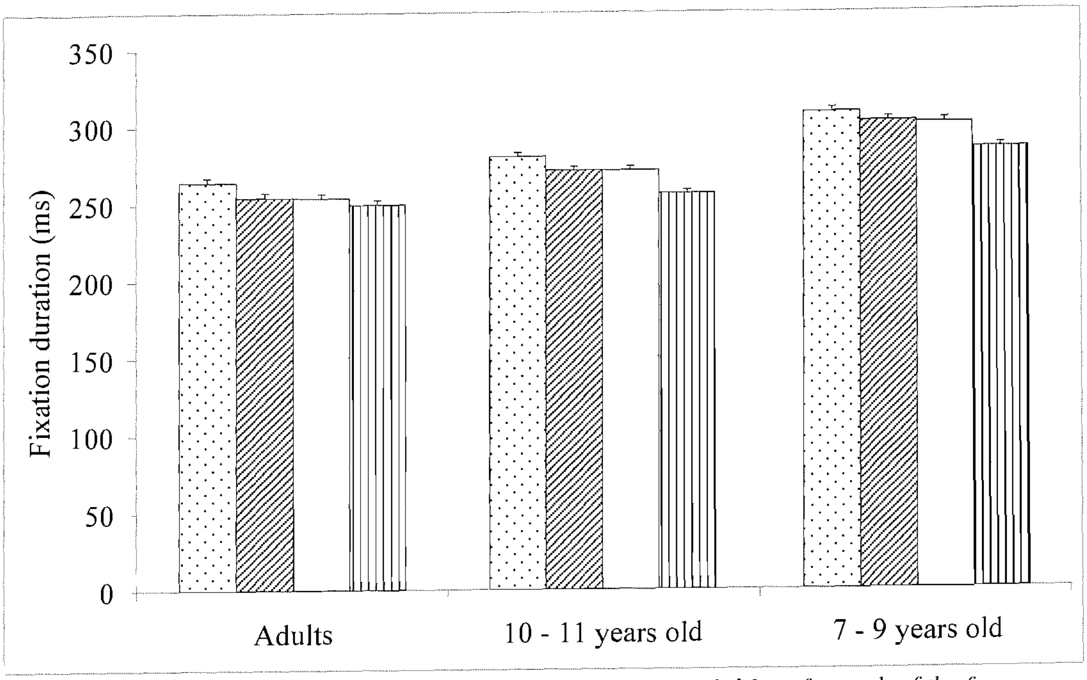

Fig. 3.2. Mean fixation durations for adults, older, and younger children for each of the four different text presentation conditions. Spotted bars represent data from the 40 ms DT condition, diagonal striped bars represent data from the 80 ms DT condition, plain bars represent data from the 120 ms condition, and vertical striped bars represent data from the normal text condition.

For the effect of text presentation condition, the three disappearing text conditions did not significantly differ from each other (all *t*s ≤ 3, all *p*s ≥ 0.01). However, fixation durations were significantly longer in the 120 ms DT condition compared to the normal condition (t_1 (47) = 3.81, $p < 0.001$; t_2 (39) = 3.11, $p = 0.003$).

These data, in line with those from Experiment One, show that there were longer fixations on disappearing text than on normal text. Further, in relation to refixation probabilities, the more quickly the word disappeared then the less likely the reader was to make a refixation but the longer the duration of the initial fixation. For this measure, the interaction between participant group and text presentation condition was not reliable (F_1 (6, 135) = 0.60, $p = 0.73$; F_2 (6, 234) = 0.71, $p = 0.64$).

While the data from refixation probabilities and fixation durations were, therefore, as predicted on the basis of previous studies, the presence or absence of interactions between participant group and text presentation conditions on other global eye movement measures will distinguish between the two possible theoretical explanations for age-related differences when reading disappearing text. The mean total sentence reading times for adults, older, and younger children across each of the four different text presentation conditions are shown in Fig. 3.3.

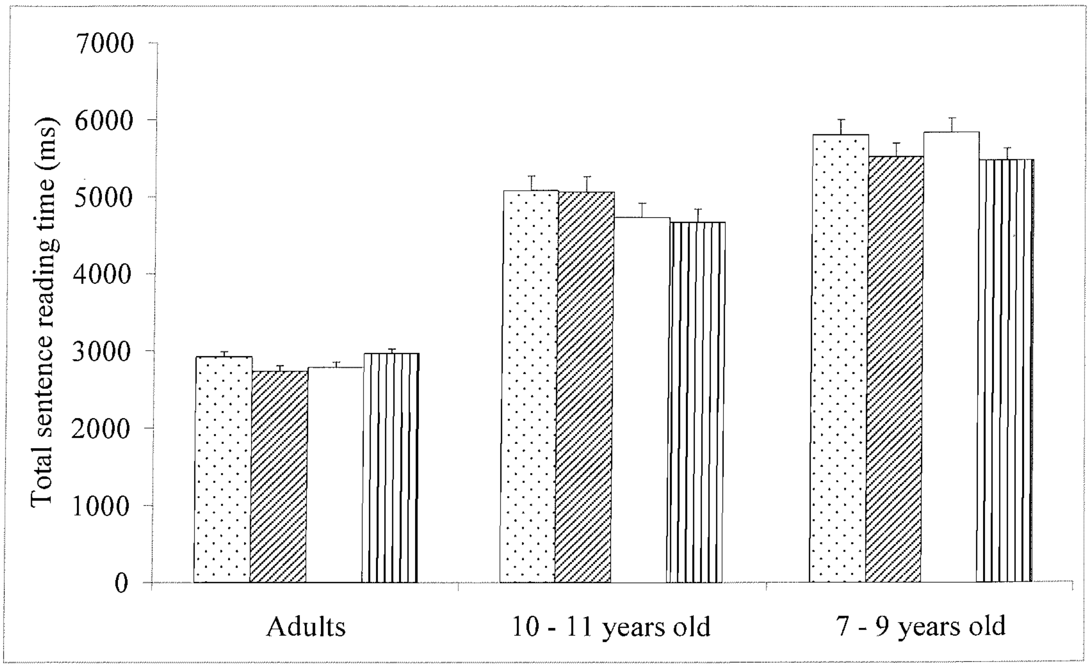

Fig. 3.3. Mean total sentence reading times for adults, older, and younger children. Spotted bars represent data from the 40 ms DT condition, diagonal striped bars represent data from the 80 ms DT condition, plain bars represent data from the 120 ms condition, and vertical striped bars represent data from the normal text condition.

Again, there was a significant main effect of participant group (F_1 (2, 45) = 17.12, $p < 0.001$; F_2 (2, 78) = 522.11, $p < 0.001$). Adults had shorter sentence reading times than either older or younger children (all ts > 4, all ps < 0.001). However, the difference between older and younger children was not reliable (t_1 (30) = -1.29, $p = 0.21$; t_2 (39) = -8.61, $p < 0.001$).

For this measure, there was no significant effect of text presentation condition (F_1 (3, 135) = 1.85, $p = 0.14$; F_2 (3, 117) = 0.641, $p = 0.59$). Further, critically, the interaction between participant group and text presentation condition was not significant (F_1 (6, 135) = 1.65, $p = 0.14$; F_2 (6, 234) = 1.45, $p = 0.20$). These data therefore suggest that adults and children across the full range of ages tested were equally undisrupted by all three text presentation durations as reflected by their total sentence reading times.

Figs. 3.4 and 3.5 show the mean number of fixations and regressions made per sentence respectively. For these two measures, the pattern of results was highly similar to that observed for the total sentence reading times.

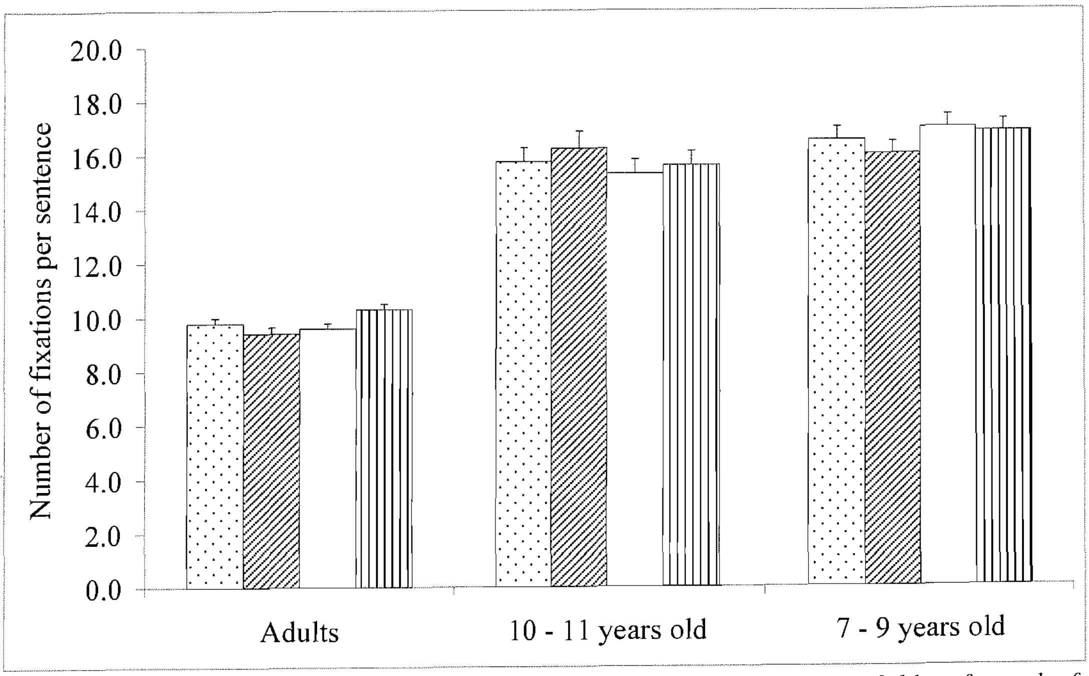

Fig. 3.4. Mean number of fixations per sentence for adults, older, and younger children for each of the four different text presentation conditions. Spotted bars represent data from the 40 ms DT condition, diagonal striped bars represent data from the 80 ms DT condition, plain bars represent data from the 120 ms condition, and vertical striped bars represent data from the normal text condition.

For both the number of fixations made per sentence and the number of regressions made per sentence, there was a significant effect of participant group (all *F*s > 14, all *p*s < 0.001). Adults made fewer fixations across the sentences, and fewer regressions, than either older or younger children (all *t*s > 4, all *p*s < 0.001). Again, the difference between older and younger children was not reliable, either for the number of fixations (t_1 (30) = -0.54, $p = 0.59$; t_2 (39) = -3.43, $p = 0.001$) or for the number of regressions (t_1 (30) = -0.257, $p = 0.80$; t_2 (39) = -1.15, $p = 0.26$) that they made per sentence.

For both measures, the number of fixations and the number of regressions made per sentence, there was no significant effect of text presentation condition (all *F*s < 1, all *p*s > 0.5). Further, for both of these measures, the interaction between text presentation condition and participant group was not significant (all *F*s < 2, all *p*s > 0.05).

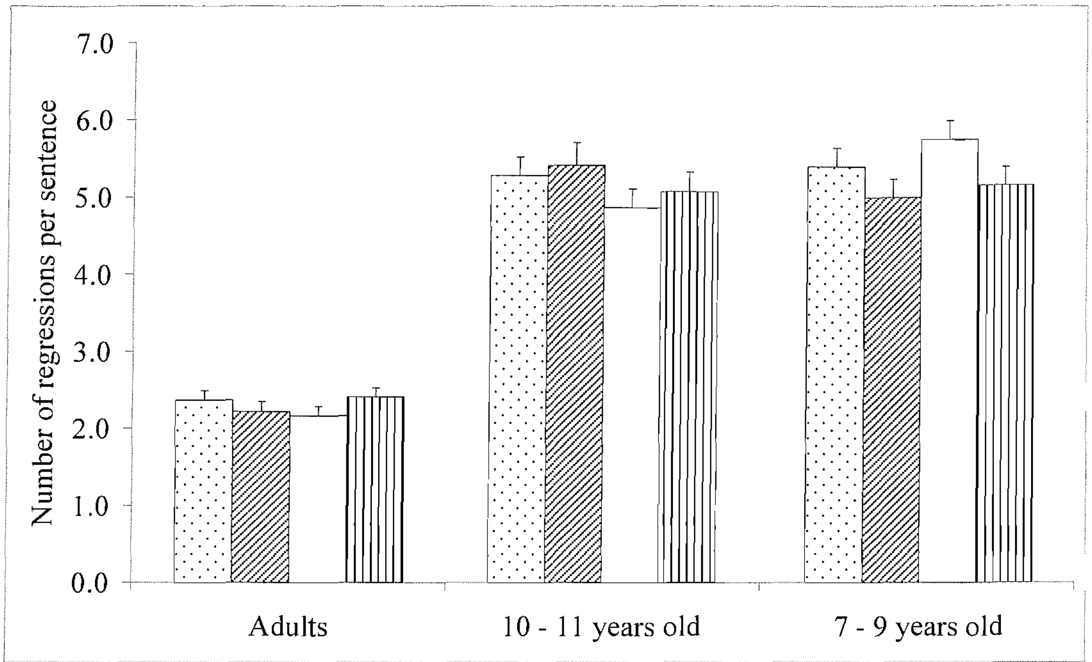

Fig. 3.5. Mean number of regressions per sentence for adults, older, and younger children for each of the four different text presentation conditions. Spotted bars represent data from the 40 ms DT condition, diagonal striped bars represent data from the 80 ms DT condition, plain bars represent data from the 120 ms condition, and vertical striped bars represent data from the normal text condition.

Therefore, for total sentence reading times, for the number of fixations made per sentence, and for the number of regressions made per sentence, the data show that readers of all ages were equally undisrupted by all three of the disappearing text presentation durations.

Finally, word skipping probabilities are shown in Fig. 3.6. For word skipping probability, there were no significant effects of either participant group (F_1 (2, 45) = 0.52, p = 0.60; F_2 (2, 78) = 2.74, p = 0.07) or of text presentation condition (F_1 (3, 135) = 0.50, p = 0.69; F_2 (3, 117) = 0.63, p = 0.60).

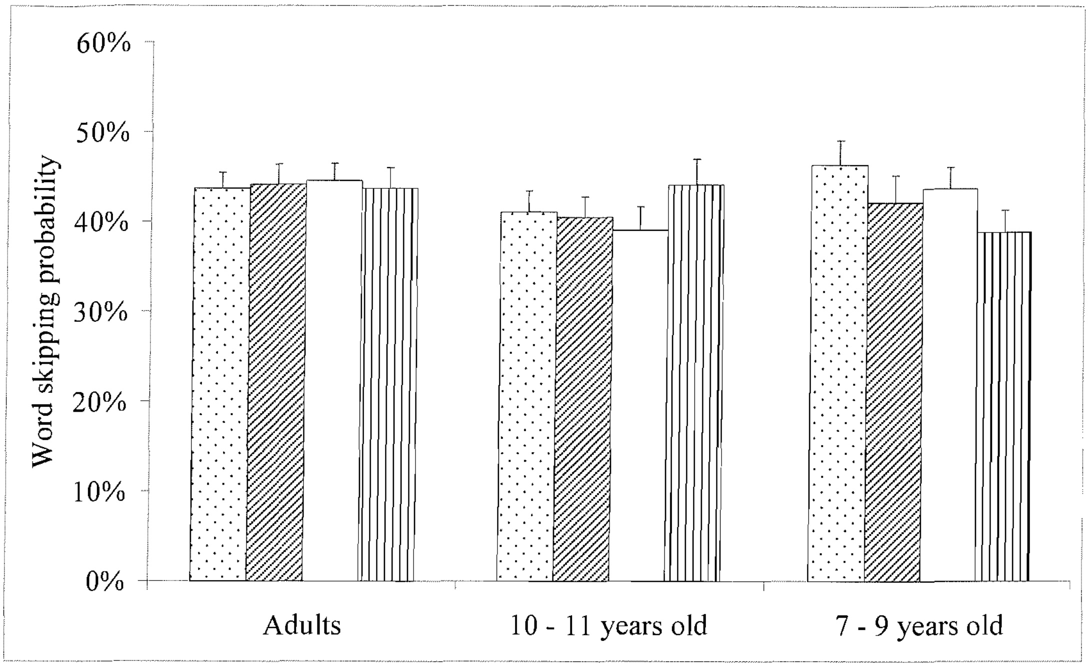

Fig. 3.6. Mean word skipping probability for adults, older, and younger children for each of the four different text presentation conditions. Spotted bars represent data from the 40 ms DT condition, diagonal striped bars represent data from the 80 ms DT condition, plain bars represent data from the 120 ms condition, and vertical striped bars represent data from the normal text condition.

There was a reliable interaction between these two variables (F_1 (6, 135) = 2.44, $p < 0.05$; F_2 (6, 234) = 2.60, $p < 0.05$). However, paired-samples t-tests showed that, for each of the three groups when analysed separately, there were no reliable differences between conditions (all ts < 3, all ps > 0.01).

Global measures – summary. The pattern of data observed in this section of the analyses was very similar to that observed in Experiment One. There were group differences on all measures except word skipping. For those measures where there was an effect of participant group, adults were always significantly different to both groups of children, but the two groups of children did not reliably differ. The exception was the mean fixation duration, where the difference between adults and older children was not reliable but older children made significantly shorter fixations than younger children. There were significant effects of text presentation condition upon fixation durations and refixation probabilities only, where readers made fewer refixations and had longer fixation durations with shorter presentation durations. However, there were no reliable interactions between participant group and text presentation condition on fixation durations, total sentence reading times, the number of fixations made per sentence, or regression probabilities.

Local measures. In a second series of analyses, the word frequency manipulation was analysed with respect to both participant group and text presentation condition. As in Experiment One, three key measures are reported – single fixation durations, first fixation durations and gaze durations.

For each measure, a 3 (Participant Group: adults vs. older children vs. younger children) x 4 (Text Presentation: 40 ms DT vs. 80 ms DT vs. 120 ms DT vs. normal text) x 2 (Word Frequency: high vs. low) repeated-measures ANOVA was carried out. For each of the three key measures, means and standard deviations are given for each participant group and for each condition in Table 3.2.

Single fixation durations, for each participant group in all four conditions, are shown in Fig. 3.7.

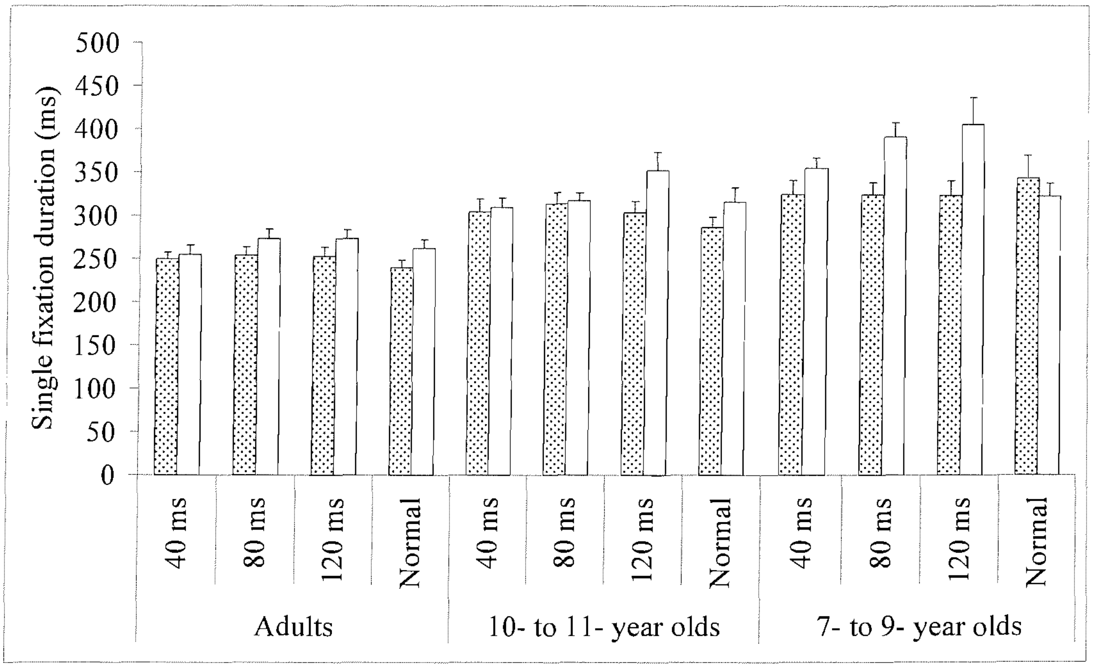

Fig. 3.7. Mean single fixation durations on high and low frequency target words for adults, older, and younger children under both normal reading conditions and the three disappearing text conditions. Spotted bars represent data from low frequency target words and plain bars represent data from high frequency target words.

For single fixation durations, there was a significant effect of participant group, where older readers made shorter fixations than younger readers (F_1 (2, 45) =

		Adults				10- to 11- years				7- to 9-years			
		40 ms	80 ms	120 ms	Normal	40 ms	80 ms	120 ms	Normal	40 ms	80 ms	120 ms	Normal
Single fixation duration (ms)	High	249 (62)	254 (72)	252 (84)	240 (69)	304 (115)	313 (92)	303 (90)	286 (83)	324 (116)	324 (96)	323 (123)	343 (173)
	Low	255 (83)	273 (88)	273 (80)	262 (75)	309 (84)	317 (67)	352 (150)	316 (109)	355 (87)	391 (121)	405 (216)	322 (102)
First fixation duration (ms)	High	249 (62)	247 (70)	251 (88)	237 (69)	295 (111)	294 (97)	281 (101)	278 (77)	312 (119)	308 (102)	309 (120)	328 (156)
	Low	252 (82)	265 (90)	270 (78)	259 (75)	306 (88)	308 (74)	328 (144)	306 (110)	342 (98)	365 (130)	360 (207)	335 (138)
Gaze duration (ms)	High	249 (62)	271 (88)	263 (91)	246 (74)	335 (204)	324 (93)	341 (208)	384 (315)	353 (164)	358 (133)	356 (167)	401 (187)
	Low	264 (88)	280 (88)	280 (88)	294 (128)	324 (109)	380 (325)	397 (250)	401 (200)	459 (466)	400 (136)	444 (249)	517 (480)

Table 3.2. Mean single fixation durations, first fixation durations, and gaze durations on high and low frequency target words for all three participant groups under all four text presentation conditions. Standard deviations are shown in parentheses.

16.57, $p < 0.001$). Adults made significantly shorter single fixations than either older or younger children (all ts > 3, all ps < 0.001). Again, the difference between older and younger children was not reliable (t_1 (30) = -2.24, $p = 0.03$; t_2 (39) = -4.98, $p < 0.001$). There was no significant effect of text presentation condition (F_1 (3, 135) = 2.07, $p = 0.11$).

There was a reliable effect of word frequency on single fixation durations, with longer fixations on low than on high frequency words (F_1 (1, 45) = 9.66, $p < 0.01$). None of the interactions were significant (all Fs < 2, all ps > 0.1). In particular, this shows that all participant groups showed effects of word frequency on single fixation durations under all text presentation conditions.

The same pattern of results was observed on first fixation durations. These results are shown in Fig. 3.8.

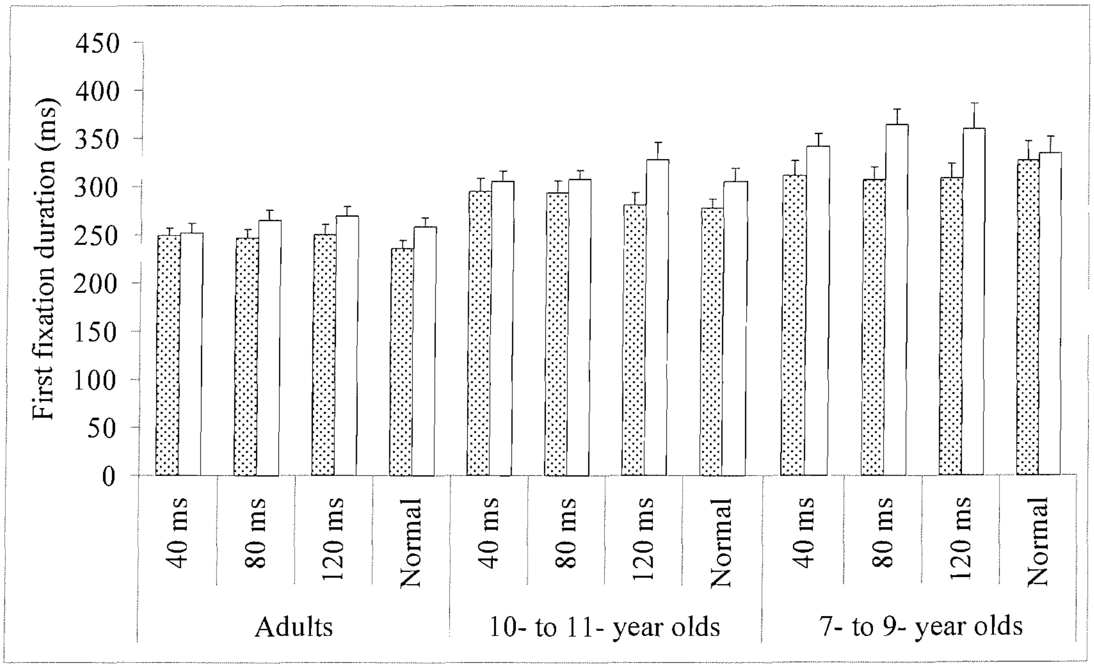

Fig. 3.8. Mean first fixation durations on high and low frequency target words for adults, older, and younger children under both normal reading conditions and the three disappearing text conditions. Spotted bars represent data from low frequency target words and plain bars represent data from high frequency target words.

There was a significant effect of participant group on first fixation durations (F_1 (2, 45) = 14.79, $p < 0.001$; F_2 (1, 78) = 98.47, $p < 0.001$). Adults made shorter fixations than either older or younger children (all ts > 3, all ps ≤ 0.01), but the difference between older and younger children was not reliable (t_1 (30) = -2.22, p =

0.03; t_2 (39) = -5.01, $p < 0.001$). Again, there was no significant effect of text presentation condition on first fixation durations (F_1 (3, 135) = 0.29, $p = 0.84$; F_2 (3, 117) = 0.46, $p = 0.71$).

There was a significant effect of word frequency, with longer first fixations on low than on high frequency words (F_1 (1, 45) = 12.71, $p = 0.001$; F_2 (1, 39) = 16.24, $p < 0.001$). As was the case with single fixation durations, there were no reliable interactions (all Fs < 2, all ps > 0.2). All participant groups showed a word frequency effect on first fixation durations under all text presentation conditions.

Finally, mean gaze durations on high and low frequency words for all three participant groups under each of the different text presentation conditions are shown in Fig. 3.9.

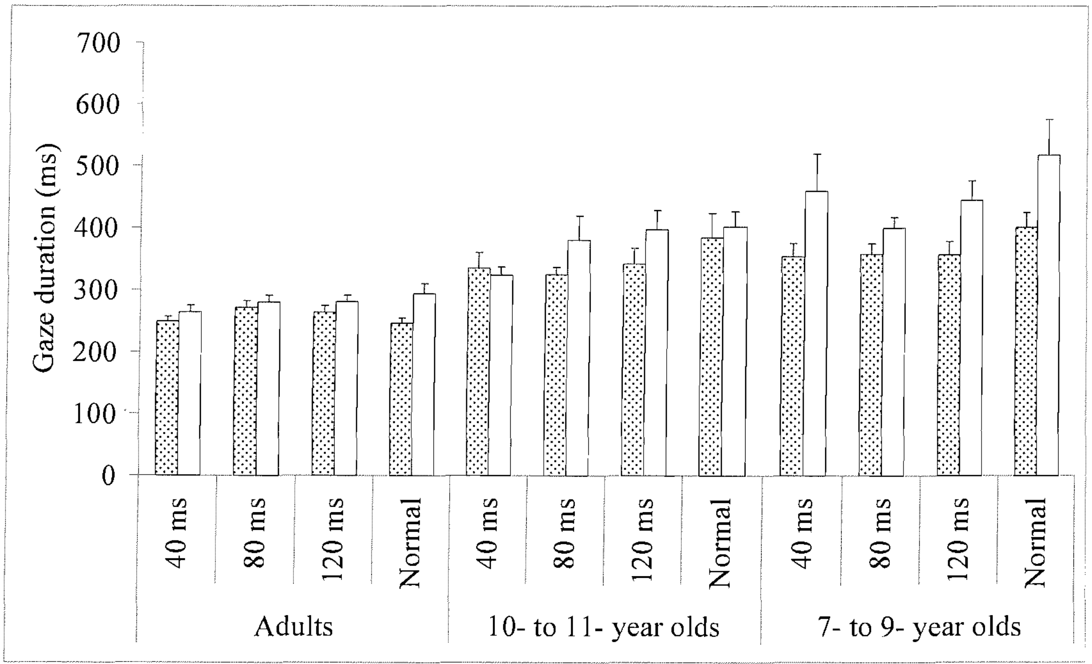

Fig. 3.9. Mean gaze durations on high and low frequency target words for adults, older, and younger children under both normal reading conditions and the three disappearing text conditions. Spotted bars represent data from low frequency target words and plain bars represent data from high frequency target words.

Once more, there was a significant main effect of participant group (F_1 (2, 45) = 9.75, $p < 0.001$; F_2 (1, 78) = 64.13, $p < 0.001$). Adults had longer gaze durations than either older or younger children (all ts $\geq$ 3, all ps $\leq$ 0.001). However, there was no reliable difference between the two groups of children in their mean gaze durations (t_1 (30) = -1.55, $p = 0.13$; t_2 (39) = -3.33, $p < 0.01$). For gaze durations, there was no effect of text presentation condition (F_1 (3, 135) = 1.38, p = 0.25; F_2 (3, 117) = 2.01, p = 0.12).

There was a reliable effect of word frequency, with longer gaze durations on low frequency than on high frequency words (F_1 (1, 45) = 19.74, p < 0.001; F_2 (1, 39) = 14.06, p = 0.001). The interaction between word frequency and participant group was not reliable (F_1 (2, 45) = 6.78, p < 0.01; F_2 (2, 78) = 2.53, p = 0.09). None of the other interactions were significant (all Fs < 1, all ps > 0.4).

Local measures - summary. There were reliable effects of word frequency upon single fixation durations, first fixation durations, and gaze durations for all participant groups under all text presentation conditions.

Response accuracy. Finally, the participants' response accuracy on the comprehension questions was analysed in order to ensure that none of the disappearing text manipulations prevented the readers from understanding the sentences normally. These data are shown in Fig. 3.10.

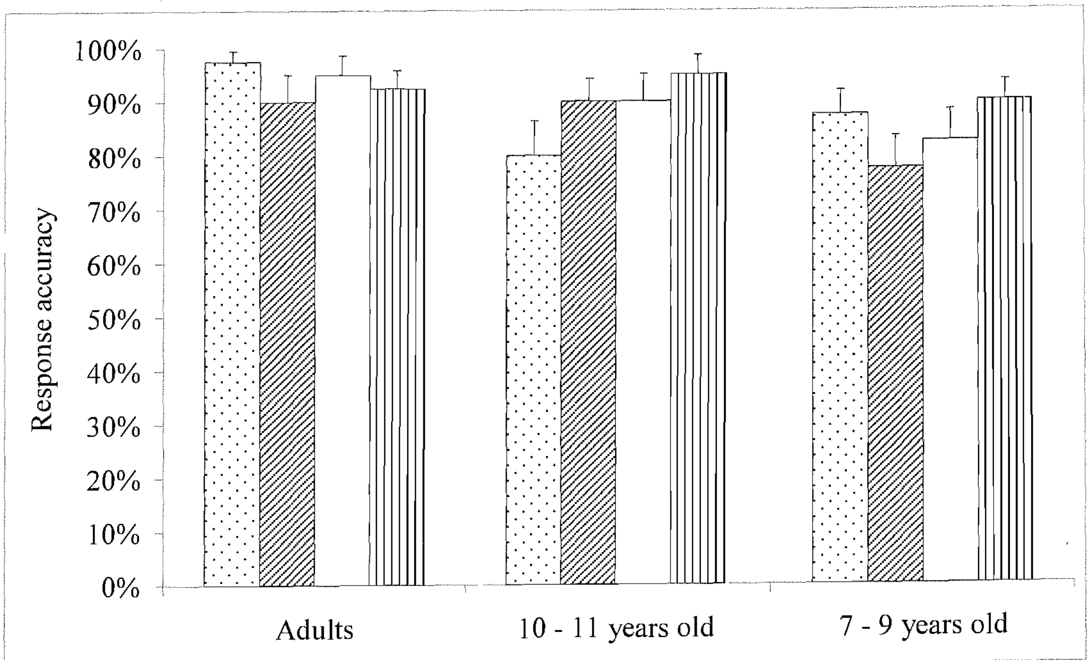

Fig. 3.10. Mean response accuracy for adults, older, and younger children for each of the four different text presentation conditions. Spotted bars represent data from the 40 ms DT condition, diagonal striped bars represent data from the 80 ms DT condition, plain bars represent data from the 120 ms condition, and vertical striped bars represent data from the normal text condition.

While numerical trends in the data suggest that response accuracy decreased with age, this effect was not reliable (F_1 (2, 45) = 4.14, $p < 0.05$; F_2 (2, 78) = 2.76, $p = 0.09$). It should be noted that all participants' overall comprehension score was at least 70%. Importantly there was no reliable effect of text presentation condition, nor was there a significant interaction between participant group and condition (all Fs < 2, all ps > 0.2). The participants' comprehension was therefore unaffected by the disappearing text manipulation.

3.4 Discussion

In Experiment One, it was found that there were systematic differences between adults and children in terms of how normal their eye movement behaviour was when reading text where every word disappeared 60 ms after fixation onset. Adult readers had no differences in their eye movement behaviour when reading disappearing text compared to normal text. Children had some disruption; specifically, there was a significant reduction in the proportion of refixations made when the fixated word disappeared, and there was a corresponding increase in fixation durations. It was noted that the same pattern had occurred for adult readers in a study which had presented them with age-appropriate sentences as disappearing text.

It would seem to be that, when reading age-appropriate text, we typically make a higher proportion of refixations than when reading very simple text. In this case, when the words disappear during fixation, refixations become relatively redundant and so participants make fewer of them. Therefore, the data across several experiments suggest that the differential refixation effects seen as a consequence of reading disappearing text are simply linked to the level of difficulty of that text in relation to the readers' age, and therefore the proportion of refixations that would be typically made.

However, this level of disruption to the eye movement behaviour when reading these sentences also raises the possibility that there is a developmental change in the speed with which a reader can take up visual information during fixations in reading. In this case, it might be that children are slower to extract the visual information from the fixated word. When the fixated word disappeared after 60 ms, adults may have been able to initiate normal lexical processing based on their visual input, but children may not have been able to do this as the period of visual stimulation was simply too short for them. Consequently, the disruption observed in the children's eye movement data when reading disappearing text would reflect their inability to proceed normally with cognitive processing of the text based upon their limited visual input.

In Experiment Two, there were two main aims. First, to examine the speed of visual processing during fixations in reading and whether this changes with the reader's age. Second, to examine the strategies adopted by readers of different ages when the presentation duration of the fixated word was varied, given that this manipulation would have prevented readers from making useful refixations.

Two possible mechanisms for age-related differences in reading disappearing text. There were two different predictions made, according to the two different possible mechanisms underlying the age-related differences observed in Experiment One. First, in the case that the effects in Experiment One were due to the reading skill and therefore the amount of difficulty associated with the stimuli for readers of different ages, it was predicted that all groups would be equally affected by the disappearing text manipulation. Further, it was predicted that there would not be effects of the manipulation on eye movement measures other than on refixation probabilities and the associated effect on fixation durations.

Alternatively, in the case that there is a developmental difference in the speed with which readers can take up visual information during fixations in reading, it was predicted that there would be significant interactions between participant group and text presentation condition, and that these effects should be seen across all eye movement measures.

The results showed effects of text presentation condition on refixation probabilities and fixation durations only. Further, there were significant interactions only on refixation probabilities and word skipping probabilities. It should be noted that the reading skill hypothesis predicted an interaction between participant group and text presentation condition on refixation probabilities. Critically, the speed of visual processing hypothesis predicted interactions across all eye movement measures, reflecting the disruption to normal cognitive processing of the text caused by the limited visual input. The disappearing text manipulation did not affect total sentence reading times, the number of fixations, or the number of regressions made per sentence, and it certainly did not affect the three participant groups in a differential manner.

Further, if it were the case that there was a developmental change in the speed of visual processing during fixations in reading, then the interactions ought to have shown a categorical shift across the conditions where there were some presentation durations which could be read as easily as normal text, and others below a given value which caused significant disruption to the eye movement behaviour. The particular time value for this categorical shift would have depended upon the reader's age. This was clearly not the case in the data from this experiment.

It should also be noted that in the earliest eye movement measure of cognitive processing, single fixation durations, there was a significant effect of word frequency but no three-way interaction with participant group and text presentation duration. With as little as 40 ms of visual input, children as young as 7-years-old showed an effect of word frequency equal to the effect for skilled adult readers. This provides extremely strong evidence that children's visual processing of the fixated word was as quick and as efficient as adults' in terms of allowing them to initiate normal linguistic processing. Therefore, the results from Experiment Two provide no evidence to support the possibility of a developmental change in the speed of visual processing during fixations in reading.

The data from this experiment fit more clearly with the hypothesis that the ability to read disappearing text is strongly related to reading ability, and the level of difficulty associated with the text for readers of a given age. The more difficult the text is for any given reader, the more frequently they will typically make refixations. When the text disappears, the reader is deprived of the opportunity to make a useful refixation. A significant reduction in the proportion of refixations, and the associated increase in fixation durations, would appear to be the characteristic pattern of eye movement behaviour associated with the reading of disappearing text, for readers of all ages. Due to the much higher proportions of refixations typically made by younger children than adults when reading the same sentences, there is a significant interaction. This interaction simply reflects readers of different ages and skills being reduced to the same, low level of refixations as a consequence of the experimental manipulation being made.

The role of refixations in normal reading. The second aim of the experiment was to examine the strategies adopted by readers of different ages when the presentation duration of the fixated word was varied, given that this manipulation would have prevented readers from making useful refixations.

It must be noted that, as was the case in Experiment One, overall there was very little disruption to participants' reading of the sentences. No increase in the number of fixations or regressions per sentence occurred, nor was there a cost to the total sentence reading times. Therefore the inability to make useful refixations seems not to be overly detrimental to the ease with which readers can progress through sentences. This is most striking in the case of younger children, where words may typically be refixated on 15% of occasions and this is reduced by more than half to 6% of occasions when reading disappearing text, yet incurring apparently only very minimal costs to fixation durations. As was speculated in the discussion of Experiment One, it may be the case that refixations serve a more critical purpose for children who are at the very early stages of learning to read and that the habit of making refixations declines as reading skill increases but with a lag between the two. Again, as was the case with the data from Experiment One, it is noted that there is a baseline level of refixations in the range of 3% - 7% for all readers in the condition where the fixated word disappeared at the shortest duration, 40 ms. Clearly readers do not completely stop making refixations, and refixations serve purposes in addition to simply affording the reader a second fixation on the current word.

Summary. Experiment Two examined whether the age-related differences observed in Experiment One were related to the reader's cognitive processing of the text, or whether there was a developmental change in the speed at which readers take up visual information during fixations in reading.

There were main effects of participant group upon fixation durations, total sentence reading times, and refixation and regression probabilities. As discussed with relation to the data from Experiment One, these main effects of participant group reflect the differences in processing difficulty associated with the age and reading skill of the participant, and are increasingly well-established in the literature (e.g. McConkie *et al.*, 1991; Rayner, 1986).

However, notably, there were few interactions between the participant age group and the text presentation condition on most eye movement measures. The presence or absence of these interactions was central to distinguishing between the two different possible accounts of the age differences observed in Experiment One.

The data from Experiment Two showed that any disruption observed in a reader's eye movement behaviour when reading disappearing text is related to the frequency with which they would normally make refixations when reading text at that level of difficulty. Therefore, the pattern of differences observed between adults and children in Experiment One was largely due to differences in cognitive processing difficulty associated with the materials used.

One of the most striking findings in these data was that children as young as 7-years-old showed an effect of word frequency upon their fixation durations with as little as 40 ms of visual input for any given word. These data provide strong evidence that from at least the age of 7-years, children are able to process visual information during fixations as rapidly as skilled adult readers.

The processing of word N+1 during fixations in reading. The next issue to be considered is the degree to which children are visually and/or linguistically pre-processing word N+1 during fixations on word N. Adult readers' parafoveal pre-processing during reading has been demonstrated both through experiments using the moving window technique (e.g. McConkie & Rayner, 1975; Rayner, 1975), and the disappearing text manipulation (Rayner, Liversedge & White, 2006). Children's parafoveal pre-processing during sentence reading has had very little investigation, although it is known that the perceptual span does extend beyond the fixated word (Rayner, 1986). The level to which children of different ages can pre-process information from the right of fixation is unknown. Experiment Three will examine the influence of temporal restrictions on pre-processing of word N+1 in children compared to adults.

3.5 Conclusions

Experiments One and Two have both demonstrated that children between the ages of 7- and 11-years show differences in their eye movement behaviour when reading disappearing text compared to normal text that do not occur for skilled adult readers. However, these differences appear to be related to the difficulty of the text for readers of different ages. There is no evidence in these data to support the hypothesis that there is a developmental change in the speed of visual information processing of the fixated word.

Chapter Four

Children's parafoveal pre-processing

4.1 Introduction

Experiments One and Two investigated the speed of adults' and children's visual information uptake during fixations in reading. The results showed that while children had differences in their eye movement behaviour when reading disappearing text compared to normal, this was linked to their increased cognitive processing difficulty as beginning readers compared to adults, and not to a developmental change in the speed of visual processing during fixations in reading. Adults' reading was entirely normal when reading disappearing text. For readers from the age of 7-years on, these experiments provided evidence that the visual system is able to take up all the necessary information to initiate normal linguistic processing within the first 40 ms of a fixation. Remarkably, an effect of word frequency was observed on single fixation durations for all readers with a presentation duration of just 40 ms.

The aim of Experiment Three was to examine the time course of parafoveal pre-processing in children compared to adults during normal sentence reading. Previous research has shown that the perceptual span is smaller in children than in adults; also, that children make less use of information to the right of fixation within the perceptual span than adults do (Rayner, 1986). These data suggest that during a fixation in reading, children devote more attention and processing capacities to the fixated word (word N) and relatively fewer to the word to the right of fixation (word N+1), compared to skilled adult readers.

In Experiment Three, the temporal availability of word N+1 was limited to 60 ms, essentially restricting any pre-processing to the initial 60 ms of fixation on word N. A previous study has shown that when adult readers were presented with sentences in which word N+1 disappeared 60 ms after fixation onset on word N, their reading was extremely disrupted (Rayner *et al.*, 2006). Longer sentence reading times were observed when N+1 disappeared after 60 ms than when reading normal sentences. This effect on sentence reading times occurred both when word

N+1 disappeared and when it was masked after 60 ms. Further, readers made longer fixations and more regressions when word N+1 was masked or disappeared than with normal sentences.

Rayner *et al.* discussed their data with an implicit assumption of serial, rather than parallel, lexical identification during fixations in sentence reading. According to them, the disruption to reading experienced when pre-processing is restricted to the initial 60 ms of a fixation, compared to the almost unimpaired reading that occurs when the fixated word disappears 60 ms after fixation onset, demonstrates that early portions of fixations are devoted to the visual uptake of information from word N, and it is the later portions of fixations in which pre-processing of word N+1 primarily occurs. The occurrence of disruption to reading when word N+1 was masked showed that pre-processing goes beyond processing the visual characteristics of the word such as its length.

A range of studies have examined the characteristics of upcoming text that skilled adult readers can pre-process in the parafovea, including word length, word shape, and external letter identities, and the eccentricity from fixation at which the varying types of information become available to the reader (McConkie & Rayner, 1975; Rayner & Bertera, 1979; Rayner, 1978; Rayner, McConkie & Zola, 1980; Rayner, Well, Pollatsek & Bertera, 1982). In stark contrast, very little is known about children's parafoveal pre-processing. While Rayner (1986) examined the overall size of the perceptual span in children of different ages compared to adults, there have been no studies which have examined the characteristics of children's parafoveal preview during reading in more detail.

The aim of Experiment Three was to compare adults', older and younger children's reading when parafoveal preview of word N+1 was restricted to the initial 60 ms of fixation on word N. Three predictions were made for this experiment. First, that adults would show significant disruption in their eye movement behaviour when parafoveal preview was restricted, consistent with the data of Rayner *et al.* (2006).

Second, it was predicted that all children would be disrupted to a lesser extent than the adults by the limited preview of word N+1. Given that previous work has demonstrated children's parafoveal pre-processing during reading to be restricted in comparison to that of adults, children should be less affected by the restrictions on parafoveal preview manipulated in the present experiment.

Third, as might be expected, it was predicted that normal word frequency effects would be observed on eye movement measures when reading disappearing text. This prediction was made because as the target words, as was the case with all the words in the sentences, would appear entirely normally once directly fixated.

4.2 Methods

Participants. The 12 adult participants were all members of Durham University with an age range of 18- to 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 24 child participants were volunteers from local schools, in both the Durham and the Southampton areas. All child participants were native English speakers with normal, uncorrected vision and no known reading difficulties. The 12 younger children were aged 7- to 9-years old, and the 12 older children were aged 10- to 11-years. Child participants were volunteers, and were naïve regarding the purpose of the study.

Apparatus. The apparatus was the same as that used in Experiment One.

Materials and Design. The stimuli were identical to those used in Experiment One. In the disappearing text condition, word N+1 disappeared 60 ms after the onset of fixation on word N.

Procedure. The procedure was the same as in Experiment One.

Analyses. The analyses were carried out in the same manner as in Experiment One. Fixations of less than 80 ms or more than 1200 ms were deleted (4.9% of the adult's data, 4.4% of the older children's data, and 3.2% of the younger children's data).

For significant main effects of group, three post-hoc t-tests were compared in order to compare each of the participant groups to the others. For significant interactions between participant group and text presentation condition, three post-hoc t-tests were also conducted in order to examine the effect of condition in each of the three groups separately. Therefore, for all these post-hoc t-tests, a Bonferroni-corrected p-value of 0.016 was used to determine the significance of these tests. For the significant three-way interaction between group, condition, and frequency, six post-hoc t-tests were conducted in order to examine the effect of word frequency for each group under each of the conditions. Therefore, for these t-tests, a Bonferroni-corrected p-value of 0.008 was used to determine significance.

4.3 Results

Data were only analysed from participants who had scored at least 70% on the comprehension questions, in order to ensure that all participants were able to understand the sentences.

Global measures. Table 4.1 shows the mean total sentence reading time, mean number of fixations per sentence, mean fixation duration, mean refixation probability, mean word skipping probability, and mean number of regressions per sentence for adults, younger and older children. Each of the measures in Table 4.1 will be analysed individually to examine the developmental effects. For each measure, a 3 (Participant Group: adults vs. older children vs. younger children) x 2 (Text Presentation: normal vs. disappearing text) repeated-measures ANOVA was carried out.

For all graphs, standard error bars are shown for each group under each presentation condition. Fig. 4.1 shows the mean fixation durations of adults, older, and younger children when reading both normal text and text where each word disappeared 60 ms after fixation onset on the prior word.

There was a significant main effect of participant group, such that younger readers made longer fixations than older readers (F_1 (2, 33) = 11.37, $p < 0.001$; F_2 (2, 39) = 266.95, $p < 0.001$). Paired-samples t-tests were conducted in order to compare the three different participant groups, and showed that younger children made longer fixations than older children or adults, and further that older children also made longer fixations than adults (all ts > 2, all ps < 0.016). The only

	Adults		Older children		Younger children	
	Normal	**DT**	**Normal**	**DT**	**Normal**	**DT**
Mean fixation duration (ms)	217 (88)	245 (115)	243 (95)	272 (137)	275 (124)	308 (163)
Mean total sentence reading time (ms)	2397 (742)	2798 (871)	3301 (1151)	4061 (1689)	4782 (1766)	5792 (1990)
Mean number of fixations per sentence	9.3 (2.8)	9.8 (2.8)	11.4 (4.0)	12.8 (5.2)	15.0 (5.1)	16.4 (5.8)
Mean number of regressions per sentence	2.4 (1.4)	2.6 (1.5)	3.6 (2.1)	4.1 (2.3)	4.9 (2.5)	5.8 (2.8)
Mean refixation probability (%)	10 (7)	11 (7)	15 (10)	18 (11)	21 (12)	20 (8)
Mean word skipping probability (%)	48 (10)	46 (7)	50 (12)	47 (14)	43 (10)	44 (6)

Table 4.1. Means and standard deviations for global measures, for sentences presented either normally or as disappearing text, for adults, older, and younger children. Standard deviations are shown in parentheses.

exception was a marginally reliable difference between older and younger children across participants (t_1 (22) = -2.52, p = 0.019).

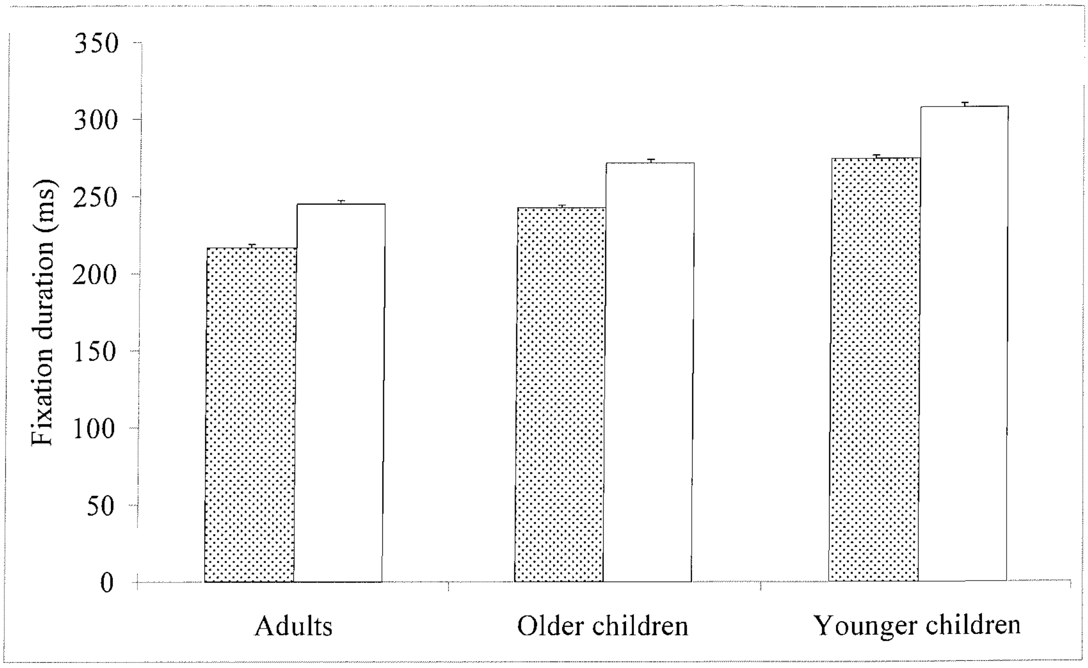

Fig. 4.1. Mean fixation durations of adults, older, and younger children for both normal and disappearing text. Spotted bars represent normal text, and plain bars represent disappearing text.

There was also a significant effect of text presentation condition, with fixation durations being longer for disappearing text than for normal text (F_1 (1, 33) = 55.90, $p < 0.001$; F_2 (1, 39) = 167.46, $p < 0.001$). However, the interaction between participant group and text presentation condition was not significant (F_1 (2, 33) = 0.22, p = 0.81; F_2 (2, 39) = 0.67, p = 0.52). The fixation duration data therefore show that the disappearance of the word to the right of fixation was disruptive to readers of all ages, such that longer fixations were made. However, this was also the case in the data from Experiments One and Two where the fixated word disappeared and yet the lack of effects on other eye movement measures (apart from refixation probabilities) indicated the participants' ease in progressing through the text. Therefore it is necessary to consider the mean fixation duration data in relation to the data from other measures to unequivocally demonstrate that reading was disrupted by the disappearance of word N+1.

The mean total sentence reading times for each of the three participant groups under both normal and disappearing text conditions are shown in Fig. 4.2.

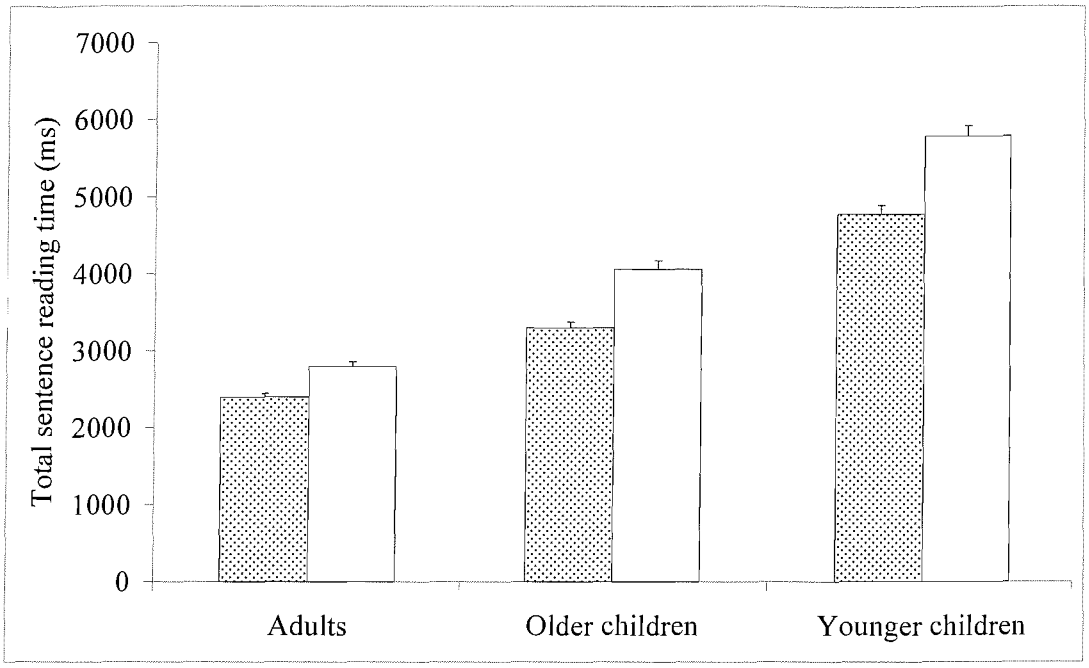

Fig. 4.2. Mean total sentence reading times of adults, older, and younger children for both normal and disappearing text. Spotted bars represent normal text, and plain bars represent disappearing text.

Again, there was a significant main effect of participant group (F_1 (2, 33) = 22.93, $p < 0.001$; F_2 (2, 39) = 717.27, $p < 0.001$). Younger children had longer sentence reading times than older children or adults, and older children also had longer sentence reading times than adults (all ts > 2, all ps ≤ 0.01). Additionally, there was a main effect of text presentation condition such that sentence reading times were longer under disappearing text conditions than under normal reading conditions (F_1 (1, 33) = 30.97, $p < 0.001$; F_2 (1, 39) = 37.37, $p < 0.001$).

For total sentence reading times, the interaction between participant group and text presentation condition was not reliable (F_1 (2, 33) = 1.83, $p = 0.18$; F_2 (2, 39) = 3.79, $p < 0.05$).

Here, for readers of all ages, there was a cost associated with reading the disappearing text, as reflected in the sentence reading times. In Experiments One and Two there were no reliable effects on sentence reading times for any participant group. The contrast here is quite striking, where all participants groups were affected by the disappearing text. Further, it is noted that although the interaction between participant group and text presentation condition was not reliable, numerical trends in the data indicate that the disruption was more pronounced in younger readers.

Similar patterns were observed for the number of fixations and the number of regressions made per sentence. The mean number of fixations made per sentence for each group in each condition is shown in Fig. 4.3.

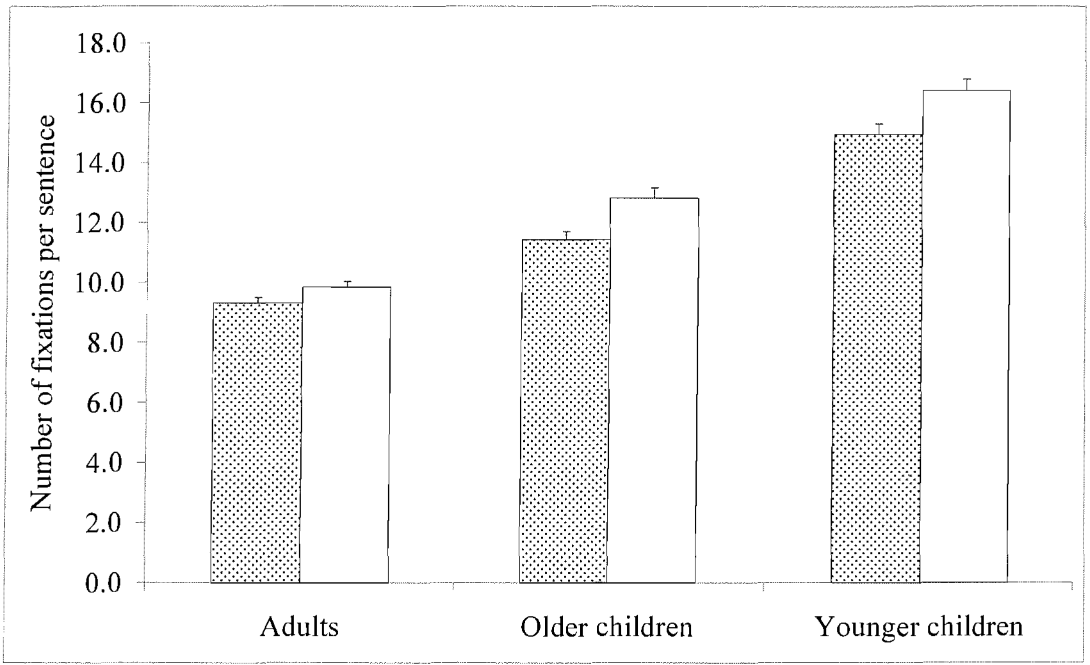

Fig. 4.3. Mean number of fixations made per sentence by adults, older, and younger children for both normal and disappearing text. Spotted bars represent normal text, and plain bars represent disappearing text.

Again, there was a main effect of participant group (F_1 (2, 33) = 12.07, p < 0.001; F_2 (2, 39) = 16.03, p < 0.001). Adults made fewer fixations per sentence than younger children (t_1 (22) = -5.16, p < 0.001; t_2 (39) = -24.48, p < 0.001). However, the differences were not reliable between adults and older children (t_1 (22) = -2.21, p = 0.04; t_2 (39) = -16.40, p < 0.001) and between older and younger children (t_1 (22) = -2.48, p = 0.02; t_2 (39) = -16.39, p < 0.001).

There was also a main effect of presentation condition, such that more fixations were made per sentence when presented as disappearing text than as normal text (F_1 (1, 33) = 8.57, p < 0.01; F_2 (1, 39) = 414.37, p < 0.001). However, for the number of fixations made per sentence, there was no significant interaction between participant group and presentation condition (F_1 (2, 33) = 0.63, p = 0.54; F_2 (2, 39) = 2.24, p = 0.11). Once again, numerical trends in the data indicate a higher level of disruption for the younger readers compared to the older readers.

Fig. 4.4 shows the mean number of regressions made per sentence, for each group in each condition. Once more, there was a significant effect of participant group (F_1 (2, 33) = 18.14, $p < 0.001$; F_2 (2, 39) = 270.30, $p < 0.001$). Adults made fewer regressions per sentence than both older and younger children, and older children also made fewer regressions than younger children (all ts > 2, all ps ≤ 0.01). There was also a significant effect of presentation condition, with more regressions being made per sentence under disappearing text conditions than under normal conditions (F_1 (1, 33) = 8.79, $p = 0.01$; F_2 (1, 39) = 25.45, $p < 0.001$).

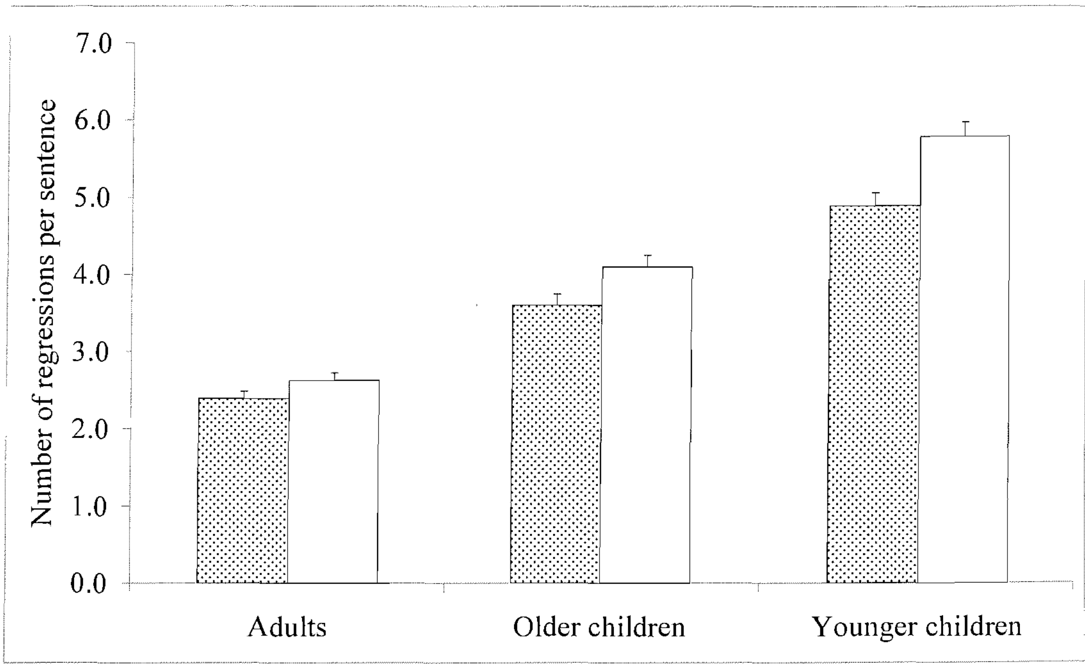

Fig. 4.4. Mean number of regressions made per sentence by adults, older, and younger children for both normal and disappearing text. Spotted bars represent normal text, and plain bars represent disappearing text.

The interaction between participant group and presentation condition was not reliable (F_1 (2, 33) = 1.16, $p = 0.33$; F_2 (2, 39) = 4.41, $p < 0.05$). However, as can be seen in Fig. 4.4, the difference in the number of regressions made per sentence when reading either normal or disappearing text was numerically more pronounced in younger than in older readers.

Thus far, the data show quite clearly the disruption caused by the disappearance of word N+1 60 ms after fixation onset on word N. Further, and somewhat surprisingly, numerical trends in the data indicate that this disruption is more pronounced for the younger readers compared to the older readers although these differences are not statistically reliable. The final two global measures that were analysed were refixation probabilities, where the most interesting patterns of results lay in Experiments One and Two, and word skipping probabilities.

Mean refixation probabilities for both normal and disappearing text, for all three participant groups, are shown in Fig. 4.5. There was a significant effect of participant group on the probability of refixating a word, (F_1 (2, 33) = 3.71, $p <$ 0.05; F_2 (2, 39) = 52.80, $p < 0.001$). All three groups were significantly different from each other, although not all effects were reliable by participants. Adults made significantly fewer refixations younger children (t_1 (22) = -2.87, $p = 0.01$; t_2 (39) = -10.01, $p < 0.001$). However, there were no reliable differences between adults and older children (t_1 (22) = -1.81, p = 0.08; t_2 (39) = -6.78, p < 0.001), or between older and younger children (t_1 (22) = -1.02, p = 0.32; t_2 (39) = -3.82, p < 0.001).

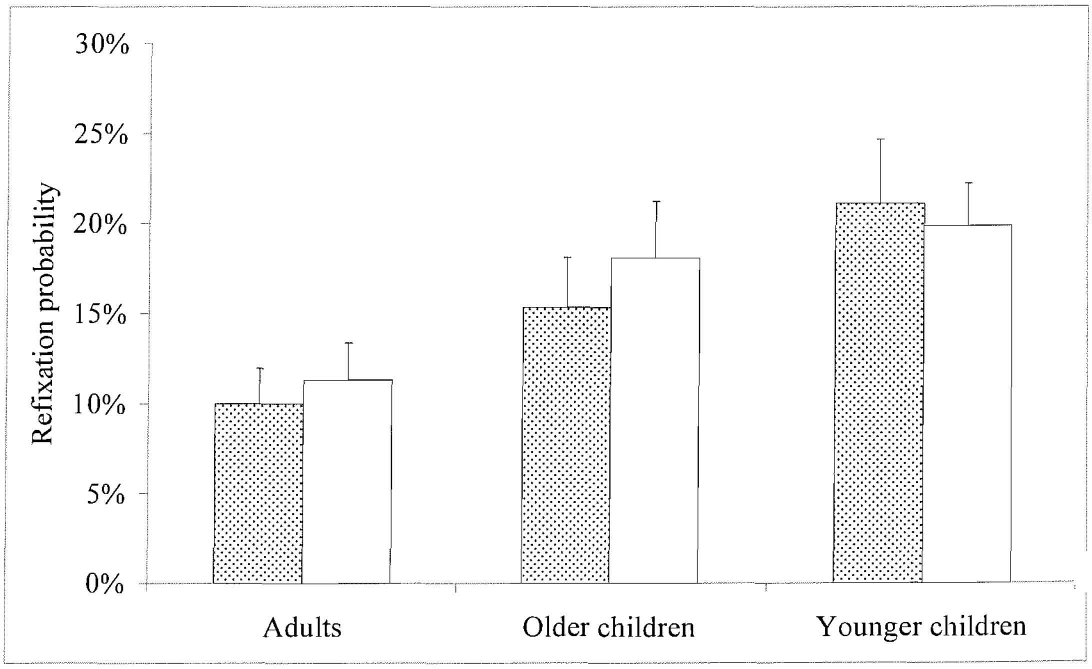

Fig. 4.5. Mean refixation probability for adults, older, and younger children for both normal and disappearing text. Spotted bars represent normal text, and plain bars represent disappearing text.

There was no significant difference in refixation probability between reading normal and disappearing text (F_1 (1, 33) = 0.87, $p = 0.36$; F_2 (1, 39) = 0.99, $p =$ 0.33), nor was there a significant interaction between participant group and text presentation condition (F_1 (2, 33) = 0.26, $p = 0.77$; F_2 (2, 39) = 1.95, $p = 0.15$). The pattern observed in the refixation probability data here is clearly very different to that observed in Experiments One and Two, where the disappearance of the fixated word had a very strong effect on refixation probabilities. In contrast, when the word to the right of fixation disappeared, there was no effect on refixation probabilities for readers across the range of ages tested in the present experiment.

Finally, the probability of skipping words is shown in Fig. 4.6. The effect of participant group was not reliable on this measure (F_1 (2, 33) = 1.14, $p = 0.33$; F_2 (2, 39) = 11.30, $p < 0.001$).

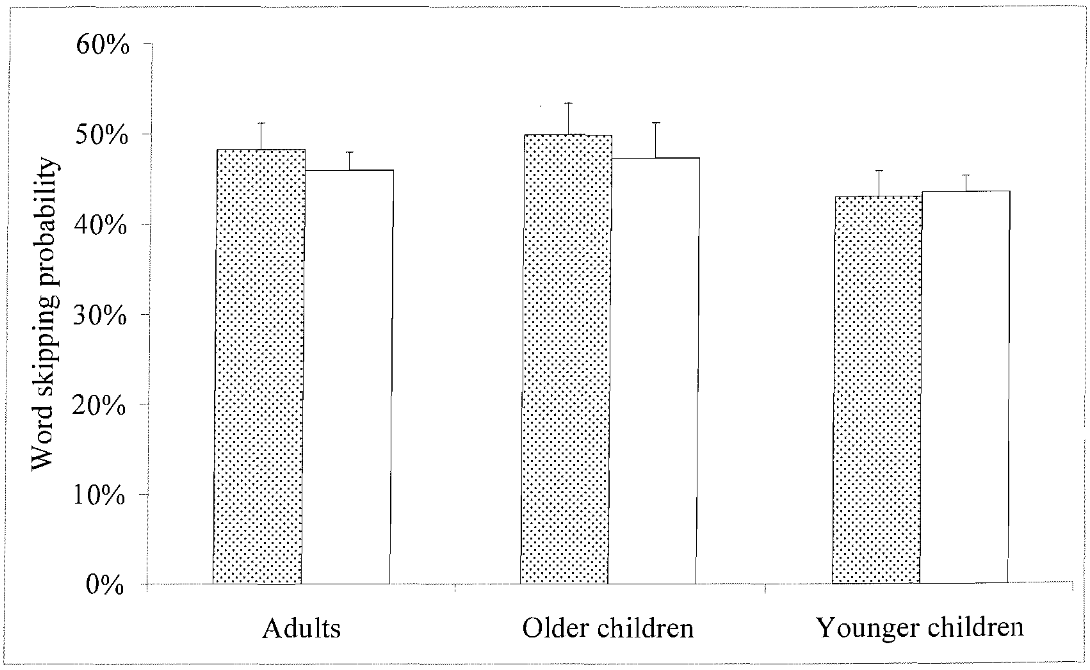

Fig. 4.6. Mean word skipping probability for adults, older, and younger children for both normal and disappearing text. Spotted bars represent normal text, and plain bars represent disappearing text.

There was no significant difference between normal and disappearing text on word skipping probabilities (F_1 (1, 33) = 0.56, $p = 0.46$; F_2 (1, 39) = 1.96, $p = 0.17$), nor was there a significant interaction between participant group and text presentation condition (F_1 (2, 33) = 0.43, $p = 0.65$; F_2 (2, 39) = 1.01, $p = 0.37$).

Global measures - summary. There was a main effect of participant group on all measures, with older readers making shorter fixations, having shorter total sentence reading times, making fewer fixations and regressions per sentence, making fewer refixations and skipping more words than younger readers.

There was a main effect of text presentation condition on some measures, where fixations were longer, sentence reading times were longer, and more fixations and regressions were made for disappearing text compared to normal text. There were no reliable differences between the two conditions in terms of refixation probabilities or word skipping probabilities. Finally, numerical trends in the data suggest that younger readers experienced more disruption when reading text in which the word to the right of fixation disappeared than the older readers did. This was evident in total sentence reading times, the number of fixations made, and the number of regressions made per sentence, although none of the interactions were statistically reliable.

Local measures. Table 4.2 shows the mean single and first fixation durations, and gaze durations for the target words, manipulated for frequency, from each sentence for adults, younger and older children. Each of the measures in Table 4.2 will be analysed individually to examine the developmental effects. For each measure, a 3 (Participant Group: adults vs. older children vs. younger children) x 2 (Text Presentation: normal vs. disappearing text) x 2 (Frequency: high vs. low) repeated-measures ANOVA was carried out. ANOVAs were conducted across both participants and items.

For all graphs, standard error bars are shown for each group under each presentation condition. The mean single fixation durations on high and low frequency words for all three participant groups, under both normal and disappearing text conditions, are shown in Fig. 4.7.

For the 3 x 2 x 2 ANOVA, there were too many missing data points to conduct items analyses. There were significant main effects of both participant group and text presentation condition, where older readers had shorter single fixation durations than younger readers, and shorter single fixation durations occurred when reading normal text compared to disappearing text (both Fs > 4, both ps < 0.05). For the main effect of participant group, paired-samples t-tests were conducted across both participants and items in order to examine where the differences were. Younger children were found to have shorter single fixation durations than either adults or older children (all ts > 2, all ps < 0.016). However, there was no reliable difference between adults' and older children's single fixation durations (t_1 (22) = -1.07, p = 0.30; t_2 (39) = -1.35, $p = 0.19$).

		Adults		10- to 11-years		7- to 9-years	
		Normal	DT	Normal	DT	Normal	DT
Single fixation duration (ms)	High	237 (87)	268 (108)	256 (94)	321 (168)	305 (95)	295 (127)
	Low	240 (90)	280 (106)	265 (81)	254 (129)	313 (101)	348 (204)
First fixation duration (ms)	High	233 (84)	268 (111)	254 (98)	312 (150)	288 (103)	305 (128)
	Low	236 (85)	274 (113)	265 (87)	259 (128)	304 (128)	333 (187)
Gaze duration (ms)	High	252 (88)	303 (132)	308 (159)	381 (208)	363 (153)	379 (239)
	Low	260 (103)	319 (129)	349 (178)	396 (293)	372 (177)	531 (564)

Table 4.2. Mean single fixation durations, first fixation durations, and gaze durations on high and low frequency words presented either normally or as disappearing text, for adults, older, and younger children. Standard deviations are shown in parentheses.

Surprisingly, there was no significant effect of word frequency on single fixation durations (F_1 (1, 33) = 1.05, p = 0.31). However, there was a marginally significant interaction between participant group and frequency (F_1 (2, 33) = 3.12, p = 0.06), as well as a significant 3-way interaction between participant group, text presentation condition and word frequency (F_1 (2, 33) = 6.23, p < 0.01). Paired-samples t-tests were conducted to examine the word frequency effect for each participant group separately, under each of the presentation conditions.

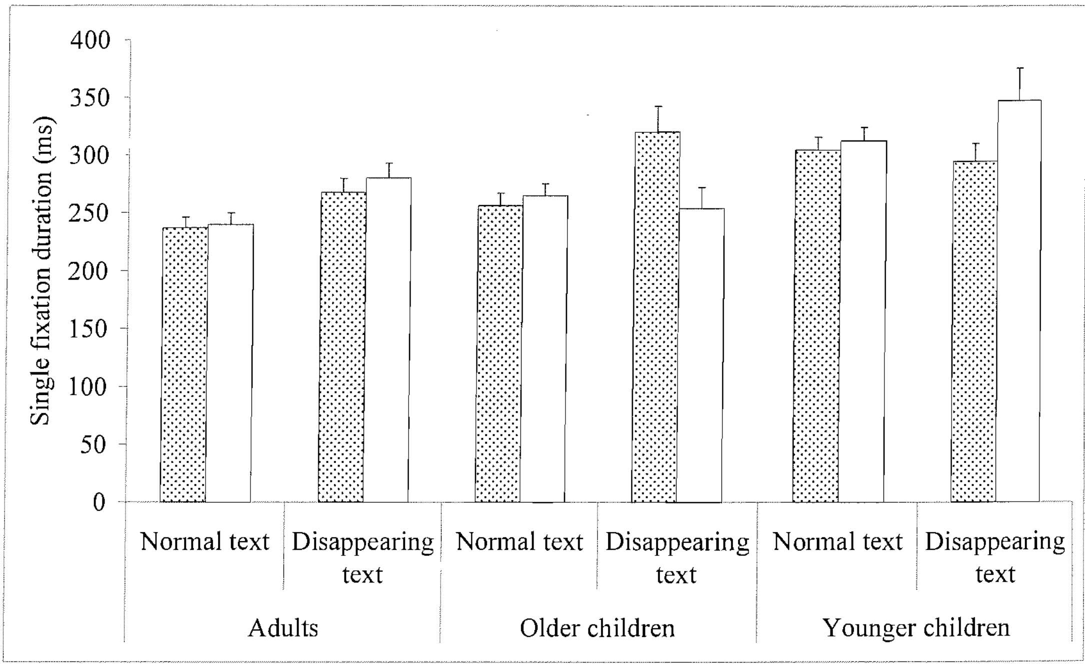

Fig. 4.7. Adults', younger children's, and older children's mean single fixation durations on high and low frequency words when presented as normal or disappearing text. Spotted bars represent high frequency target words and plain bars represent low frequency target words.

None of these separate comparisons reached significance (all *t*s < 4, all *p*s > 0.008). It should be noted that relatively few data points contribute to the measure of single fixation durations, particularly for children who make a high proportion of refixations, and therefore an analysis of single fixation durations will be inherently less powerful than either first fixation durations or gaze durations. Neither the participant group nor word frequency had a significant interaction with text presentation condition (both *F*s < 1, both *p*s > 0.8).

Mean first fixation durations are shown in Fig. 4.8. The pattern of results for first fixation durations was highly similar to that observed for single fixation durations. There were only three differences.

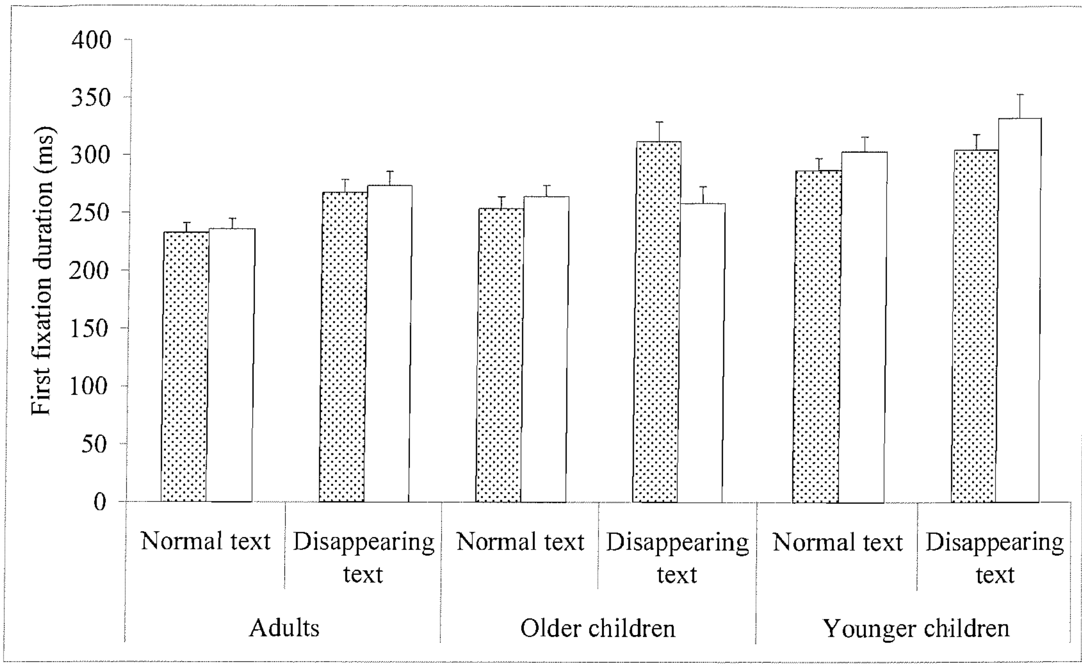

Fig. 4.8. Adults', older children's, and younger children's mean first fixation durations on high and low frequency words, under both normal and disappearing text conditions. Spotted bars represent high frequency target words and plain bars represent low frequency target words.

First, when looking at the t-tests conducted to examine the main effect of participant group, here the difference between older children's and younger children's fixation durations was not reliable (t_1 (22) = -2.37, p = 0.03; t_2 (39) = -3.12, p < 0.01). For single fixation durations, this difference was reliable. Second, in the single fixation duration analyses there was a marginally significant interaction between participant group and word frequency. Here, in contrast, the interaction between participant group and word frequency was found to be not reliable (F_1 (2, 33) = 2.97, p = 0.07; F_2 (2, 78) = 2.35, p = 0.10). Third, the 3-way interaction between participant group, text presentation condition and word frequency was not significant in the first fixation duration analyses (F_1 (2, 33) = 3.14, p = 0.06; F_2 (2, 78) = 1.825, p = 0.17).

This three-way interaction was reliable in the single fixation duration analysis. However, the t-tests did not reveal any reliable differences in single fixation durations on high and low frequency words when each of the three participant groups were analysed independently in both of the text presentation conditions. It was noted that the data from single fixation durations are less reliable than the measures of first fixation durations or gaze durations due to the relative numbers of data points contributing to the analyses.

So, for single and first fixation durations, there were no reliable effects of word frequency observed across the three participant groups. However, the analyses showed that the predicted effect of word frequency did occur in the measure of gaze duration. The mean gaze durations for high and low frequency words are shown in Fig. 4.9.

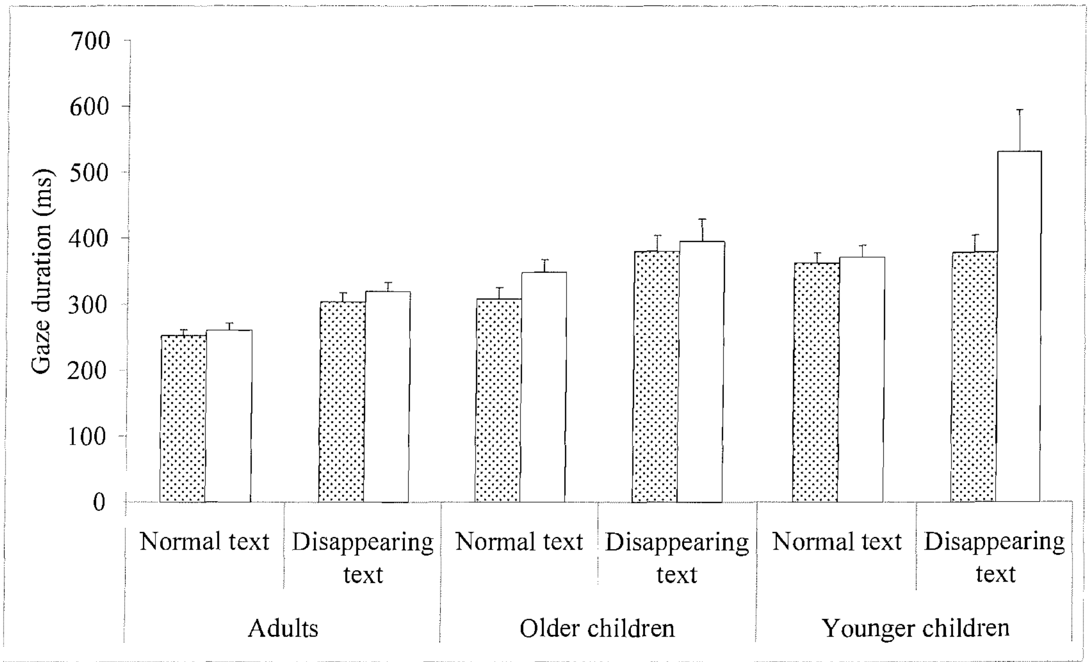

Fig. 4.9. Mean gaze durations for adults, older and younger children on high and low frequency words, under both normal and disappearing text conditions. Spotted bars represent high frequency target words and plain bars represent low frequency target words.

For gaze durations, there were significant effects of participant group, text presentation condition, and word frequency (all Fs > 4, all ps < 0.05). Gaze durations were longer on low frequency words than high frequency words, and were higher for text presented as disappearing text than as normal text. For the group effect, adults had shorter gaze durations than younger children (t_1 (22) = -3.82, p = 0.001; t_2 (39) = -7.94, $p < 0.001$). However, the differences were not reliable between adults and older children (t_1 (22) = -2.33, $p = 0.03$; t_2 (39) = -5.88, $p <$ 0.001), or between older and younger children (t_1 (22) = -1.21, $p = 0.24$; t_2 (39) = -2.79, $p = 0.01$). There were no significant interactions for gaze durations (all Fs < 3, all ps > 0.1).

The unexpected lack of word frequency effects on single fixation durations and first fixation durations, and the occurrence of word frequency effects on gaze durations will be considered in more detail in the Discussion.

Local measures - summary. There was no effect of word frequency upon single or first fixation durations. However, there was an effect of word frequency upon gaze durations for all participants. Importantly, there were no significant interactions between word frequency and text presentation conditions – word frequency effects were not affected by the temporal restrictions upon parafoveal pre-processing of word N+1.

Response accuracy. Participants' response accuracy to the comprehension questions was examined in order to ascertain that all participants were able to read and understand the sentences presented in the two different text presentation conditions. Mean comprehension scores for all thee participant groups under normal and disappearing text conditions are show in Fig. 4.10.

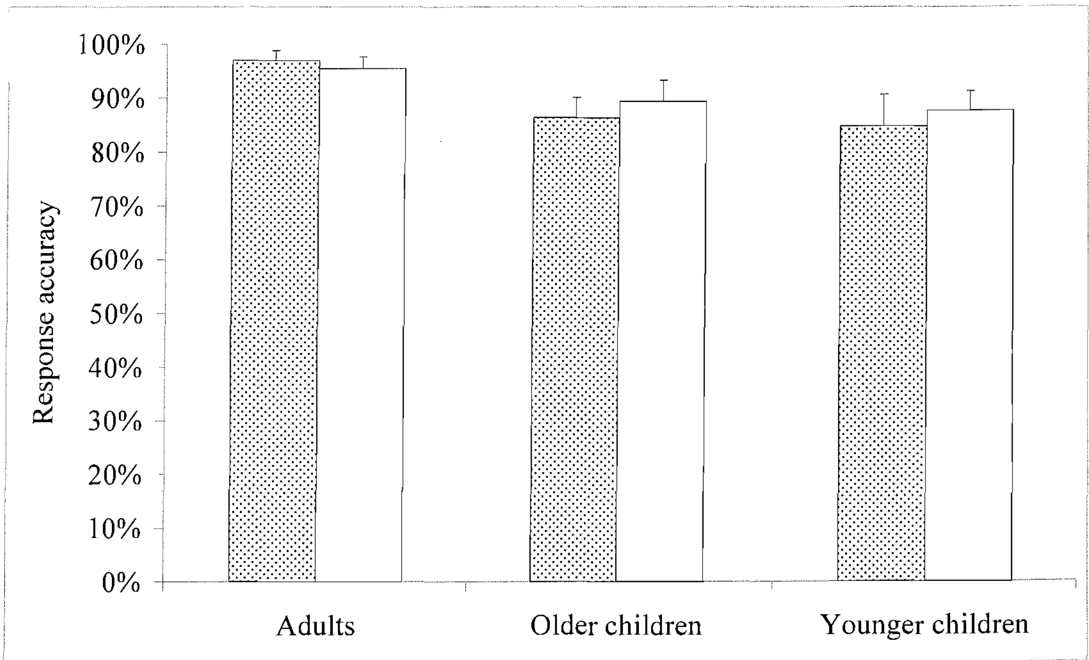

Fig. 4.10. Mean response accuracy for adults, older, and younger children for both normal and disappearing text. Spotted bars represent normal text, and plain bars represent disappearing text.

There was a main effect of participant group upon response accuracy (F_1 (2, 33) = 5.83, p = 0.01; F_2 (2, 39) = 7.05, p = 0.01). Adults had significantly higher comprehension scores than either older or younger children (all ts > 2, all ps $\leq$ 0.01). However, there was no difference between the older and younger children in terms of their comprehension scores (t_1 (22) = 0.47, p = 0.64; t_2 (39) = 0.43, p = 0.68). Importantly, there was no main effect of text presentation condition, nor was there a significant interaction between participant group and text presentation condition (all Fs < 1, all ps > 0.5). So, all participants were able to understand the text equally well under both normal and disappearing text conditions, despite their overall level of comprehension, which was related to their age.

4.4 Discussion

The time course of adults' parafoveal pre-processing. In Experiments One and Two, the data showed that skilled adult readers were minimally disrupted by presenting text in such a way that the fixated word disappeared as little as 40 ms after fixation onset. These data were consistent with the existing literature examining the time course of adult readers' visual processing during fixations in reading, where the uptake of visual information is completed extremely quickly at the beginning of a fixation, and very brief presentation durations are sufficient to allow the initiation of normal cognitive processing of the text. In stark contrast, previous research has demonstrated that adult readers' eye movement behaviour during reading is highly disrupted when the word to the right of fixation, N+1, disappears (Rayner *et al.*, 2006). The first prediction for this experiment was, therefore, that adult readers would show considerable disruption in their eye movement behaviour when the temporal availability of word N+1 was restricted to the initial 60 ms of fixation on word N. The data from this experiment strongly supported this hypothesis. In the disappearing text condition, adult readers were found to make longer fixations, have longer total sentence reading times, and to make more fixations and more regressions per sentence than when reading normal text. Refixation probabilities and word skipping probabilities were not affected by the disappearing text manipulation.

Word skipping rates were quite high in this study, with adult readers skipping over 45% of words in both the normal and the disappearing text conditions. It should be noted that these skipping rates were comparable to those which occurred in Experiments One and Two (41% - 42% and 44% - 45% respectively). The same stimuli were used for all three experiments. These sentences were targeted at children aged 7-years. Forty four per cent of words were between one and three characters long. Further, all of the words would have been fairly high frequency and the sentences would have been highly predictable. The aim in constructing these stimuli was to have a set of sentences that young children would be able to easily read and understand, and the comprehension data indicate that this was the case. For these reasons, it does not seem surprising that word skipping rates were so high. The lack of a significant difference in word skipping rates between the two conditions is consistent with the data reported by Rayner *et al.* (2006). Although they only report skipping rates from the target word in the sentence, they find a comparable pattern of data to those reported here across the entire sentences, where the disappearance of word N+1 60 ms after fixation onset on word N did not significantly affect word skipping rates.

The time course of children's parafoveal pre-processing. Experiments One and Two examined the speed of children's visual information processing during fixations on word N. Children's disruption by the disappearance of word N was minimal, and was related to their difficulty with the text as beginning readers compared to skilled adult readers. The data showed no evidence at all for a developmental change in the speed of visual processing during fixations in reading.

The second prediction for Experiment Three was that children would be less disrupted by the disappearance of word N+1 during reading in comparison to adults. Previous work has demonstrated not only that the perceptual span is smaller in children than in adults, but also that children pre-process text to the right of fixation within their perceptual span to a lesser degree than adults during normal reading (Rayner, 1986).

However, the data from the present experiment clearly did not support this hypothesis. The children experienced just as much disruption to their reading when word N+1 disappeared as did the adults. The reasons for predicting that children would be less disrupted by this manipulation must therefore be considered more carefully.

First, the argument that children conduct less parafoveal pre-processing than adults may have been overstated to some degree. Rayner (1986) found that when the window of available text was made smaller, children were relatively less disrupted compared to adults. The argument made was that for the smallest window size used, five characters, the youngest readers were reading at 62% of their normal rate, while adults were reading at 34% of their normal rate. However, it must also be considered that, due to the basic difference in perceptual span size, the proportional reduction of useful information in the five character space window condition was not equal. The youngest readers were found to reach their asymptotic reading rate with a window size of 23 characters. By presenting them with a moving window of five characters, they were being given a window that was 22% of their perceptual span.

In contrast, adult readers reached an asymptotic reading rate with a window size of 29 characters. For them, a window of five characters is equivalent to 17%. So the adult readers, in the five character space condition, had a 5% greater reduction in the amount of useful information available to them compared to the youngest children. This may not be a sufficient difference to account for all of the age-related differences in reading with the reduced window size – adult readers were far more disrupted by this condition than the children were. However, it must be considered that children may not be so different in their parafoveal processing capacities to adults as was suggested, and that the difference in overall span size is the more dominant factor.

However, it was also noted in the results that there were several measures on which there was a main effect of text presentation condition, and on which it appeared that the younger readers were more disrupted by the disappearance on word N+1 than the older readers. These interactions were not statistically significant. Despite this, some consideration will be given to the observation that, on three independent measures, the same numerical trend occurred. On total sentence reading times, the mean increase from normal text to disappearing text was 401 ms for adults, 760 ms for older children, and 1010 ms for younger children. For the number of fixations made per sentence, the mean increase was 0.5 for adults, and 1.4 for both older and younger children. On the number of regressions made per sentence, the mean increase was 0.2 for adults, 0.5 for older children, and 0.9 for younger children.

If it is indeed the case that children pre-process information from words to the right of fixations less efficiently than adults, then it is not immediately clear why the disappearance of word N+1 was numerically more detrimental to the reading of children compared to adults.

A factor that is perhaps relevant to this possibility is the timing of parafoveal pre-processing. Following Rayner *et al.* (2006), the data from Experiment Three will be discussed within a theoretical assumption of serial word identification rather than parallel word identification during fixations in reading. As will be made clear, the pattern of age-related differences observed across Experiments One, Two, and Three suggest that it may be the timing of the shift of processing from word N to word N+1 that changes with age, and changes in timing associated with this mechanism underlie the data obtained in these experiments. It is not clear how these data could be explained within a theoretical assumption of parallel word identification during reading.

Data from the adult disappearing text studies have supported the idea that, during reading, processing is initially focussed upon the fixated word and then, at some moment during the fixation on word N, shifts to word N+1. Further, the adult data suggest that this shift occurs relatively early during the fixation, hence word N disappearing 60 ms (or, indeed, 40 ms) after fixation onset is minimally disruptive while word N+1 disappearing at the same moment is extremely disruptive. However, the exact timing of this shift may be critical to understanding the differences between adults and children in the present experiment.

It is possible that the start of pre-processing for word N+1 during the fixation on word N shows a developmental change, such that it occurs later during the fixation for younger readers compared to adults. Further, it may be the case that the shift does occur within the initial 60 ms of fixation for adults. Therefore, in the disappearing text condition where word N+1 disappeared 60 ms after fixation on word N, adult readers had already had some, limited opportunity to begin pre-processing word N+1. In contrast, if the shift occurs later for children, then they would have conducted even less pre-processing, possibly none at all, by the time word N+1 disappeared. This would explain why children, who are reported to pre-process information in the parafovea less than adults, were slightly more disrupted by the disappearance of word N+1. This explanation of the pattern of data from Experiment Three is entirely dependent upon the assumption that lexical identification occurs serially during reading, and that a certain stage of processing of the fixated word must be achieved before processing can shift to word N+1. As will now be discussed, the finding that children were not less disrupted than the adults by the disappearance of word N+1 seems to be incompatible with a framework of parallel lexical identification during reading.

There are two key experimental findings which make these data incompatible with theories of parallel lexical identification. First, children have been shown to have a smaller perceptual span to the right of fixation, from which they make less use of information available to them in comparison to adults (Rayner, 1986). Therefore, if the process of lexical identification occurs in parallel for multiple words during a fixation in reading then these data would suggest that children are somehow less efficient in processing words to the right of fixation and that their processing capacities are focussed more upon the fixated word. Therefore, the prediction of parallel processing theories ought to be that children would be less disrupted by the disappearance of word N+1 than adult readers. This was not the case.

Second, a key finding is that the speed at which children take up information during fixations in reading seems to be equal to that of adults. One caveat to the argument made in relation to parallel processing models would be if children were shown to be somehow slower than adults in the uptake of visual information from the page. In this case, the disappearance of either word N or word N+1 ought to be more disruptive for children than for adults as they would have completed less of their processing of that word by the time that it had disappeared. However, the data from Experiments One and Two taken together provide strong evidence that children are as quick as skilled adult readers at processing visual information during fixations in reading.

Therefore, given children's reduced perceptual span in comparison to adults, in the absence of any developmental difference in the speed of visual processing, parallel processing theories would clearly predict that children ought to be less disrupted by the disappearance of word N+1 than adults.

If there is no shift in visual processing from word N to word N+1 during a fixation (this being an intrinsic argument of parallel processing models), the timing of which may change with age, then there is no reason why child readers would be more disrupted by limitations to the temporal availability of the word to the right of fixation than adults. Therefore, the data from Experiment Three appear to be incompatible with a theoretical framework of parallel lexical identification during reading, and are far more compatible with serial lexical identification theories.

What causes developmental changes in the timing of pre-processing? Data from Experiments One and Two suggested that there are no developmental changes in the speed of visual processing during fixations in reading. However, some data from Experiment Three suggest a difference in the timing of the initiation of pre-processing. Therefore, there must be other, cognitive variables which show developmental changes which are involved in determining when the reader begins parafoveal pre-processing of word N+1.

For example, it is well established that factors associated with the cognitive processing of a word determine when the reader moves their eyes during reading. In Experiments One and Two, the frequency of the word that had disappeared determined the duration of the fixation on that word for readers as young as 7-years-old, even though the visual stimulus was no longer present. Further, developmental differences in eye movement behaviour during reading have been shown to be at least partially determined by the reader's ability, as discussed in Chapter One.

So, cognitive processing difficulty affects the timing of eye movements during reading, and this has been shown to at least partially account for developmental trends in eye movement behaviour. Given the robust evidence from Experiments One and Two that the speed of visual processing during fixations in reading does not change with age, it seems likely that the suggested age-related changes in the timing of visual pre-processing are largely determined by the reader's cognitive processing of the text. For example, a certain stage of lexical processing and identification must be achieved before the reader can initiate pre-processing of the word to the right of fixation. It may be the case that adults are somehow faster or more efficient in their lexical processing than are children, and so achieve this stage at an earlier moment during fixations than do children. Subsequently, adult readers may begin pre-processing of word N+1 at an earlier moment during the fixation on word N than do children.

Word frequency effects. The final prediction for this experiment was that normal word frequency effects would be observed on the target word, given that it appeared entirely normally once directly fixated. During normal reading, word frequency effects occur on very early measures of processing such as first fixation durations, for children as well as adults (Hyönä & Olson, 1995). While there were robust effects of word frequency, they only became manifest in the measure of gaze duration, and did not occur in single or first fixation durations. It must be noted that while the interaction between participant group and word frequency on single or first fixation durations was not reliable, the frequency comparison in the disappearing text condition for older children looks very different to all of the other frequency comparisons.

For all other groups in both normal and disappearing text conditions, as well as for the older children's normal data, there was a numerical increase on fixation durations on low frequency words compared to high frequency words. In contrast, older children's fixation durations were longer on high frequency words than low frequency words in the disappearing text condition, and the magnitude of this difference was much larger than the other word frequency effects which went in the predicted direction.

The frequency data from this experiment can be examined in relation to those from Experiments One and Two where the same stimuli were used. In both of these experiments, there were reliable effects of word frequency upon first and single fixation durations, but no interactions with the presentation condition.

		First fixations	Single fixations
Adults	Experiment One	14 ms	11 ms
	Experiment Two	16 ms	17 ms
	Experiment Three	4 ms	6 ms
10- to 11-years	Experiment One	41 ms	34 ms
	Experiment Two	25 ms	21 ms
	Experiment Three	-19 ms	-25 ms
7- to 9-years	Experiment One	0 ms	22 ms
	Experiment Two	37 ms	41 ms
	Experiment Three	21 ms	27 ms

Table 4.3. Mean word frequency effects in single and first fixation durations by adults, older, and younger children in Experiments One, Two and Three.

For comparison, Table 4.3 shows the mean word frequency effects on first and single fixation durations for each participant group, collapsed across presentation conditions.

There seem to be two possible reasons why there was no reliable effect of word frequency on these measures in Experiment Three. First, the older children showed a large difference in their fixation durations between high and low frequency words in the disappearing text condition, but in the opposite direction to that which is normally observed, and which is observed in the two other groups' data.

Second, that the numerical differences for word frequency effects in the adult data are much smaller than the differences observed in Experiments One and Two. There are no clear reasons why these differences may have occurred across the three experiments, where all three have used identical stimulus sets. However, it seems entirely possible that the combination of a small effect in the adult data, and a large effect in the contradictory direction in the older children's disappearing text data are the reason why there was no main effect of word frequency on single or first fixation durations despite the observation that on five out of six of the frequency comparisons for both measures (adults, normal and disappearing text, older children normal text, younger children, normal and disappearing text), as shown in both Figs. 4.7 and 4.8., the numerical trends suggested that word frequency was influential in the expected manner.

4.5 Conclusions

Experiment Three examined adults', older children's and younger children's reading performance when parafoveal preview of word N+1 was restricted to the initial 60 ms of fixation on word N. Readers of all ages showed significant disruption in their eye movement behaviour as a consequence of this temporal limitation on parafoveal pre-processing. However, contrary to predictions, it seemed that younger readers were more disrupted than older readers. This may be due to a developmental change in the timing of the shift of processing from word N to word N+1 during fixations in reading. Experiments One to Three, therefore, demonstrate that although there is no developmental change in the speed of visual processing during fixations in reading, the initiation of pre-processing of word N+1 may occur earlier during the fixation on word N as the reader's age increases.

4.6 Summary of Experiments One to Three

The aim of Experiments One to Three was to examine the time course of visual processing of the fixated word, as well as the word to the right of fixation. There are two, distinct mechanisms which must be considered together in relation to the data from these experiments – the speed of visual information processing during fixations, and the timing of processing for word N and subsequently for word N+1.

Experiment One compared the eye movement behaviour of adults, older, and younger children as they read sentences in which every word disappeared 60 ms after fixation onset. While adults showed no differences when reading disappearing text compared to normal text, both older and younger children showed quite marked differences in their eye movements with the disappearing text. When reading disappearing text, the children made fewer refixations but had longer fixation durations and longer total sentence reading times.

This difference between adults and children in their ability to move their eyes fluently through a sentence in which the visual uptake of information for the fixated word was limited to 60 ms lead to the suggestion that there might be an age-related difference in the speed with which a reader can extract the visual information from the printed page. Experiment Two was designed to investigate this further.

In Experiment Two participants again read disappearing text but here, the presentation duration of each word after fixation onset was manipulated. Also, a second explanation for the pattern of results in Experiment One was formulated. If the disappearing text effect on children's fixation durations was a consequence of the effect on refixation probabilities, then refixations were the critical measure of eye movement behaviour that was affected by the disappearing text manipulation. Given that readers make a higher proportion of refixations when reading text which is more difficult to process, and that the sentences in these experiments would have been more difficult for the children than for the adults (hence the children had a higher baseline level of refixations), then the pattern of differences between adults and children in Experiment One may simply have been a consequence of children's increased processing difficulty.

These two explanations for age-related differences in reading disappearing text – a developmental change in the speed of visual information processing, or a developmental change in the ease of cognitive processing associated with the text – predicted quite different patterns of results. In the first case, there ought to have been reliable interactions between the participant age group and the text presentation manipulation, reflecting the given duration at which readers in each age group were able to visually process the fixated word and subsequently read normally. In the latter case, with the exception of an interactive effect on refixation probabilities, all participants should have been equally affected by the disappearing text manipulation and so there ought to have been no interactions on other eye movement measures between group and text presentation condition.

The data strongly supported the cognitive processing difficulty account, suggesting that the reader's baseline level of refixations, associated with the ease with which they could read the materials, determined the level of disruption to eye movement behaviour that would be experienced as a consequence of the text disappearing. There was no evidence to support the hypothesis that there might be an age-related change in the speed of visual information processing during fixations in reading.

Experiment Three examined parafoveal pre-processing in children compared to adults. Again the disappearing text paradigm was used, but here it was the word to the right of fixation, word N+1, that disappeared 60 ms after the onset of fixation on word N. Parafoveal preview was, therefore, restricted to the initial 60 ms of fixation on the previous word.

Numerical trends in the data suggested that, surprisingly, children were more disrupted by the disappearance of word N+1 than adult readers. Note, however, that these effects were not reliable. However, given that children have been shown to have a reduced perceptual span, then it seems highly unusual that they were more disrupted by the manipulated temporal restriction on the availability of word N+1. A clear prediction was made for this Experiment, based on the perceptual span study by Rayner (1986), that there would be significant interactions between group and condition such that children would be less disrupted than adults by the disappearance of word N+1. This prediction was not supported, as none of the interactions between group and condition were reliable. However, numerical trends in the data went in the opposite direction to that predicted, suggesting that children were actually more disrupted by the disappearing text manipulation than adults. Therefore, these trends were considered in some detail.

Consistent with a theoretical framework assuming serial lexical identification during reading, it was argued that the age-related differences in the eye movement data are a consequence of a developmental change in the initiation of pre-processing of word N+1 during fixations in word N. Adults begin pre-processing of word N+1 at an earlier moment in the fixation than children, the timing of this shift of processing being determined by the ease of cognitive processing of the fixated word. When word N+1 disappears, children have had a shorter amount of time to pre-process that word than the adults have, and so are more disrupted by the manipulation than the adult participants.

The data from Experiments One to Three suggest two key theoretical points. First, there is no evidence to support the hypothesis that there is a developmental change in the speed of the uptake of visual information during fixations in reading. Rather, the disruption observed for both adults and children when reading age-appropriate sentences presented as disappearing text reflects a strategy adopted by the reader as compensation for the inability to make useful refixations. Second, that while the speed of visual processing does not seem to change with age, the timing of the shift of processing from word N to word N+1 may change with age. It is suggested that the timing of this shift is, again, determined by the difficulty associated with text processing for readers of a particular age or reading ability.

Chapter Five

Introduction to children's binocular coordination

5.1 Terminology and key measures

It has been an underlying assumption of eye movement research for many years that the two eyes fixate the same position within the text as we read. However, a body of research has demonstrated quite clearly that adults' eyes become diverged during saccades, and it is suggested that there may be residual disparity between the eyes at the end of the saccade, i.e. at the beginnings of fixations (see Collewijn, Erkelens & Steinman, 1988). A more recent set of studies has examined adults' binocular coordination during reading (Liversedge, White, Findlay & Rayner, 2006a; Liversedge, Rayner, White, Findlay, & McSorley, 2006b; Juhasz, Liversedge, White & Rayner, 2006). However, there has been little work which has examined children's binocular coordination, particularly in reading. The research into adult binocular coordination, both on reading and non-reading tasks, will be briefly reviewed first, before a more detailed discussion of the work in this area that has been carried out with children.

When recording and analysing binocular eye movements, there are several components to the eye movements which can be considered either independently or in combination. Within the literature, there exists some inconsistent use of terminology when referring to binocular saccade metrics. To clarify, some key definitions for binocular, horizontal saccades will be given here that will be referred to consistently throughout this thesis.

The term, "saccade", will be used to refer simply to the rapid, ballistic eye movements that serve the purpose of bringing the points of fixation of the two eyes onto a new area of information (as opposed to the slower drift and vergence movements that occur during a fixation).

Within a saccade, there are two different types of movement that occur. First, there is usually a horizontal or vertical component (referred to as version) where both the eyes move by an equal amount in the same direction, i.e. there is no change in the angle between the two eyes. Note that, in some papers, the horizontal component of an eye movement is referred to as the saccadic component; here, the horizontal component of an eye movement will be referred to as version, and the overall eye movement itself is referred to as the saccade.

Second, there can be a vergence component, where the angle between the two eyes changes such that the intersection of the two points of fixation has altered in depth. The eyes can either converge, where the positions of both eyes move in a nasal direction, bringing the intersection of these two lines of sight closer to the person, or diverge, where the fixation positions of the eyes move outwards serving to move the intersection of the two lines of sight further away from the person. In pure vergence movements, there is no change in the horizontal or vertical position of the eyes – the movement purely serves to change the binocular fixation point in depth.

Finally, and most commonly in normal, day-to-day situations, combined movements are made – these are movements of the eyes which contain both a version (horizontal) component and a vergence (depth) component. Studies will be reviewed which have examined the characteristics of both pure vergence and version movements and of combined movements, in order to determine how these movements are generated and how the components function in relation to each other.

Certain key parameters have been used to examine the binocular coordination of saccades. Typically, measures of amplitude, velocity and duration are reported for the movement of each eye. The velocity of an eye movement is often reported as the peak velocity – during the movement, there is a period of acceleration, a period when the eye is moving at the maximum speed (the peak velocity), and then a period of deceleration. Within eye movements, a close relationship between amplitude and peak velocity occurs – the main sequence (Bahill, Clark & Stark, 1975; cited in Collewijn *et al.*, 1988), where the larger the amplitude of the eye movement, the higher the peak velocity. Finally, a measure referred to as skewness is often reported, describing the symmetry of the velocity profile of an eye movement. While this is often symmetrical, with relatively equal periods of acceleration and deceleration around the peak velocity, skewness tells us whether the peak velocity occurred relatively early with a long deceleration phase or relatively late with a slower acceleration phase. These measures – amplitude, duration, peak velocity, and skewness, are key parameters in describing the binocular coordination of eye movements.

5.2 Adult binocular coordination

Some of the earliest work that took binocular eye movement recordings looked at the coordination of the eyes during saccades between LEDs – a task with minimal processing demands (Collewijn *et al.*, 1988). The LEDs were placed on an isovergence circle – a circle around the participant on which movements of the eyes between any two points require pure version only, so that the angle between the eyes is constant and therefore no vergence movement is required. However, changes in the angle between the two eyes were found to occur during the eye movements, despite there being nothing in the stimulus which would have driven vergence movements.

It was found that the abducting eye (the eye moving in an outward direction) typically moved with a larger amplitude, higher velocity, shorter duration, and greater skewness than the adducting eye (the eye moving in a nasal direction). This larger, faster saccade in one eye lead to disparity at the end of the saccade, where the abducting eye typically had a landing site further away from the launch site of the saccade than the adducting eye - an uncrossed fixation with about 3° of disparity.

This recording of non-conjugate saccades in adults has been replicated many times (e.g. Collewijn, Erkelens & Steinman, 1995; 1997; Zee, Fitzgibbon & Optican, 1992). Among other questions, the demonstration of disparities between the saccades of the two eyes has raised the issue of whether or not this disparity persists into fixations; more specifically, whether or not there is disparity between the eyes during fixations when we read.

Further, if it is the case that disparity between the eyes occurs during fixations in reading, do slow vergence movements also occur during fixations in order to correct that disparity? There has been a widely held assumption within the field of eye movements in reading that the two eyes fixate the same position within a word, i.e. that light from the same letter within the word is falling onto the middle of the two foveas where acuity is highest. For this reason almost all of the research in this field has measured the movements of only one of the two eyes, and models of eye movements in reading are therefore based on data from monocular experiments.

Very little research has looked at coordination of the two eyes during reading. Within the little binocular research that has used reading tasks, most of this work has looked at special populations (e.g. dyslexics) or has examined binocular eye movements on tasks other than natural reading. Consequently, there are very few findings that can be generalised to the normal adult population when reading sentences. Hendriks (1996) compared vergence movements during fixations when adults read either prose passages or lists of words, using different strategies (reading for meaning vs. sub-vocal pronunciation). It was found that, overall, convergent movements occurred in 74% of fixations, and divergent movements occurred in 17% of fixations (in the remaining 9% of fixations, no vergence movement was detected). These proportions were not affected by the text type, nor by the task. However, participants made faster vergence movements when reading prose passages than word lists, and when reading for meaning rather than sub-vocal pronunciation.

Similar to the results of Collewijn *et al.* (1988), it was reported that the adducting eye makes a proportionally larger contribution to post-saccadic vergence than the abducting eye. Hendriks concluded that vergence movements during fixations are related both to preceding saccade size, and to the size of the text units that the reader was attending to which reflected their difficulty in extracting information. When reading word lists, or subvocally pronouncing text rather than reading for meaning, it is argued that the reader is much more dependent on the visual input, and so attends to relatively smaller units as a consequence of their difficulty.

Considering more specifically adults' binocular coordination on a natural reading task, Heller and Radach first considered the asymmetry of saccades during sentence reading (Heller & Radach, 1999). They found that the magnitude of saccadic asymmetry was around 5% of the amplitude of 10-12 letter saccades, and 15% of the amplitude of two to three letter saccades. It was reported that this disparity accumulated slightly throughout the reading of a line of text but did not systematically do so throughout the reading of a whole passage of text. To investigate the influence of task demands on binocular co-ordination, reading of normal and mIxEd CaSe text was compared, as the extraction of visual information is more difficult from mixed case text. It was observed that vergence velocity was significantly slower for reading of mixed case text, therefore supporting Hendriks' (1996) suggestion that increased processing difficulty decreases vergence velocity. In addition to the effect on vergence velocity, saccadic asymmetry between the two eyes was increased for mixed case text. This suggests that the slower vergence velocity observed when reading mixed case text was a consequence of the smaller disparity that occurred between the eyes and was not in itself a direct consequence of the manipulation of processing difficulty. It is argued that the binocular system can tolerate more disparity under normal reading conditions than more difficult conditions.

Although not the main focus of their study, Kliegl, Engbert and Nuthmann (2006) reported some binocular disparity data in order to confirm that both eyes were fixating within the same word in the sentence. They had recorded the binocular eye movements of adults as they read single sentences from a computer monitor. Movements of the two eyes were highly correlated both temporally and spatially; however, the subsequent fixations were less well spatially correlated between the two eyes. They found that 58% of fixations were aligned, such that both eyes were fixating within the same character space of the word. 26% of fixations were crossed, where the left eye was fixating a character space to the right of that fixated by the right eye, and just 15% were uncrossed where the left eye was fixating a character space further to the left than that fixated by the right eye. It is unclear why fixation disparities were found in this study, given that binocular saccades were reported to be well correlated. However, only saccadic amplitudes and fixation durations were analysed; the reported fixation disparities may have arisen from differences in peak saccadic velocity, skewness, or duration (see Collewijn *et al.*, 1988). These measures were not reported.

In a set of more recent studies, fixation alignment patterns during reading have been directly investigated, as well as effects of processing difficulty upon these patterns (Liversedge *et al.*, 2006a; Juhasz *et al.*, 2006; see also Liversedge *et al.*, 2006b). Liversedge *et al.* (2006a) examined adult readers' binocular coordination at the beginnings and ends of fixations during reading. They found that on just over half of adults' fixations (53%), the two eyes are aligned to within one character space. On those fixations where the two eyes are more than one character space apart, the eyes are far more likely to be uncrossed such that the left eye is fixating further to the left than the right eye (39%). Only on a very small proportion of occasions are adults' eyes literally crossed during reading fixations (8%). They also observed that the vergence movements which occurred during fixations tended to be in a corrective direction for the disparity which was residual from the preceding saccade.

When considering the different proportions of crossed and uncrossed fixations among those which are unaligned by more than one character space, there are clear differences between the results of Kliegl *et al.* and those of Liversedge *et al.* and Juhasz *et al.* (Liversedge *et al.*, 2006a; 2006b; Juhasz *et al.*, 2006). Kliegl *et al.* find crossed fixations to be more prevalent in adult readers while Liversedge *et al.* and Juhasz *et al.* find uncrossed fixations to be more prevalent. However, in addition to the repeated replication of the pattern of results from within their own laboratory, the results of Liversedge *et al.* are in line with those of Collewijn *et al.* who found that adults' eyes become transiently uncrossed during saccades. It seems likely that this uncrossed disparity persists into fixations during reading, as opposed to becoming reversed between the saccade and the subsequent fixation. It is not clear what caused the differences between the data from Kliegl *et al.*'s study and those of Liversedge and colleagues. One possibility is differences in the calibration procedure used in the different studies. Kliegl *et al.* calibrated each eye whilst the participants were viewing binocularly. In contrast, Liversedge *et al.* and Juhasz *et al.* occluded one eye whilst calibrating the other eye, in order to ensure that each eye was being accurately tracked, independent of the other.

Extending these findings, Juhasz *et al.* examined adult readers' fixation alignment patterns, making two manipulations of processing difficulty. The sentences were either presented normally, or in mixed case, and also contained a target word that was manipulated for frequency. The overall descriptive data concerning patterns of fixation alignment largely replicated those of Liversedge *et al.*, where around half of fixations were aligned to within one character space, and out of those fixations which were unaligned the majority were uncrossed. In terms of processing difficulty, both word frequency and text case had significant effects on fixation durations, showing that both were reliable and effective manipulations of processing difficulty. However, neither word frequency nor text case had any effect on the measures of binocular coordination; namely, disparity magnitudes, or fixation alignment patterns. These results therefore contradicted those of Heller and Radach (1999), and Hendriks (1996) who do find an influence of processing difficulty on binocular coordination. It was suggested that the frequency of calibrations, and differences in equipment may account for the differences in results between these studies.

It seems quite clear, from this literature, that the two eyes do not always fixate the same letter position during fixations in reading. The magnitude of disparity, as well as the direction of that disparity, vary on a fixation-by-fixation basis but do not seem to be systematically affected by the cognitive demands of the task. However, our understanding of children's binocular coordination is far less well understood.

5.3 Children's binocular coordination on non-reading tasks

Several studies have examined in detail the parameters of combined version-vergence eye movements in adults (Collewijn, Erkelens & Steinman, 1995; Zee, Fitzgibbon & Optican, 1992). Typically, pure version movements (i.e. horizontal/vertical saccades with no vergence component) have much faster peak velocities than do pure vergence movements (i.e. movements in depth with no horizontal/vertical change). However, vergence components of combined movements were found to have higher peak velocities than pure vergence movements. The opposite was true for version – saccade components of combined movements had lower peak velocities than pure saccades. Thus, when combined eye movements are made, the peak velocity of the version component is decreased, relative to that from pure version, through its combination with vergence while the peak velocity of the vergence component is accelerated relative to that from pure vergence. It is noted that pure vergence and version movements are relatively unusual, in that they are very rarely required in normal day-to-day viewing situations. The majority of eye movements that are made will require both horizontal/vertical movement and depth movement. Highly unnatural tasks are required (e.g. the isovergence circle) to elicit pure version or pure vergence).

Research of these basic binocular saccadic parameters is less well researched in children. Yang, Bucci and Kapoula (2002) found that, overall, children aged 4- to 12-years had longer latencies for pure version, pure vergence, and combined movements than adults. These findings support previous research into basic saccadic latencies, where children between the ages of 5- and 11-years have longer saccadic latencies than adults, but extend the finding to both vergence and combined version/vergence movements (Cohen & Ross, 1978; Groll & Ross, 1982; Fukushima, Hatta & Fukushima, 2000). Further, when the children's group was broken down into categories of 4- to 6-years, 7- to 8-years, and 10- to 12-years, there were significant decreases in latency across these age groups for all categories of pure and combined movements.

Additionally, it was found that all children's movement latencies were shorter for pure vergence movements than for pure version movements, but this did not occur in the adult data. The authors argued that the difference in latencies between pure version and vergence in children but not in adults were evidence of differential maturation of these two oculomotor systems. Both version latencies and vergence latencies decrease with age; control of the version subsystem is attributed to the frontal lobe, while cortical control of the vergence system is reported to be less well understood but possibly similar. The authors therefore suggested that differential initiation of cortical subsystems is responsible for the different latencies of vergence and version in children. Within the analysis of vergence movements, it was found that adults' divergent movements had a shorter latency than convergent movements. Although this trend did occur in children, it was unreliable. No explanation was offered for this finding of differences in latencies between convergence and divergence for adults but not for children.

The results from the components of combined movements were less clear. In children, there were increased latencies for the version component of convergence but not for divergent combined movements compared to pure version. In contrast, the vergence component showed longer latencies compared to pure movements in divergent but not convergent combined movements. However, in adults there were longer latencies for both version and vergence components of combined movements compared to pure movements. No explanation was provided for these developmental differences.

Finally, the sequence in which the individual components of combined movements occurred was examined. In children, on the majority of movements, the vergence component was initiated first. There was no change in this proportion across the different age groups of children; however, in adults there was no difference in occurrence between version or vergence being initiated first, or whether both were initiated simultaneously. It was suggested that this difference between adults and children reflects the improving ability with age to simultaneously program multiple movements; however, it is not made clear why children showed a tendency to initiate vergence before version. It may be that this occurs due to the relatively slow nature of vergence compared to version, particularly in children. Overall, the results from this analysis of movement latencies showed clear age-related trends in the programming of both pure version and vergence movements and in the more natural combined movements.

A further investigation into the development of combined version and vergence movements has examined additional parameters such as peak velocity and movement duration. Yang and Kapoula (2004) found, in line with the results of Fukushima, Hatta and Fukushima (2000) who examined monocular saccade parameters, that peak velocities and movement durations for any of the categories of binocular eye movements did not differ between adults and children. However across all participants' pure movements, version was found to have higher peak velocities and shorter durations than either convergence or divergence. So, as Collewijn *et al.* and Zee *et al.* found with adults, children's eye movements that do not contain any change in the depth of the binocular fixation point are quicker than movements which only change the depth of the binocular fixation point but which do not change the horizontal/vertical location.

Within pure vergence, convergence showed higher peak velocities and shorter durations than divergence. Further, in combined movements, the vergence components were found to have higher peak velocities than pure vergence movements, while the version components showed relatively lower peak velocities than their pure counterparts. When the children's sample was sub-divided into age groups of 4- to 6-years, 7- to 8-years, and 10- to 12-years, the only parameter that showed developmental change was the durations of both pure vergence and of vergence components of combined movements. It was suggested that the longer durations of vergence in children without a corresponding trend in peak velocity were due to differential maturation of two subcomponents of the vergence system, where processing of visual depth feedback is slower than the quick, pre-programmed subcomponent.

The majority of parameters measuring pure and combined eye movements show no developmental change. The most interesting developmental effects are observed in eye movement latencies. Vergence movements in children have shorter latencies than version, and are often the first initiated component of a combined movement. In adults, vergence and version movements have similar latencies, and there are no systematic differences in which component is initiated first, or whether they are initiated together. Within combined movements, latencies of both components are relatively slow compared to pure movements in adults, while convergence and divergence show different patterns of latency changes compared to pure movements in children. Overall, these developmental data strongly support the argument that version and vergence components of eye movements are controlled by separate subsystems.

Other studies examining children's binocular saccades have gone on to examine the precise differences between the two eyes, extending the basic documentation of binocular saccade parameters. The basic finding of Collewijn *et al.*'s (1988), that the eyes do not make perfectly conjugate saccades, has also been investigated in children. Fioravanti, Inchingolo, Pensiero and Spanios (1995) used LEDs placed along an isovergence circle as their stimulus, and looked at the binocular saccades of children compared to adults. On this task, with minimal processing demands, they replicated the findings of Collewijn *et al.* for older children (11- to 13-years) and adults, but found the opposite pattern for younger children (5- to 10-years). For this latter group, saccades of the adducting eye had larger amplitudes, higher peak velocities, shorter durations, and greater skewness. This lead to the younger children's eyes becoming crossed during the saccade. The mean 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 mean size of resulting disparity is also greater in younger children. The authors concluded that the observed differences in younger children could be due to developmental immaturity of the oculomotor plants, resulting in poorly balanced pulse-step innervation during saccades, or due to increased directional asymmetry in oculomotor stiffness in children, or both. These data suggested that binocular control of saccades develops across early childhood, and reaches adult performance levels somewhere between 11- and 13-years of age. Unfortunately, no analysis of fixations is reported; however, a small remaining uncrossed disparity at saccade offset is reported in adults. They do not directly report whether the same is true or not for children. Yet, if children's eyes become crossed during saccades with a greater magnitude than that of the uncrossed disparities observed during adult saccades, it seems likely that children will have residual crossed disparity at saccade offset (i.e. at the start of fixations).

Further research examining children's saccadic binocular coordination has found that there is an effect of viewing distance on binocular coordination in children but not in adults (Yang & Kapoula, 2003). Fioravanti *et al.* (1995) used LED stimuli, and placed them at 100 cm; Yang and Kapoula compared viewing at 150 cm with viewing at 20 cm. They found that viewing at a closer distance significantly increased disparity in children (4- to 12-years old) but not in adults. They reported saccadic disparities of over 2° for children at close distances, which were significantly greater than adult's disparities at the same distance. Further, they report that at a viewing distance of 150 cm, there was no significant difference in saccadic disparity between adults and children. The disparity which occurred during saccades was reported to be predominantly divergent in all participants, but less so in children than in adults. There was no statistical analysis of the developmental trends in saccadic divergence. However, numerical trends in the data suggest that the proportion of divergent saccades does increase across the age range tested (4- to 12-years-old), from 67% to 72% at close distances, and from 70% to 73% at far distances. When the results were broken down into different age ranges, it showed that saccadic disparity magnitudes reached adult values around the age of 10- to 12-years, in keeping with the results of Fioravanti *et al.*

Considering the source of these age-related changes in binocular coordination, the authors argue that these data favour a neural-level explanation as opposed to one at the level of the musculature of the eyes. They suggest that, were the relatively increased saccadic disparities in children the result of increased muscular asymmetry between the two eyes, this would also be reflected in measures such as saccadic peak velocity. Their results showed that although saccadic disparity was mediated by viewing distance, saccadic peak velocity was not. They therefore argue that saccadic disparity cannot be explained by muscular asymmetry between the two eyes – peak velocity and disparity were not both mediated by viewing distance and so these two mechanisms do not appear to be tightly linked. The authors subsequently claim that binocular disparities are more likely to be due to developmental changes in cortical control of saccades. The effect of viewing distance on binocular coordination was argued to be a consequence of the increased vergence angle required to fixate at close distances, and which must be maintained to some degree during the saccade to the next target which also requires an increased vergence angle.

To summarise, the results of studies of children's binocular coordination on non-reading tasks show that greater disparities occur between the eyes in children than in adults, and that this disparity magnitude decreases gradually with age. Further, developmental changes in the direction of the observed disparities have been recorded, such that the eyes of younger children become converged during saccades more often, and this decreases with age until the point where the eyes become diverged during the majority of saccades as is known to occur in adults.

5.4 Children's binocular coordination in reading tasks

Very little research has looked at coordination of the two eyes during reading. Also, within the literature in this area, not all of the studies have employed natural reading tasks. Those studies that have been undertaken will now be reviewed and these findings will be compared against those from non-reading tasks. Further, a comparison will be made between adults and children.

An early study which examined children's binocular coordination looked at both saccades and movements during fixations as their participants – 10-year-old children – read text passages (Bassou, Pugh, Granié & Morucci, 1993). They found that children with right visual privilege had significantly smaller disparities between their eyes occurring during saccades than did children with left or unfixed visual privilege, as determined by a sighting test. This test determines which of the two eyes is preferred when viewing diplopic stimuli, i.e. when pointing a finger at a distant object which is being fixated, the finger will appear double and the image from one of the eyes will typically be dominant. They found, in the majority of their participants, that non-conjugate gaze-shifts between 0.25° and 1° occurred when reading. The direction of these shifts is reported to be in a corrective direction for the disparity that is residual from the preceding saccade. However, they reported that saccades of the two eyes were well coordinated temporally, despite these spatial disparities.

Disparities between the two eyes have also been found in a reading task where participants read lists of non-related words presented as lines of text (Cornelissen, Munro, Fowler & Stein, 1993). They compared the binocular co-ordination of adults and 9- to 12-year-old children, and found that adults had less fixation disparity (0.01° - 0.46°, mean of 0.08°) than children (0.01° - 2.3°, mean of 0.12°), and that the inter-individual variation was significantly greater in children than in adults. Although all subjects read material appropriate for their age, the authors deliberately did not discriminate between good and poor readers in order to obtain a representative sample. While it is entirely possible that the eye movement behaviour elicited by this task may be different to the more normal movements associated with reading prose passages, the finding here of greater disparity magnitudes in children than in adults is in line with the results of non-reading research.

A large, longitudinal study compared typically developing readers with poor readers, some of whom were later diagnosed as dyslexic (Lennerstrand, Ygge & Jacobson, 1993; Lennerstrand, Ygge & Rydberg, 1994; Ygge & Jacobson, 1994). The children's binocular eye movements were recorded as they read text passages of varying difficulty. The aim of the study was to assess whether poor binocular coordination could be considered as a precursor to a later diagnosis of dyslexia. However, the data are informative to our understanding of binocular eye movement characteristics in typically developing children.

The results from this study have been published across several papers. Lennerstrand, Ygge and Jacobson (1993) analysed data from the children at the age of 8- to 9-years, when the poor readers had not yet been diagnosed as dyslexic. They assessed the degree of disparity, in each direction, which could be successfully fused, based on both the children's report of the occurrence of diplopia, and also the measurement of vergence eye movements to ensure that the children's self-report was reliable. The children were presented with visual stimuli (both non-reading and reading, but unspecified) through a synoptophore, which allowed the images presented to the two eyes to be gradually moved apart. When the images are aligned, they are seen as a single image. When they are moved too far apart for the visual system to successfully fuse the two images, diplopia (double vision) occurs. The children were asked to report when diplopia occurred. During this presentation, their binocular eye movements were recorded in order to examine vergence movements that occurred, and their correspondence with the subjective reports of diplopia. They found that the normally reading children could fuse small (2.5°) targets at up to 4.1° when diverging, and up to 11.7° when converging. This suggests that children's oculomotor systems are less well able to fuse diverged than converged stimuli. Finally, they reported that the asymmetry of binocular saccades did not change between binocular and monocular viewing, in line with the findings of Heller and Radach (1999) who reported the same result in adults. Later analyses are based on the same sample but as a follow-up when the children were 11- to 12-years-old (Lennerstrand, Ygge & Rydberg, 1994). For the small targets, there was no real difference across ages in the magnitude of convergence or divergence tolerated. However, they also reported here results of fusion of larger targets (7.0°). Overall, these could be fused at greater vergence angles than the smaller targets. Further, it was found in the older children that they could be fused at up to 16.4° convergence angles – a higher convergence angle than that found at the younger age. Therefore the only developmental trend observed was an increased tolerance for the large, converged targets.

Further data from this sample of children at the age of 11- to 12-years were reported by Ygge and Jacobson (1994). In these data, the children had read passages of text between five and 11 lines long, with a maximum presentation of 40 seconds. The texts were presented either normally or upside down, and were viewed both monocularly and binocularly. They found that saccades were temporally conjugate, but not spatially. There were differences between the two eyes in terms of both saccadic amplitude and velocity, with no consistent pattern of one eye moving ahead of the other. These disconjugacies caused fast vergence movements during fixations, with both divergence and convergence in equal proportions. However, the amplitude of divergent shifts tended to be smaller than the amplitude of convergent shifts. The asymmetry between the eyes during saccades was not found to vary with text difficulty. Further, it is again reported that monocular viewing did not induce any change in saccadic asymmetry compared to normal binocular viewing.

5.5 Summary

The results of these studies consistently find that children's saccades when reading are temporally conjugate, but show spatial disparities which persist into fixations. The occurrence of disparities between the eyes in children has been shown to occur during saccades on both reading and non-reading tasks. However, the reading studies have provided less detailed analyses of binocular coordination than have the non-reading studies. The observed characteristic of binocular saccades on non-reading tasks that divergence is less common in children compared to adults (Fioravanti *et al.*, 1995; Yang & Kapoula, 2003) has not been documented in the reading experiments. Rather, Ygge and Jacobson (1994) report that there was no tendency for either eye to move ahead of the other in saccades when reading. Differences in the ages of the children tested, as well as the recording equipment used, may account for these differences. Alternatively, it may be the case that different oculomotor behaviour is elicited by reading and non-reading tasks in children.

Chapter Six

Children's binocular coordination during sentence reading

6.1 Introduction

The purpose of this study was 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, as discussed in section 5.2 (adults' binocular coordination) there is a growing body of literature detailing the disparities which are known to occur between adults' eyes when reading (Heller & Radach, 1999; Hendriks, 1996; Juhasz *et al.*, 2006; Liversedge *et al.*, 2006a; Liversedge *et al.*, 2006b). In addition to this, there has been some work to examine children's binocular coordination in reading (Bassou *et al.*, 1992; Cornelissen *et al.*, 1993; Lennerstrand *et al.*, 1993; Lennerstrand *et al.*, 1994; Ygge & Jacobson, 1994). However, none of these studies provided a detailed examination of children's binocular coordination during fixations on a normal reading task. Based on the results of Juhasz *et al.* (2006) and Liversedge *et al.* (2006a), who showed that fixation disparity was prevalent even at the end of a fixation, the first prediction was that disparity would remain between the positions of the two eyes at the end of fixations, both for adults and for children.

The most detailed work on children's binocular coordination has used non-reading tasks, and it was from that work that the developmental hypotheses for the present experiment were formed. Fioravanti *et al.* (1995) found that, in addition to children showing greater disparity magnitudes during saccades than adults, younger children's saccades also showed a reversed direction of that disparity relative to adults. Younger children's eyes became crossed during saccades, whereas adults' eyes are known to become uncrossed (Collewijn *et al.*, 1998, Fioravanti *et al.*, 1995). Therefore, the second prediction was that the magnitude of disparity at the end of fixations would be greater in children than in adults.

Also, the present experiment allowed examination of the third prediction that children would exhibit a higher proportion of crossed than uncrossed fixations (i.e., the pattern of fixation alignments will be reversed from that seen in adults).

The fourth prediction concerned processing difficulty. Previous research has shown that children's binocular saccades are more poorly coordinated than those of adults. This developmental difference could be due to differences in processing difficulty, where children find the tasks relatively more demanding than adults. In addition to this possible consequence of age-related changes in processing difficulty, there has also been some debate in the adult literature concerning an effect of processing difficulty on binocular coordination (Heller & Radach, 1999; Juhasz *et al.*, 2006). Therefore a target word was included in the experimental stimuli which was manipulated for frequency. The aim was to induce an effect of processing difficulty, and to examine whether or not this manipulation systematically affected binocular coordination.

The final prediction for this experiment was related to the possibility of finding an influence of word length on binocular coordination. Yang and Kapoula 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 (2003). This difference was not observed in adults. If children's binocular coordination is affected by the size of the visual target, i.e. by targets appearing larger at close distances relative to far distances, then a similar effect should be observed with a manipulation of word length where long words are larger visual targets for saccades than are short words. A second target word was therefore included in the experimental stimuli, which was manipulated for word length. It was predicted that children's binocular coordination would be poorer on long words than short words, but that no such effect would be observed in adult readers.

6.2 Methods

Participants. The twelve adult participants were all members of the Durham University community. The age range of adult participants was 18- to 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 twelve child participants were contacted through local schools, with permission from parents and head teachers 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- to 11-years (mean 9-years and 11-months). All were volunteers, and naïve regarding the purpose of the study.

Apparatus. Binocular eye movement recordings were made using two 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.

Children's stimuli. 56 experimental items were constructed, 28 of which contained a high or low frequency target word, and 28 of which contained a long or short target word. Simple syntactic structures were used to maximise children's comprehension. The high and low frequency target words were always six letters long. The median frequency for high frequency target words was 93 counts per million (range: 19 to 1,480 per million) and the median frequency for low frequency target words was seven counts per million (range: one to 14 per million). Inter-quartile ranges were seven for the low frequency words, and 128 for the high frequency words. The "short" target words were always four letters long, and the "long" target words were always eight letters long. All target words for length were controlled for frequency so that there was no significant difference between the long and short words (t_2 (1, 27) = 1.29, $p > 0.05$). All word frequencies were taken from the CELEX English word form corpus (Baayen, Piepenbrock, & Gulikers, 1995). In addition to manipulating the frequency and length of target words, it was 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 characters from the start/end of the sentence. Examples of the children's stimuli with the frequency manipulation are given in Table 6.1. For a full stimulus list, see Appendix B.

Participant Group	Condition	Sentence
Adults	High frequency, short	Once he saw the retired *worker* in the local *pool* looking very sad indeed.
	Low frequency, long	Once he saw the retired *healer* in the local *restaurant* 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.
	Short target	I ignored the argument to avoid any more *harm* and upset.
	Long target	I ignored the argument to avoid any more *distress* and upset.

Table 6.1. Sample experimental sentences for adults and children containing target words manipulated for length and frequency.

In addition to the 56 items, five practise 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.

Adult Stimuli. 40 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 six 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: one to two per million). Inter-quartile ranges were one for the low frequency words, and 115 for the high frequency words. The "short" target words were always four letters long, and the "long" target words were always 10 letters long. All target words for length were controlled for frequency so that there was no significant difference between the long and short words (t_2 (1, 39) = 1.26, $p > 0.05$). 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, five practise 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. For a full stimulus list, see Appendix C.

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 practise 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 minutes for adults.

Analyses. Fixations were manually identified in order to avoid contamination by dynamic overshoots (Deubel & Bridgeman, 1995; see also Liversedge *et al.*, 2006a). 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, four of the children completed 75% – 99% of the experiment, and five of 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 two 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 two standard deviations from the mean for any given participant (1.7% of these fixations were from adults, 1.8% were from children).

6.3 Results

Global measures. First, the mean fixation durations, saccade lengths, and regression frequencies are reported for children and adults (presented in Table 6.2). As can be seen from Table 6.2, the children made, on average, longer fixations, shorter saccades, and more regressions than adults during reading. These differences between children and adults in oculomotor behaviour during reading reflect increased processing difficulty of children compared to skilled adult readers. Further, 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 discussion in section 1.4).

	Children	Adults
Fixation duration (ms)	279 (135)	240 (88)
Saccade length (characters)	7.1 (5.6)	8.2 (6.2)
Regression frequency (%)	27.8 (3.6)	20.5 (9.3)

Table 6.2. Mean fixation duration, saccade length, and regression frequency for adults and children. Standard deviations are shown in parentheses.

Second, the accuracy scores from the comprehension questions are reported to further demonstrate that the participants did not experience any difficulty in reading the experimental sentences. The mean adult score was 78% 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 experienced greater difficulty 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 basis that increased on-line processing difficulty does not necessarily imply a lack of comprehension. To be clear, these data suggest that while children may find it more difficult 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 this experiment.

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, they were sub-divided as being either uncrossed or crossed. An uncrossed fixation was defined as the left eye fixating to the left of the right eye. A crossed fixation was defined as one where the fixation position of the right eye was to the left of the left eye.

Table 6.3 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.

	Children	Adults
End of fixations	1.58 (1.22)	1.26 (0.95)
Start of fixations	1.53 (1.11)	1.26 (0.89)

Table 6.3. Absolute disparity magnitudes in character spaces at the start and the end of fixation. One character space is equal to 0.19° visual angle. Standard deviations are shown in parentheses.

The 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 6.4.

		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%

		All start data	End aligned	End crossed	End uncrossed
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%

Table 6.4. Mean alignment proportions at the start and end of fixation (note that percentages have been rounded to the nearest whole number).

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). Firstly, the likelihood of making an aligned (as opposed to an unaligned) fixation was considered. In this first stage, the unaligned fixations were not broken down 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.

Fixations categorised as unaligned were further categorised as either crossed or uncrossed. As these two categories are still dependent, a comparison was made 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. One-sample t-tests were used to compare the proportion of crossed fixations to 50% (i.e. chance). Numerically, both children and adults made fewer than 50% crossed fixations. However, while this effect was reliable for the adults (t_1 (11) = 3.26, $p < 0.01$; t_2 (39) = 16.50, $p < 0.001$), the effect was not reliable for the children (t_1 (11) = 1.30, $p = 0.22$; t_2 (55) = 5.99, $p < 0.001$). To investigate the possibility that children made a higher proportion of crossed fixations than adults, an independent-samples t-test was used to compare the proportions of crossed fixations made by the two different participant groups. While the data showed a numerical trend such that children make a higher proportion of crossed fixations than adults, this effect was not reliable (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 although this effect was not reliable.

Start of fixation disparity analyses. Disparity magnitudes and the proportions of different types of fixation disparity at the beginnings of fixations were also examined to investigate whether disparity characteristics are similar at fixation onset and fixation offset. 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 6.3 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, $p < 0.001$).

An independent-samples t-test was conducted 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 6.4. As with the data from the end of fixation, numerically, the majority of fixations were unaligned. Again, an independent-samples t-test was used to directly compare the proportion of aligned fixations observed in both participant populations. As anticipated, the 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, one-sample t-tests were conducted to compare the proportions of crossed fixations to 50% (chance). Again, it was found that while adults made significantly fewer than 50% crossed fixations (t_1 (11) = 3.79, $p < 0.05$; t_2 (39) = 18.83, $p < 0.001$), the same trend in the children's data was not reliable (t_1 (11) = 1.32, $p = 0.21$; t_2 (55) = 6.63, $p < 0.001$). While children did make a higher proportion of crossed fixations than adults, as shown to be the case in the end of fixation disparity analyses, here the effect was not reliable (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. 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, adults made crossed fixations less often than chance. While children did make fewer than 50% unaligned fixations, this was not reliable. In line with this, the proportion of crossed fixations was greater in children than in adults; this increased proportion of crossed fixations was marginally reliable at fixation offset but not at fixation onset.

Comparison of start and end of fixation disparity. By comparing the data from the beginnings and ends of fixations, it is possible to examine whether there are movements of the eyes during fixations, and whether any movements during fixations differ between children and adults. Table 6.3 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) x 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 6.4 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. Repeated-measures ANOVAs were conducted 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 (Fs < 1). The interaction between participants group and sample point in fixation was also non-significant (Fs < 1).

Finally, a repeated-measures ANOVA was conducted 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, group differences in both the mean disparity magnitude and the proportion of aligned fixations were found both at the beginning and at the end of fixations that were either reliable or marginal. However, no significant differences were observed in either the disparity magnitudes or the fixation alignment proportions between the start and the end of fixations.[i]

Movements during fixations. Four categories of movement (or non-movement) were defined, following Liversedge *et al.* (2006a). For each of the categories of movement, an independent-samples t-test was conducted 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 spaces. 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 (ts < 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 (ts < 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. Such fixations were defined as those during which vergence had occurred. Further discrimination was made within this category of fixation in order to discriminate between two different types of vergence movement which formed the final two categories. The third category of movement was defined 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, the fourth category of movement during a fixation was defined 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. 6.1.

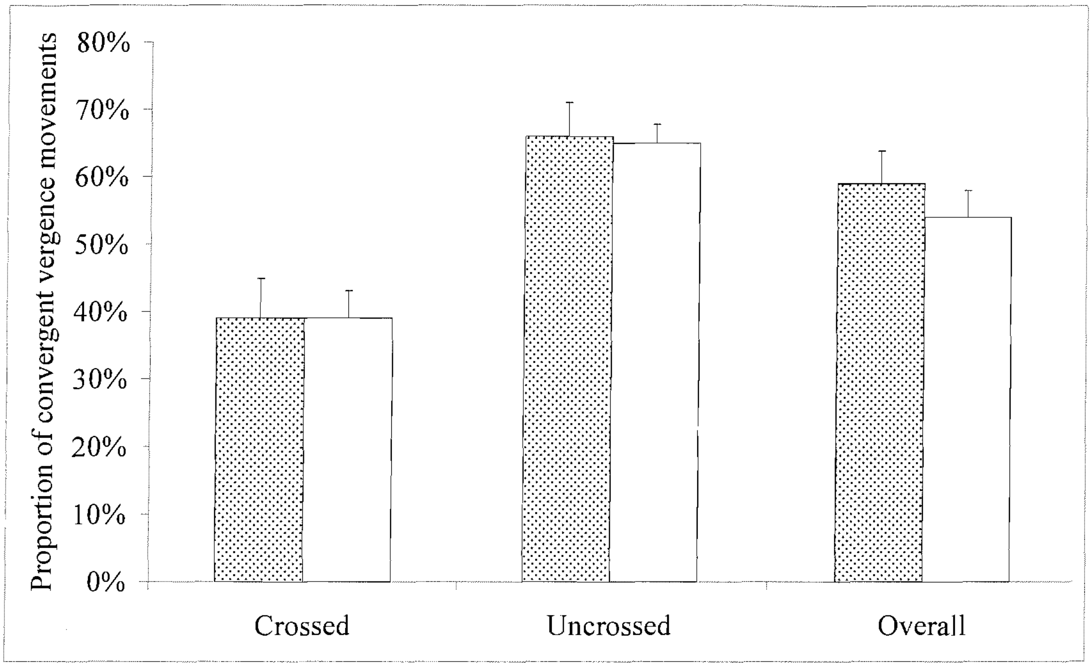

Fig. 6.1. The likelihood of vergence movements during a fixation being convergent (as opposed to divergent) for crossed and uncrossed fixations. Spotted bars represent adult data and plain bars represent child data.

Overall, these data demonstrate that when the eyes were making non-parallel vergence movements, they were more likely to be converging than diverging in both participant groups. The data suggest that that adults made a higher proportion of convergent movements than did children; however, this effect was unreliable (t_1 (22) = 1.01, p = 0.32; t_2 (94) = 3.66, p < 0.001).

In summary, both the children's and the adults' data show that the eyes were more likely to move during a fixation than not, that this movement was more likely to be vergence than drift, and that convergence was more likely than divergence.

Effects of word frequency. The analysis of the effect of frequency on binocular coordination is based on the single target word within each sentence that was manipulated for word frequency. This word was included in order to determine whether linguistic processing difficulty modulated any binocular disparity effects that were 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 two 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 anticipated, 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) were computed. 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 children 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 (ts < 1). Given that there were no reliable frequency effects for the child participants, it was necessary to restrict the analysis of whether processing difficulty modulated disparity effects to the data for the adult population alone. Consistent with the findings of Juhasz *et al.* (2006), no evidence of a frequency effect was found on either disparity magnitude or on the proportions of different fixation alignments for adults (all Fs < 2, all ps > 0.1).

Effects of word length. Again, the analysis of the length manipulation was based on data from a single target word within each sentence. The manipulation was intended to determine whether the size of a visual target affected binocular coordination in children differentially to adults. Nineteen per cent of the data in this critical region were excluded from the analysis due to first fixations less than 80 ms or more than 1200 ms (10% were made by adults and 9% were made by children). A further 6% of the data were excluded due to the end fixation absolute disparity being more than two standard deviations from the individual participant's mean (3% of these data were adults', and 3% were children's data).

The first fixation durations and gaze durations were analysed to examine the efficacy of the manipulation. As might be expected from prior research (Hyönä & Olson, 1995), the manipulation of word length in adults had a significant effect on gaze durations (t_1 (11) = 3.59, $p < 0.01$; t_2 (39) = 5.59, $p < 0.001$), but not on first fixation durations (t_1 (11) = 1.04, $p = 0.32$; t_2 (39) = 1.09, $p = 0.28$). These results reflect the increased refixation probability of adults on longer words, leading to mean gaze durations of 308 ms on long words compared to 229 ms on short words. The same pattern of results was observed in children, with mean gaze durations of 513 ms on long words and 254 ms on short words (t_1 (11) = 6.22, $p < 0.001$; t_2 (28) = 5.10, p < 0.001), but no significant effect of word length on first fixation durations (t_1 (11) = 0.22, $p = 0.83$; t_2 (27) = 1.04, p = 0.31).

A series of 2 (Participant Group: adults vs. children) x 2 (Word Length: long vs. short) repeated-measures ANOVAs were carried out to examine the influence of word length on binocular disparity in adults and children, with both participants and items as between-group variables. Word length was found to have a marginal effect on both absolute disparity magnitude (F_1 (1, 22) = 3.12, $p = 0.09$; F_2 (1, 66) = 3.77, $p = 0.06$) and on the proportion of aligned fixations made (F_1 (1, 22) = 3.08, $p = 0.09$; F_2 (1, 66) = 3.66, $p = 0.06$), but not on the proportion of crossed to uncrossed fixations (F_1 (1, 22) = 1.21, $p = 0.28$; F_2 (1, 66) = 0.14, $p = 0.71$). These marginal effects reflect participants showing greater disparity magnitudes and a higher proportion of unaligned fixations on short words than on long words. There were no significant interactions between participant group and word length on any measures of disparity (Fs < 2, ps > 0.2).

Overall, these data from the word length manipulation show a trend such that greater disparities occurred for short words than for long words. This tendency was apparent in all participants, and so the predicted interaction between participant group and word length effects on binocular coordination did not occur in these data.

6.4 Discussion

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 one 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 higher proportion of crossed fixations than did adults, and the difference in the children's data between the proportions of crossed and uncrossed fixations was not reliable. 4) When the eyes made vergence movements during a fixation, convergence was more likely than divergence for all participants.

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 the participants reported this experience. Thus, it appears that despite two disparate retinal signals a unified perceptual representation of the text is achieved.

Furthermore, the 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 for 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.

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 the child participants reported having any difficulties at all with reading from the screen. In addition, the comprehension data indicate that the 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. The possible mechanisms by which perceptual unification is achieved will be discussed 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. It was therefore anticipated that children would exhibit a greater proportion of crossed than uncrossed fixations, the opposite pattern to that observed in adults. The data did not fully support this hypothesis. While children did show a higher proportion of crossed fixations than adults, the proportion of crossed fixations was still numerically smaller relative to the proportion of uncrossed fixations that was 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 were tested in the present study. The 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- to 9-years) and a group of older children (aged 11- to 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, the proportion of unaligned fixations which were crossed were examined in relation to each participant's age.

Consistent with this possibility, it was found that for the three youngest participants (aged 7-, 8-, and 9-years) crossed fixations occurred on 43% of fixations. However, for the remainder of the children (aged 10- or 11-years) crossed fixations occurred on 36% of fixations. Thus, the data are at least suggestive of a developmental trend such that the proportion of crossed fixations children make during reading is reduced with age. Further, 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 the present study), then a greater proportion of crossed fixations and saccades in younger children might be anticipated compared to older children and adults. Yang and Kapoula (2003) found differential patterns of effects between adults and children on binocular coordination reflected by either saccade amplitude or peak velocity. They therefore argue that it is unlikely that developmental differences in binocular coordination are due to muscular differences alone.

One other important conclusion can also be formed 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 the data in which differences between children and adults are found 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, vergence movements might be expected 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 the child participants was far larger than was the case for adults. Consequently, while a tendency for a prevalence of convergent vergence movements was still observed, 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. 6.1), support this argument. From Fig. 6.1 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.

The final hypothesis which predicted differences between adults' and children's binocular coordination was that an effect of word length would be observed in children but not in adults. Based on the results of Yang and Kapoula (2003), it was predicted that children would show greater disparities on long words than on short words. However, this was not the case in the present data. There was a trend for more unaligned fixations and greater disparity magnitudes on short words than long words for all participants. Therefore not only did the data fail to support the predicted difference between adults and children, but also the observed trend in the data for all participants was in the opposite direction to that which was predicted by previous research. Yang and Kapoula argued that children's poor binocular coordination at close distances may have been due to an immature interaction between the saccadic and vergence systems, such that children are poor at maintaining a close vergence angle during saccades. Here, it has been argued that children's overall increased tendency to make crossed fixations in normal sentence reading may be due to their having a nearer focal point. These two lines of argument are entirely compatible, given the relative viewing distances used in each experiment. Here, when reading at a distance of one metre, it may be the case that the younger readers tend to have a focal point of a closer distance than the viewing distance used in this experiment. In Yang and Kapoula's data, where children's binocular coordination was particularly poor they were viewing at a distance of 20 cm, this may simply have been too close for children to maintain their normal vergence control.

While the findings from these two experiments appear to complement each other, the present data do suggest that any effects of viewing distance on binocular coordination are not driven by the size of the visual stimulus on the retina, but that developmental changes in vergence control may account for the two sets of results. Further, the finding of poorer binocular coordination on short words than on long words cannot be explained by fixation durations, which were not significantly different across word length. A possible explanation for the finding of greater disparities on short than on long words may be the distribution of binocular landing positions across a word. Given that a range of disparity magnitudes is known to occur in fixations during normal reading, this range will be symmetrically distributed across the letters of the word, i.e. the possible landing positions on that word. This distribution is likely to be much broader, with smaller tails, on the short words where the full range of disparities must occur across only four character spaces, compared to long words where there will be a narrower distribution with longer tails. The finding in these data of larger disparities on short words than on long words may therefore simply reflect the relative distribution of disparity across character spaces of those words, and not any systematic effect of word length on binocular coordination. This is further supported by the lack of an effect of word length on the proportions of crossed and uncrossed disparities. It is only the proportion of aligned fixations, and the mean disparity magnitudes, which vary with word length.

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 normally 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). 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 discrimination 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 in adults 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.

Effects of processing difficulty on binocular coordination. Despite a reliable effect of word frequency on first fixation duration in the adult data, the effect of frequency did not modulate either fixation disparity magnitude or alignment proportions. In this respect the 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).

A reliable frequency effect was not obtained 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 this particular manipulation of word frequency. Word frequency is commonly confounded with age of acquisition (Juhasz & Rayner, 2003, 2006). Here, the age-of-acquisition metrics associated with our target words were very carefully controlled 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 were used was constrained by the control of age-of-acquisition and therefore the frequency manipulation may not have been as strong as possible.

6.5 Conclusions

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. While previous research has suggested that adults fuse the two retinal images when they read, it is unknown as yet how children's visual systems cope with the relatively greater disparities that occur for them in natural reading. 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 vergence control rather than being due to differences in high level cognitive function associated with reading development.

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[i] These data differ from those of Liversedge, Rayner, White, & Findlay (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 saccades were manually identified. 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. This selection procedure was undertaken in order 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.

Chapter Seven

Panum's fusional area for linguistic stimuli

7.1 Introduction

The overall aim of Experiment Five was to examine the range of horizontal disparities between the two retinal inputs that children and adults can fuse when presented with linguistic stimuli. Additionally, two simple hypotheses were made concerning the mechanism by which we achieve a single, unified percept despite binocular fixation disparity, and whether this applies to the range of binocular disparities that occur during normal sentence reading.

The perceptual consequences of retinal disparities. When retinal disparity occurs, there are several possible perceptual experiences. First, we can see a single image. This can arise in one of two ways – fusion or suppression. Particularly with small disparity magnitudes, the two retinal inputs can be fused to form a single, unified percept. Note that, usually, fused retinal disparities lead to a sense of depth for the stimulus. For example, if a different image is received by each eye independently and the locations of those images are horizontally offset relative to each other, then the fused image would appear to be closer to or further from the perceiver than the depth of the screen. Alternatively, if the disparity is not fused, then one of the two retinal inputs might be suppressed. For example, uncorrected strabismus (causing abnormally large binocular disparities) can lead to suppression of the input from one of the eyes (Pickwell, 1984).

Second, rather than perceiving a single percept, we can experience double vision – diplopia. This occurs with greater retinal disparities, where the magnitude of that disparity is simply too large for the visual system to fuse. This will be discussed in more detail later. To summarise, we can experience a single percept either from fusing the two retinal inputs or by suppressing one of them, otherwise we experience diplopia.

In Experiment Four it was found that, for both child and adult readers, the two eyes do not always fixate the same character space when reading sentences normally. On 52% of adults' fixations and 61% of children's fixations in reading, the two eyes were fixating different letters within the word. The magnitude of this disparity was, on average, 1.58 character spaces in children (0.3°) and 1.26 character spaces in adults (0.2°). While adults' eyes tended to be uncrossed during a fixation, so that the fixation position of the right eye was further to the right than the fixation position of the left eye, children's eyes had an increased tendency to be crossed during fixations in reading.

Adults' fusion of retinal disparities. The first question of interest for this experiment concerned the mechanism by which readers tolerate retinal disparity, given that we do not typically experience diplopia when reading. Somehow the visual system achieves a single percept from two slightly different patterns of retinal stimulation. As discussed, there are two possible mechanisms by which this might be achieved.

First, it may be that the visual system simply suppresses the input from one of the two eyes during fixations in reading. Previous work with adult readers has indicated that this is not the case (Liversedge, Rayner, White, Findlay, & McSorley, 2006b). The second alternative is that the visual system combines the two different retinal inputs to form a single, unified percept.

Liversedge *et al.* (2006b) presented adult readers with sentences containing a dichoptically-presented target compound word, such as "cowboy". Through use of shutter-goggles, they were able to present a different image to each of the two eyes independently. These pairs of dichoptically-presented images were comprised of the two component word-parts, i.e. "cowb" to the left eye, and "wboy" to the right eye. They argued that if participants suppressed the signal from one of the eyes during reading, then landing positions of saccades onto the target word would be determined by the location of the portion of the word that was presented to the non-suppressed eye (landing positions fall typically just left of the centre of a word). However, if the two retinal signals were fused during normal reading then the distribution of landing positions on the dichoptically-presented word would be normal.

They found a normal distribution of landing positions on the target words as wholes when presented dichoptically, this being strong evidence of fusion rather than suppression in adults during normal reading.

Children's fusion of retinal disparities. While Liversedge *et al.*'s experiment indicated that the mechanism for coping with binocular disparity during fixations is fusion, the analyses were primarily concerned with saccade-targeting parameters. The process of fusion during the course of fixations in reading has not been examined in children in comparison to adults.

However, there is evidence to suggest that children may be able to fuse retinal disparities of larger magnitudes than adults (Dowd, Clifton, Anderson & Eichelman, 1980). Children aged 4-, 6-, and 8-years were compared with adults on their ability to perceive shapes from random-dot stereograms. Children between the ages of 6- and 8-years-old were able to perceive depth more quickly, and from greater disparities, than adults when presented with random-dot stereograms over a range of disparities between 0.3° and 1.1°. It was therefore suggested that Panum's fusional area is larger in children than in adults, and that it shows a developmental decrease in size.

Given the data from these two studies, it seems likely that both adult and child participants will at least attempt to fuse the disparate retinal inputs. The first prediction for this experiment was therefore that the mechanism by which both adult and child readers tolerate binocular disparity is one of fusion, and not suppression.

Panum's fusional area for linguistic stimuli. In addition to examining the basic mechanism for coping with binocular disparity and achieving a single percept during fixations in reading, this experiment also examined the range of binocular disparities over which fusion could be achieved. If the mechanism was one of suppression then it ought not to matter how disparate the two retinal inputs are – reading should proceed unimpaired. However, on the assumption that participants will attempt to fuse the disparate retinal inputs, there will be a range of disparities for which this is possible before the disparity becomes too large and participants experience diplopia.

If light from an object falls upon the same location on both of the retinas (corresponding retinal points), then a single object's image will be perceived. However, there are small areas around the corresponding retinal points within which light can fall and the image will still be perceived as a single object (Panum, 1858; as cited in Ogle, 1950). In this way, we can tolerate small retinal disparities without experiencing diplopia. The range over which binocular disparities can be successfully fused is referred to as Panum's area. While a full review of the literature concerning Panum's fusional area is beyond the scope of this thesis, there are several pertinent findings that will be discussed.

Traditional measurements of the range of Panum's area have used very simple stimuli such as vertical lines, presented independently to each eye through use of mirror systems. These images can be presented with varying degrees of disparity, and typically rely on the participant's self-report of their perceptual experience. One such experiment, which is widely cited within the literature, reports that the upper limit of disparity magnitude that can be fused in central vision is between 0.1° and 0.2° (Ogle, 1950). Note that these values were estimated from a graph, and also that there were inter-individual differences between the four participants for whom data was reported. At greater disparities, participants were reported to still experience a strong sense of depth even though they were experiencing diplopia (Ogle, 1952). However, for fusion to occur, this work using very simple visual stimuli has suggested that a relatively small range of binocular disparities can be tolerated.

Later estimates of the size of Panum's fusional area have given larger ranges than that suggested by Ogle (1950; 1952). Further, later work has suggested that there are at least two caveats to this estimate of Panum's area. Fender and Julesz (1967) used retinally-stabilised images which were gradually drawn apart. That is, they presented stimuli to each eye independently using a system of mirrors that allowed them to counteract any eye movements. So if the eye moved in one direction by a given amount, the mirrors made a contradictory movement to ensure that the stimulus continued to fall on the same position on the retina. Then, the two images were gradually drawn apart so that their respective positions on the two retinas were increasingly disparate. They argued that previous work had not accounted for movements of the eyes, and so there would have been some inaccuracy in the measure of retinal disparity. Through using retinally-stabilised images this study provides a highly accurate estimate of the range of Panum's fusional area.

Fender and Julesz's results showed that, when presented with retinally-stabilised stimuli, smaller disparities can be fused than when functional vergence eye movements intervene (i.e. normal vision). In each case, two measures were taken –

the value at which fusion broke when the images were being moved apart, and the value at which fusion was regained when the images were moved back toward each other again. The latter was, in every case, the smaller of the two values. They found that fusion could be maintained for up to 1.1° of horizontal disparity in stabilised vision compared to 1.5° in normal vision. These values were obtained with vertical line stimuli (note that the baseline values for normal vision are larger than those given by Ogle, 1950; 1952). When the stimuli were moved back toward each other after fusion had broken, fusion was regained at 0.7° of horizontal disparity for stabilised vision and 1° for normal vision.

The increased tolerance for disparity in normal vision as opposed to stabilised vision was argued to be a consequence of vergence eye movements, which move in a compensatory direction for the stimulus and so serve to reduce retinal disparity. When eye movements are effectively redundant in stabilised vision, the range of disparity that can be fused is much smaller and it is these values which give a truer estimate of retinal disparity and, hence, Panum's area. So, the first caveat to any estimate of the size of Panum's fusional area is that eye movements appear to play a compensatory role when presented with disparate stimuli, and so must be taken into account when estimating the range of disparities than can be fused.

The second caveat is that the range of Panum's area was shown to vary with the type of stimulus used. When participants were presented with random-dot stereograms – relatively complex stimuli – that were gradually drawn apart, fusion could be maintained for up to 3° in normal vision and up to 2.2 ° in stabilised vision. Fender and Julesz's data across several experiments therefore suggest that the visual complexity of the stimulus can alter the range of disparities which can be fused. In the present experiment, linguistic stimuli were used. White text presented on a black background is a stimulus with high spatial frequency containing a range of orientations. Therefore, these stimuli are visually more complex than single lines or dots and so it may be possible that larger disparity magnitudes can be fused for linguistic stimuli than for more visually simple stimuli.

Based on Fender and Julesz's data, the second prediction for the present experiment was that participants would be able to successfully fuse disparities within the range that is normally experienced during reading. On average, when reading, children's points of fixation are disparate by 0.3°, and adults' points of fixation are disparate by 0.2°. Irrespective of the limits of disparity for fusion of linguistic stimuli, this range of binocular disparity would seem to be well within the limits of Panum's area as defined by Fender and Julesz (1967).

Critically the overall aim of this experiment was to investigate the range of horizontal disparities that can be fused when participants are presented with linguistic stimuli. There is a range of disparities that is known to occur naturally as a consequence of binocular disparity during fixations in reading, and which can be predicted with some certainty to be within Panum's area. However, Experiment Five will examine the extent to which disparities outside this range can also be successfully fused.

Age-related changes in the size of Panum's area. In order to know the full range of disparities which children are able to fuse, the measurement of the disparity itself must be precise. Fender and Julesz noted that vergence eye movements compensate for disparity manipulations within a stimulus, and so eye movements must be taken into account in order to give an accurate estimate of the size of Panum's area. Any manipulation of disparity must account for both that which is manipulated within the stimulus, and that which occurs naturally between the eyes, in order to make any claims about the total amount of disparity between the two retinal inputs. The data from Dowd *et al.* (1980) suggest that children also ought to be able to fuse the range of disparities that is typically experienced during reading; possibly even better than adults. However, they did not measure participants' eye movements, so making their manipulation of disparity inaccurate as they could not account for the binocular disparity and vergence movements that occur.

Further, the specific perceptual demands of a given task may influence the range of disparity which can be tolerated. Varying levels of stereopsis can be achieved, beyond the range of disparities for which full fusion is possible, such that a strong sense of depth occurs despite diplopia intervening (Ogle, 1952). Therefore, it must be considered that, although children can perceive depth at larger disparities than adults, the mechanism by which they perceived depth may not necessarily have been one of perfect fusion. Specifically, it is possible that the children were able to perceive depth in the stimuli and thus successfully complete the task without actually fusing the stimuli. Therefore Dowd *et al.*'s data may overestimate the range of disparities that children can fuse through the use of a task which did not necessarily require full fusion.

The overall aim for this experiment was to examine the limits of Panum's fusional area for linguistic stimuli. The first prediction was that, for both adults and children, a process of fusion and not suppression would be used to achieve a single visual percept from the dichoptic stimuli. We do not typically experience diplopia when we read; the second prediction was, therefore, that the range of Panum's area must extend to at least 0.2 ° in adults and 0.3° in children if not further (this being the range of binocular disparity observed in Experiment Four). Given that previous work has demonstrated that stimulus complexity can modulate Panum's fusional area, then it is entirely possible that, when reading, the visual system can tolerate relatively large disparity magnitudes. Therefore the third prediction was that participants would be able to fuse a larger range of disparities than they typically experience during fixations in reading.

7.2 Methods

Participants. Participants were 10 adults aged 18- to 21-years, and 10 children aged 7- to 11-years. The mean age of the children was 9-years, 8-months (ST Dev = 1-year, 7-months). Adult participants were all undergraduate student volunteers at Durham University, and children were all volunteers from local schools.

Apparatus. Dichoptic presentation of the target words was achieved through use of Cambridge Research Systems shutter goggles, interfaced with a Pentium 4 computer and a Philips 21B582BH 24" monitor on which the target words were displayed. Binocular eye movement recordings were taken with two Fourward Technologies Dual Purkinje Image eye trackers. The positions of both eyes were recorded every millisecond. The display monitor was set at a viewing distance of 100 cm. All words were presented in block capitals, as white text on a black background, in Courier New size 18 font. At the specified viewing distance, one character space subtended 0.37° of visual angle. All participants bit on a wax dental mould and used forehead rests during the experiment, to eliminate head movements.

Materials and design. All participants viewed 100 trials, each trial consisting of a single 6-letter word. Ten counterbalanced files were created from the set of 100 words, so that every word appeared in each of the five experimental conditions, both correctly and incorrectly spelled. The misspellings were always a single-letter substitution, of either the third or the fourth letter of the word (i.e. the misspelling was always in the centre of the word). The misspelling always created an orthographically illegal letter string (for example, changing HAMMER to HAQMER) in order to ensure that the younger children would detect the misspellings easily if they were able to see them clearly. The task was not intended to be a test of reading ability in any way. The words were controlled for age of acquisition (the latest acquired word would typically known by children aged 7-years), so that they should have been familiar to the youngest participants. For a full stimulus list, see Appendix D.

The five experimental conditions were created through use of the shutter goggles, and refer to the horizontal displacement between the images presented to the two eyes. Words could either be presented as uncrossed by one or two character spaces, where the image presented to the left eye was shifted to the left on the display relative to the image presented to the right eye, aligned, where the two images were in the same location on the display, or crossed by one or two character spaces, where the image presented to the left eye was shifted to the right of the image presented to the right eye.

Procedure. All participants were given both written and verbal instructions upon arrival. For child participants, information sheets were sent to parents in advance in order that the procedure could be explained prior to arrival. Children were given lots of encouragement throughout the experiment.

Participants were instructed to look at the fixation cross, which appeared on the left of the screen for one second at the beginning of each trial, before looking at the word, which was presented in the centre of the screen simultaneously with the offset of the fixation cross. This was to ensure that, on each trial, participants made a rightward saccade onto the target, rather than continuously fixating the centre of the display throughout the experiment. Participants were instructed to make a lexical decision using a yes/no button box. Before beginning the experiment, all child participants were given five practise trials with the button box, sat at a table, using words printed on paper, to ensure that they were confident with the task.

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 practise and experimental trials were then presented. All participants had five practise trials, in addition to those given to the children before setting them up in the eye trackers, with their eye movements being recorded in order to make sure they were fully familiar and comfortable with the procedure before the experimental trials began.

Following every four trials, 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 as often as required. The entire experiment lasted approximately 40 minutes for children, due to their need for frequent breaks, and 20 minutes for adults.

Statistical 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, White, Findlay & Rayner, 2006a).

Trials were examined on an individual basis, and only those in which the participants had first fixated the cross of the left side of the screen at the beginning of the trial were included in the analysis (23% of adults' trials and 21% of children's trials were excluded). Further, fixations less than 80 ms or more than 1200 ms were deleted (7% of adults' fixations and 5% of children's fixations). Finally, fixations in which the absolute binocular disparity was more than two standard deviations above the mean (mean and SD calculated on an individual basis) were deleted (4.5% of adult trials and 6.4% of children's trials). The final data set consisted of 2316 adults' fixations and 2776 children's fixations.

Throughout the analyses, there were cases where there were missing cells of data. In these cases, where less than 5% of the cells were missing, they were filled with a global mean taken across groups and conditions. In cases where more than 5% of cells were missing, the analysis was not conducted.

For every fixation, the disparity that was manipulated in the display was combined with that which was recorded to have occurred between the eyes. In some cases, these two sources of disparity were additive and in some cases they served to cancel each other out. By combining these two sources of disparity, the categorical, experimental manipulation of the stimulus, and the continuous, natural binocular disparity, a composite measure was formed which represented the nature and magnitude of disparity on a fixation by fixation basis as it fell on the retina. This measure of binocular disparity was divided into bins of character spaces, forming the categories of retinal disparity as can be seen in Table 7.1.

			Dichoptic stimulus disparity				
			U2	**U1**	**A**	**C1**	**C2**
Binocular disparity	**-1.11° to -0.74 °**	**U2**	*A*	*U1*	*U2*	*U3*	*U4*
	-0.73 ° to -0.37°	**U1**	*C1*	*A*	*U1*	*U2*	*U3*
	-0.36 ° to 0.36 °	**A**	*C2*	*C1*	*A*	*U1*	*U2*
	0.73 ° to 0.37°	**C1**	*C3*	*C2*	*C1*	*A*	*U1*
	1.11° to 0.74 °	**C2**	*C4*	*C3*	*C2*	*C1*	*A*

Table 7.1. Categories of total retinal disparity formed by combinations of oculomotor disparity and disparity created through the dichoptic presentation. The letter U refers to uncrossed disparity of a given magnitude, the letter C refers to crossed disparity of a given magnitude, and the letter A refers to aligned fixations, where the total retinal disparity was 0. The disparity magnitudes are given in character spaces.

Throughout the results section, some analyses are presented with the disparity variable being the dichoptic stimulus disparity while other analyses are presented with the disparity variable being retinal disparity. Thus, some analyses will examine the oculomotor system's response to the dichoptic stimulus, while in other cases it is the fusion process which is of interest and so retinal disparity is the more meaningful measure. In each case, it will be made clear which form of disparity is being considered.

In most cases, a 2 (Participant group: adults vs. children) x 5 (Disparity: U2 vs. U1 vs. A vs. C1 vs. C2) repeated-measures ANOVA was carried out. Where different, details will be given. For all significant main effects of disparity, post-hoc paired-samples t-tests were conducted. Based on the a priori expectation that participants would find it increasingly difficult to fuse the increasingly large disparities, both crossed and uncrossed, the four levels of disparity were each compared individually to the aligned condition. Therefore, in each case, four t-tests were conducted and so a Bonferroni-corrected p-value of 0.01 was used to determine significance. For interactions between participant group and disparity, these four t-tests were conducted for each group separately, such that eight t-tests were conducted overall. Therefore, for t-tests to investigate a significant interaction, a Bonferroni-corrected p-value of 0.006 was used to determine significance.

For all graphs, the error bars show the standard error for each group in each condition.

7.3 Results

In order to ensure that all the children were able to perform the task reasonably well, response accuracy was checked in the aligned stimulus condition, i.e. the condition in which the words would have appeared normally and the participants simply had to decide whether or not the word was misspelled. All adult participants scored at least 95% in this condition. Five of the children scored 100%, one child scored 94%, three scored over 70%, and the final child scored 69%. Note that, critically, there was not a floor effect where child participants were entirely unable to carry out the task. The purpose of Experiment Five was to examine the relative changes in eye movement behaviour and response accuracy that occurred in relation to the disparity manipulation.

The first section of these analyses will examine landing positions on the target word, following participants' initial saccade from the fixation cross. The second section will examine the slow movements of the eyes that occurred during fixations on the target word, following the initial landing positions, as a function of retinal disparity at the start of fixations. Third, a comparison will be made of changes in binocular vergence during initial saccades onto the target and initial fixations on the target. Fourth, the dependent measures of total trial viewing time and the number of fixations per trial will be analysed as a function of retinal disparity at the end of the first fixation, i.e. at the end of the participants' initial attempt to fuse the disparate stimuli. Finally, response accuracy will be analysed as a function of the retinal disparity at the end of the final fixation of the trial, i.e. the moment at which the participant made a decision for the task, following their efforts to fuse the stimuli.

Landing position analyses. Mean landing positions were calculated from the fixation positions of the two eyes at the start of the first fixation on the target word. Fig. 7.1 shows the mean binocular landing positions of adult and child participants on words presented with different amounts of dichoptic stimulus disparity. The data were screened to ensure that these initial fixations were always preceded by a rightward saccade from the fixation cross (i.e. that participants were following the instructions).

In this case, a 2 (Participant group: adults vs. children) x 5 (Dichoptic stimulus disparity: U2 vs. U1 vs. A vs. C1 vs. C2) x 2 (Mean landing position: left eye vs. right eye) repeated-measures ANOVA was conducted in order to examine whether there were any systematic differences in the landing positions of the two eyes across either participant group, or across the manipulation of dichoptic stimulus disparity. A significant main effect of disparity was found, showing that landing positions were shifted further to the right within the word-space with increasing amounts of disparity (F_1 (4, 72) = 20.61, $p < 0.001$). Specifically, landing positions were increasingly further to the right for uncrossed disparities of both one and two character spaces, and for crossed disparities of two character spaces relative to the aligned stimulus condition (all ts > 4, all ps < 0.001). The rightward shift in landing positions between aligned stimuli and those crossed by one character space failed to reach significance (t_1 (19) = -1.88, $p = 0.08$).

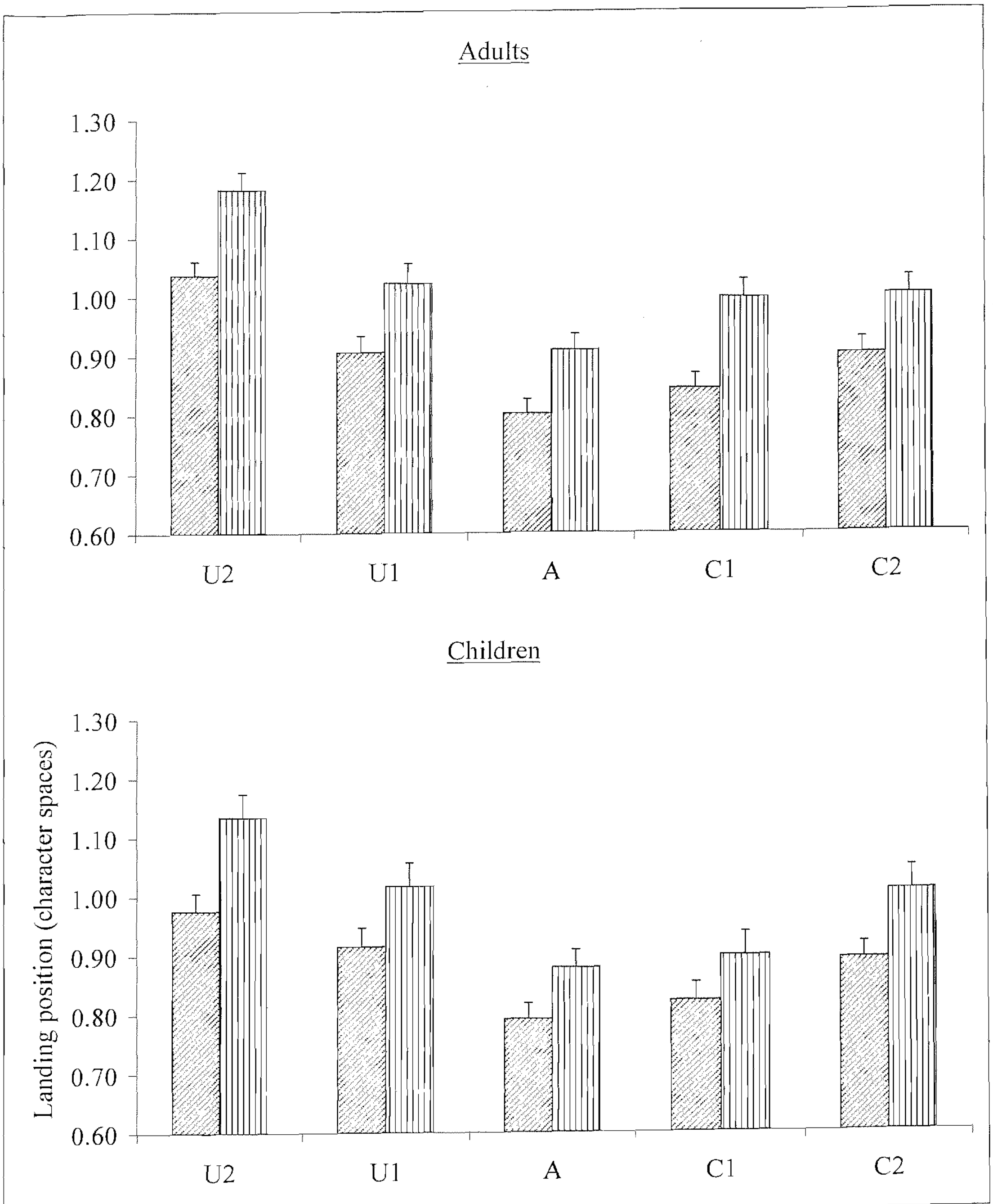

Fig. 7.1. Mean binocular landing positions on target words presented with different magnitudes of dichoptic disparity. Adult data is shown in the top panel and child data is shown in the bottom panel. Bars with diagonal lines represent landing positions of the left eye and bars with vertical lines represent landing positions of the right eye.

No difference was found in landing position disparities between adults and children (F_1 (1, 18) = 0.001, $p > 0.9$). However, there was a significant difference between landing positions of the left and the right eyes, such that the right eye consistently landed further to the right within the word than the left eye did (F_1 (1,

18) = 10.49, $p < 0.01$). None of the interactions were significant (all Fs < 2, all ps > 0.1).

Summary. These data show that, for participants of all ages, the right eye landed further to the right within the word than the left eye did. This finding is consistent with data from Experiment Four showing that, both for adults and for older children at least, the eyes tend to become transiently diverged during a saccade. The lack of an interaction between landing positions of the two eyes and the disparity of the item as manipulated with the shutter goggles indicates that the dichoptic presentation of the stimulus did not systematically affect binocular saccadic targeting to that stimulus. However, the significant main effect of disparity showed that the greater the offset between the two, dichoptically presented images, the further across to the right the eyes landed. This is consistent with the idea that participants were not fusing the dichoptic stimulus in the parafovea but instead were targeting their saccades to a blurry object that became increasingly large with larger magnitudes of dichoptic disparity. See Discussion for further detail.

Fixations on the target. As per Liversedge *et al.* (2006a), movements during fixations fell into one of four categories – a stable fixation, equal drift, convergence, or divergence. The criterion for one of the eyes having moved during a fixation was a minimum of 0.1 character spaces difference between its start and end of fixation positions. Due to the dependent nature of these categories of movements, an independent analysis was carried out for each. As the probability of, for example, a movement being vergence is dependent upon the alternative, in this case an equal drift movement, whatever analyses hold for one must necessarily hold for the other. Therefore, for each of the following sets of results, only one of the two alternatives is analyzed.

Figs. 7.2 and 7.3 below show the relative proportions of different types of movements during fixations on the stimulus, as a function of the total retinal disparity at the start of each fixation. During fixations, the oculomotor system must attempt to move the two eyes so that they are roughly aligned on the stimulus, at whatever depth it might appear. As can be seen in Table 7.1 (categories of combinations of dichoptic and binocular disparity), were the eyes perfectly aligned at the correct depth for the stimulus (i.e. both the stimulus and the eyes uncrossed by two character spaces) then the retinal disparity would be zero even though, at the depth of the screen, the binocular disparity was measured as being minus two. Therefore, irrespective of the depth being fixated, a retinal disparity of anything other than zero indicated that the eyes were not perfectly aligned with each other at the depth of the fused stimulus.

First, a comparison was made between the two different types of slow eye movement that can be made during fixations – equal drift and vergence.

When examining the probability of a movement during a fixation being vergence, a significant main effect was found (F_1 (4, 72) = 9.20, $p < 0.001$). T-tests showed that vergence movements were more likely to occur for both crossed and uncrossed retinal disparities of two character spaces, and for crossed retinal disparities of one character space than for aligned retinal inputs (all *t*s > 2, all *p*s ≤ 0.01). For uncrossed retinal disparities of one character space, the likelihood of vergence movement being made was not significantly different to that observed for aligned retinal inputs (t_1 (19) = -1.27, $p = 0.08$).

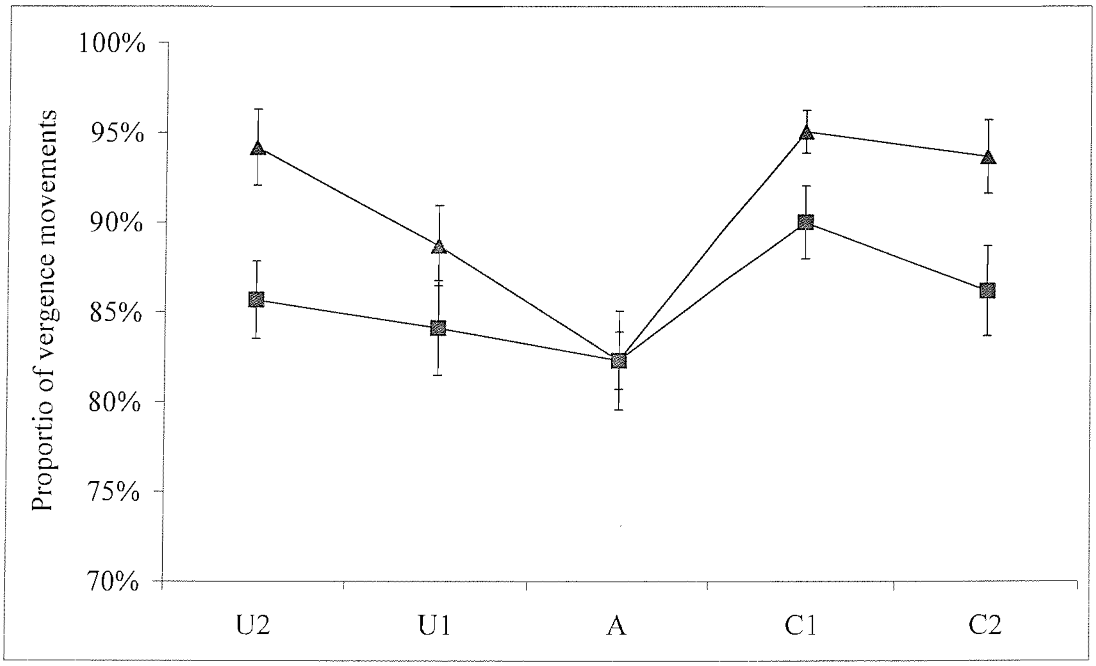

Fig. 7.2. Mean proportions of vergence movements at different retinal disparities. ▲ symbols represent adult data and ■ symbols represent child data.

There was also a significant main effect of participant group (F_1 (1, 18) = 14.27, $p = 0.001$), where children were more likely than adults to make equal drift movements. Finally, there was no significant interaction between the participant group and disparity (F_1 (4, 72) = 1.18, p = 0.33).

These data show that a larger magnitude of uncrossed retinal disparity was required in order to elicit a vergence movement, whereas smaller magnitudes of crossed retinal disparities would elicit a vergence movement.

Second, the relative probabilities of two types of vergence movement – convergence and divergence – were compared (Fig. 7.3). A significant main effect of disparity was found (F_1 (4, 72) = 52.76, p < 0.001).

Paired-samples t-tests were conducted to further investigate this main effect. Convergent movements were significantly more likely to be made for uncrossed retinal disparities of both one and two character spaces compared to aligned retinal inputs (both *t*s > 3, both *p*s < 0.001). Further, convergent movements were significantly less likely to be made with crossed retinal disparities of one or two character spaces compared to aligned retinal inputs (both *t*s > 2, both *p*s ≤ 0.01).

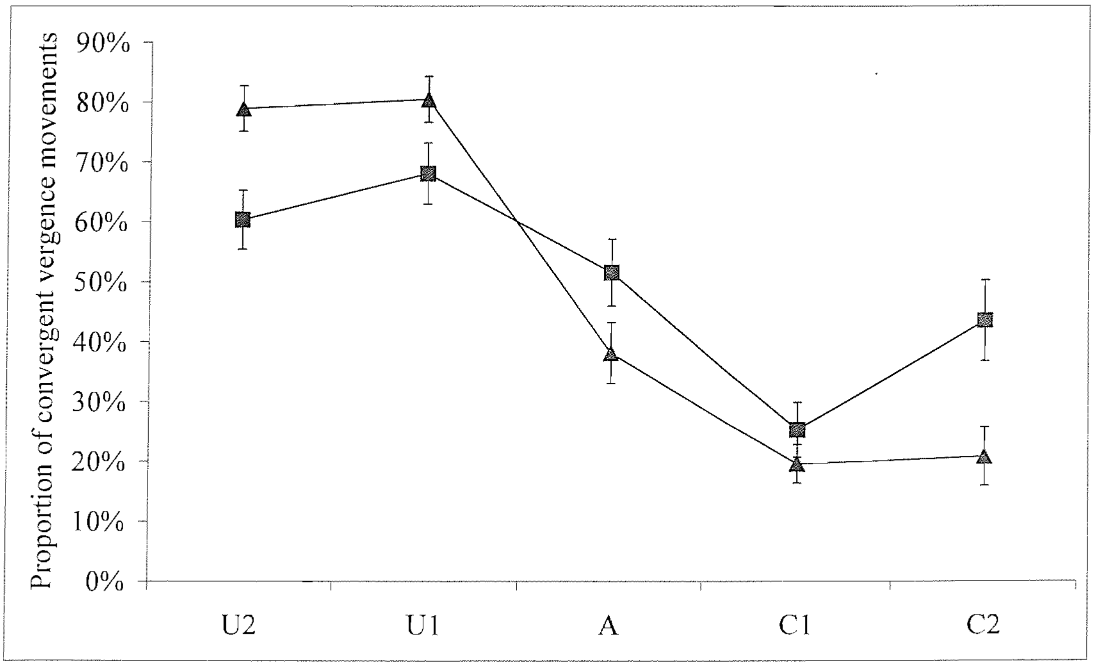

Fig. 7.3. Mean proportions of vergence movements being convergent at different retinal disparities. ▲ symbols represent adult data and ■ symbols represent child data.

There were no significant differences between adults and children in their respective probabilities of making convergent or divergent movements (F_1 (1, 18) = 0.04, p = 0.84). However, there was a significant interaction between participant group and retinal disparity (F_1 (4, 72) = 8.60, p < 0.001). For the adults, the pattern of differences across disparities was the same as that described for the main effect – disparities of both one and two character spaces in either direction lead to a significant change in the proportion of convergence. These effects were significant for uncrossed disparities (both ts > 6, both ps < 0.001), but were only marginal for the crossed disparities (both ts > 2, both ps ≤ 0.02). It was also noted that while the direction of disparity leads to a direction-appropriate movement being made, the magnitude of the disparity does not seem to affect this measure for the adults – the mean proportions of convergence were 79% and 80% for the two magnitudes of uncrossed disparity, and were 20% and 21% for the two magnitudes of crossed disparity.

For the children, there was a change in the proportion of convergence made to disparities of one character space in either direction compared to aligned retinal inputs although these effects were marginal (both ts > 2, both ps ≤ 0.01). However, there were no significant differences in the proportions of convergent movements made by children for retinal disparities of two character spaces in either direction compared to aligned retinal inputs (both ts < 2, both ps > 0.1). Overall, these data show clearly that children made lower proportions of direction-appropriate vergence movements in response to large retinal disparities. For adults, the proportions of vergence movements in either a convergent or a divergent direction were direction-appropriate across all disparity magnitudes, but were not modulated by the disparity magnitude.

In order to further examine the response of the vergence system to retinal disparities, the magnitude of these vergence movements was examined (Fig. 7.4). There was a significant effect of disparity (F_1 (4, 72) = 11.35, p < 0.001). Paired-samples t-tests showed that the magnitude of the vergence movements increased significantly in relation to all retinal disparities (all ts > 3, all ps < 0.001).

The difference in the magnitude of vergence movements between adults and children was marginal (F_1 (1, 18) = 4.18, p = 0.06). However, there was a reliable interaction between participant group and retinal disparity (F_1 (4, 72) = 5.03, p = 0.001). For the adults, the magnitude of disparity was greater for crossed disparities of one and two character spaces, and for uncrossed disparities of one character space compared to aligned fixations (all ts > 3, all ps < 0.006). For uncrossed disparities of two character spaces, the effect was marginal (t_1 (9) = 3.18, p = 0.011). Here, in contrast to the analysis of the proportion of direction-appropriate vergence movements, it can be seen that the magnitude of the vergence movements increased in response to larger retinal disparities.

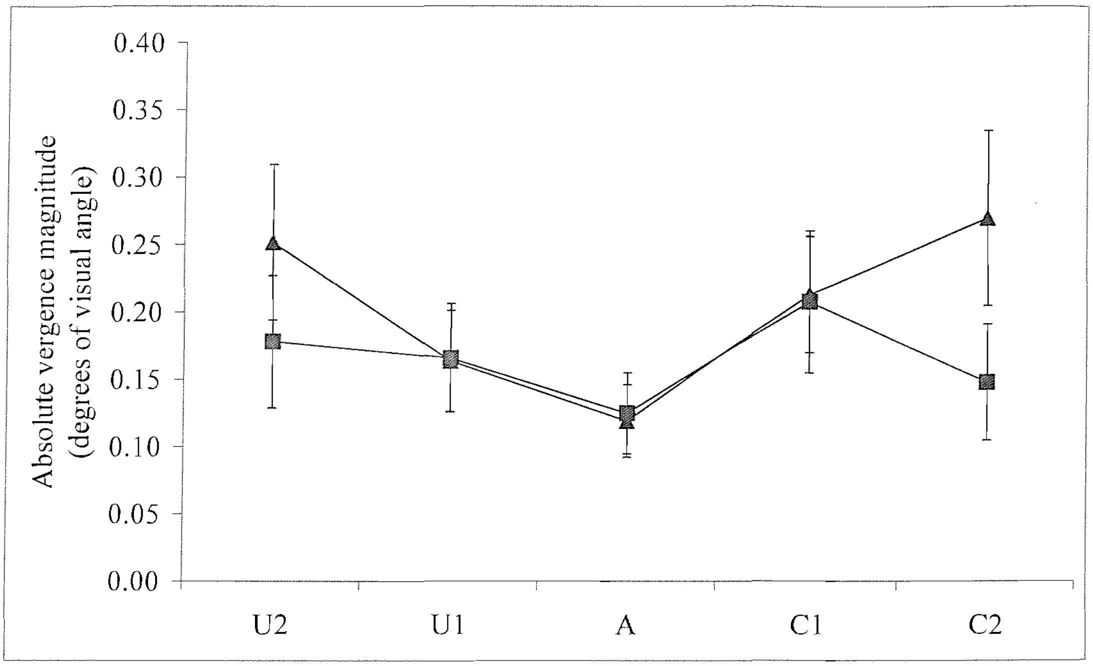

Fig. 7.4. Mean magnitude of vergence movements at different retinal disparities. ▲ *symbols represent adult data and* ■ *symbols represent child data.*

For the children, the magnitude of vergence movements made in response to retinal disparities of one character space in either direction was significantly larger than the magnitude of vergence movements associated with aligned fixations (both ts > 4, both ps < 0.006). There was a marginal increase in vergence magnitude for uncrossed retinal disparities of two character spaces (t_1 (9) = 3.14, $p = 0.012$), but there was no reliable difference in vergence magnitude between aligned retinal inputs and crossed retinal disparities of two character spaces (t_1 (9) = -2.64, p = 0.03).

So, the children did not make magnitude-appropriate vergence movements in response to large retinal disparities. Further, for large retinal disparities, vergence magnitude was not reliably different to that baseline level observed during aligned fixations. In contrast, for the adults, the magnitude of the vergence movement was mediated by the particular magnitude of retinal disparity.

Finally, the durations of first fixations were analysed as a function of disparity at the start of the fixations. A significant effect of disparity was found, where first fixations were longer with greater retinal disparity magnitudes (F_1 (4, 72) = 7.80, p

< 0.001). The durations of fixations were increased significantly compared to aligned retinal disparities for uncrossed retinal disparities of both one and two character spaces (all ts > 3, all ps < 0.001). However, there were no significant changes in fixation durations between aligned disparities and those crossed by one or two character spaces (all ts < 2, all ps > 0.09).

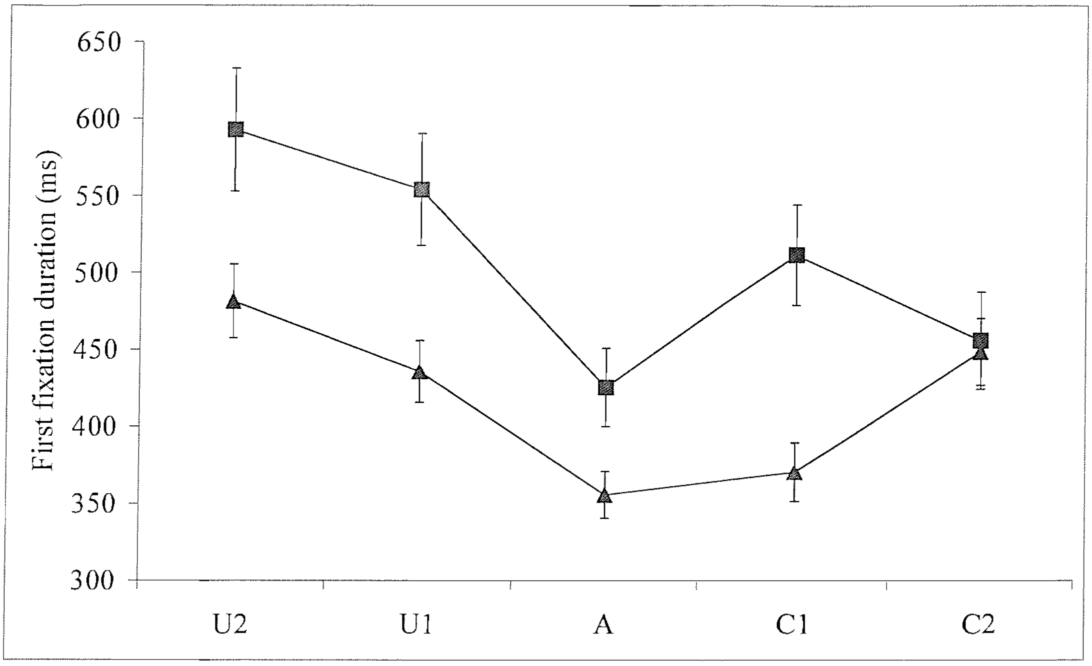

Fig. 7.5. Mean first fixation durations at different retinal disparities. ▲ symbols represent adult data and ■ symbols represent child data.

A significant difference was found between adults and children (F_1 (1, 18) = 6.75, $p < 0.05$), where children's fixations were longer overall than adults' fixations were. Further, there was a significant interaction between participant group and retinal disparity (F_1 (4, 72) = 2.87, $p < 0.05$). For adults, there was a significant increase in fixation durations for retinal disparities of two character spaces in either direction (both ts > 3, both ps < 0.006). However, the numerical increases in fixation durations associated with retinal disparities of one character space in either direction were not reliable (ts < 3, ps > 0.01).

For the children, fixation durations were significantly longer with uncrossed retinal disparities of two character spaces compared to aligned fixations (t_1 (9) = 4.62, $p = 0.001$). All other comparisons failed to reach significance (all ts < 3, all ps > 0.01).

Numerically, for all participants there was a greater increase in fixation durations associated with uncrossed retinal disparities. This asymmetry was only reliable in the children's data. For children, there was no reliable increase in fixations durations associated with crossed retinal disparities. For the adults, it was only the larger magnitudes of disparity that lead to significant increases in fixation durations, and although there is a numerical asymmetry in terms of crossed and uncrossed disparities, this was not reliable.

Summary. A larger magnitude of uncrossed retinal disparity was necessary for vergence movements to occur, while vergence movements were made in response to crossed retinal disparities of all magnitudes. This was the case for both adults and children. When examining the direction of these vergence movements, there was a significant interaction with the participant's age group. For all participants, the proportion of direction-appropriate vergence (i.e. vergence in the direction that would serve to reduce retinal disparity) was significantly different from that observed for aligned retinal inputs for both crossed and uncrossed disparities. However, for the children, the proportions of direction-appropriate vergence movements were poorer for retinal disparities of two character spaces. For both groups the effect was greater for uncrossed disparities than for crossed disparities.

In terms of the magnitudes of those vergence movements, these were influenced to a greater degree by the magnitude of the retinal disparity than was the likelihood of making a direction-appropriate vergence movement in the adults. In contrast, children did not increase the magnitude of their vergence movements in response to increasing magnitudes of retinal disparities. Therefore in terms of both the proportions of direction-appropriate vergence and the magnitude of vergence, children's vergence response was smaller than the vergence response of adults for retinal disparities of two character spaces.

Finally, the durations of fixations were examined at different retinal disparities, given that it might be reasonably be expected that these fixation durations would, to some degree, reflect the participants' efforts at fusing the two retinal inputs through processes such as vergence. While a main effect of retinal disparity was found, again there were differences between adults and children. For adults, fixation durations increased significantly for disparities of two character spaces, but not one. For the children, there was no significant increase in fixation durations for any crossed retinal disparities. Across both groups, although the effects were not always reliable, the asymmetry is clear – fixation durations increased more with uncrossed than with crossed retinal disparities.

Overall, there is some suggestion in these data that the visual system does not respond equally to crossed and uncrossed retinal disparities. A larger magnitude of uncrossed retinal disparity was needed to elicit vergence movements than was the case for crossed retinal disparities. Corresponding to this, fixation duration data indicated that crossed retinal disparities were tolerated more easily than uncrossed retinal disparities. However, when vergence did occur then there was some suggestion in the children's data that larger retinal disparities were responded to less efficiently by the vergence system.

Overall changes in retinal disparity. As can be seen from the preceding data, the magnitude of vergence movements was, on average, less than the retinal disparity that had elicited the vergence movement. The mean magnitude of vergence movements in response to each category of retinal disparity is shown in Table 7.2, both as an absolute measurement and as a proportion of the experienced retinal disparity.

		U2 0.74°	U1 0.37°	A 0°	C1 0.37°	C2 0.74°
Adults	Absolute vergence (degrees)	0.25	0.16	0.12	0.21	0.27
	Proportion of retinal disparity	34%	43%	N/A	57%	36%
Children	Absolute vergence(degrees)	0.18	0.17	0.12	0.21	0.15
	Proportion of retinal disparity	24%	46%	N/A	57%	20%

Table 7.2. Mean absolute vergence change during fixations in response to each category of retinal disparity (degrees of visual angle).

This section of the analyses will examine the changes in retinal disparity that occurred between the first and the final fixations of each trial. Fig. 7.6 shows the proportion change between first and final fixations for each of the categories of retinal disparity. For example, as shown within the graph, there was a decrease of 1% in the proportion of uncrossed retinal disparities of two character spaces between the first and the final fixations of trials in both adults and children. In contrast, there was increase of 7%, again for both adults and children, in the proportion of aligned retinal inputs from the first to the final fixations of each trial.

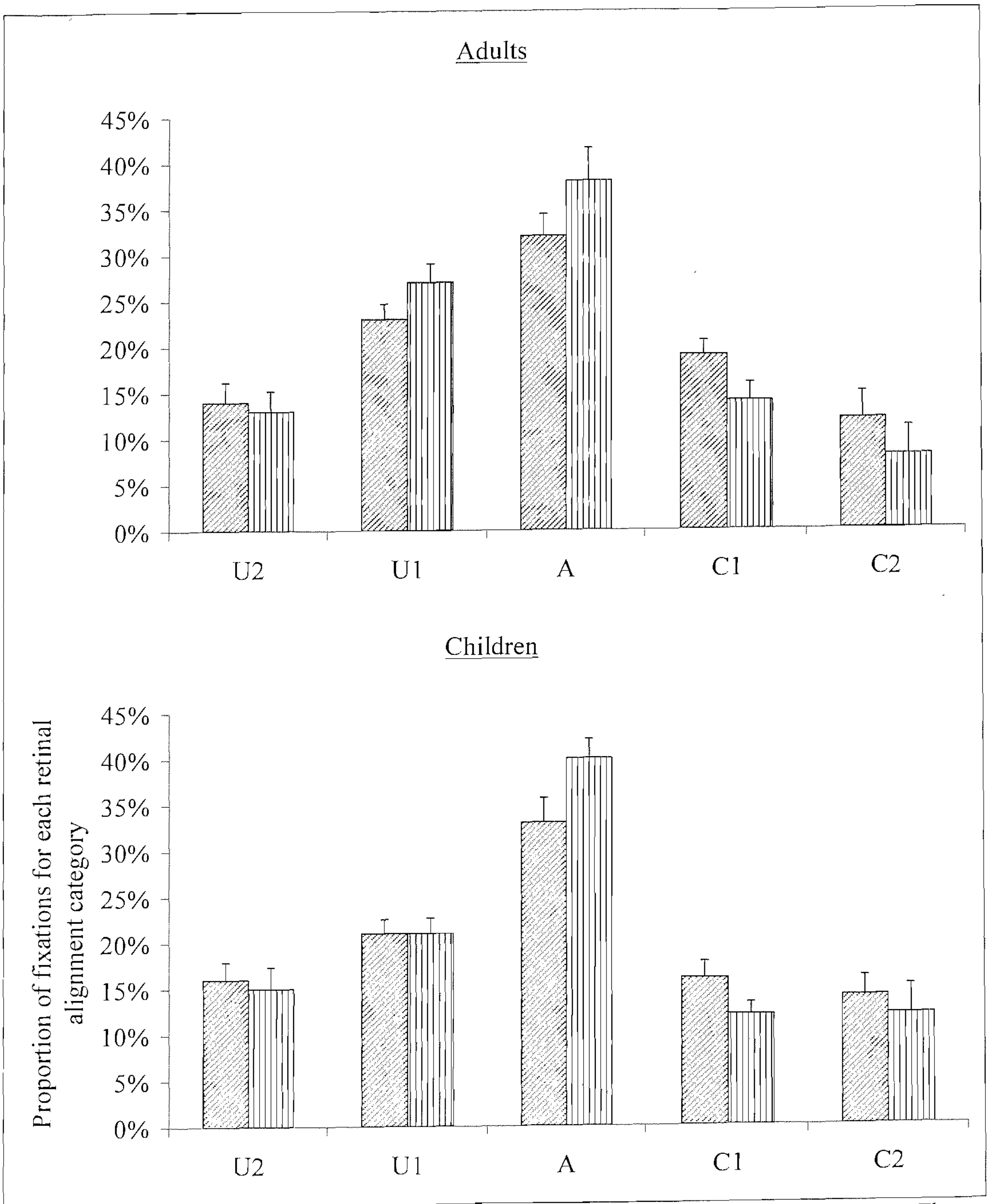

Fig. 7.6. The change in proportion of different retinal alignments from first to final fixations. The top panel represents adult data and the bottom panel represents child data. Diagonal stripes represent data from first fixations and vertical striped bars represent data from final fixations.

Due to the dependent nature of these categories (percentages), the data could not be analysed using an ANOVA. Instead, paired-samples t-tests were conducted to examine in adults and in children, for each category of retinal disparity, the relative change in proportion from first to final fixations. For these 10 t-tests, a Bonferroni-corrected p-value of 0.005 was used to determine significance.

For adults, the increase in the proportion of fixations with one character space uncrossed retinal disparity from first to final fixations was significant. Further, there was a marginally significant increase in the proportion of aligned fixations and marginally significant decreases in the proportions of crossed fixations of one and two character spaces from first to final fixations (all ts > 2, all ps ≤ 0.01).

For the children, the increase in proportion of fixations with aligned retinal inputs from first to final fixations was significant (t_1 (19) = -4.64, $p = 0.001$). However, none of the other comparisons approached significance (all ts < 3, all ps > 0.05).

Summary. These data demonstrate clearly that, through the course of the trials, participants' vergence movements did serve the purpose of changing the alignment of the eyes on a significant proportion of trials. However, the effects were not equal across groups. There were higher proportions of changes in retinal disparity for the adults than for the children. Further, these changes in proportions were not equal for crossed and uncrossed disparities. For the adults, decreases in proportions of crossed retinal disparities were marginal whereas the decreases in uncrossed retinal disparities of the same magnitude were not significant.

Vergence during fixations and saccades. The analysis of the slow movements that occurred during fixations clearly demonstrated that participants were making vergence movements in response to retinal disparities. Further, the analysis of landing positions suggested that the initial saccade onto the target did not position the eyes in the correct alignment that would be optimal for the fusion of the disparate, dichoptic stimulus. Briefly, some analyses here compare vergence during the initial saccade onto the target with vergence during the initial fixation on the target. Fig. 7.7 shows the raw data for one adult participant, that illustrates the changes in eye position and the corresponding changes in vergence angle between the two eyes throughout three different trials – one where the stimulus was perfectly aligned, one where the stimulus had an uncrossed dichoptic offset of two character spaces, and one where the stimulus had a crossed dichotic offset of two character spaces. This figure is included for illustrative purposes, to demonstrate the striking vergence movements that occurred during fixations in response to the disparity manipulation within the stimulus.

Two different aspects of vergence were considered – the magnitude of the vergence movement, and the direction of the vergence (convergent or divergent) in relation to the direction of the dichoptic disparity manipulated in the stimulus. In these data, the relative contributions of each eye are not considered; these analyses exclusively examine changes of any magnitude in the vergence angle between the two eyes.

First, the absolute magnitude of any change in vergence that occurred either during the initial saccade onto the target or during the initial fixation on the target was compared (Fig. 7.8).

A 2 (Participant group: adults vs. children) x 2 (Vergence type: fixation vs. saccade) x 5 (Stimulus dichoptic disparity: U2 vs. U1 vs. A vs. C1 vs. C2) repeated-measures ANOVA was conducted in order to examine the magnitude of vergence movements made. Most of this analysis will not be reported here, as the results from these initial fixations are largely a duplication of the analyses in the preceding section of the results (where the analyses were based upon all fixations on the stimuli).

There was a significant difference in the magnitude of vergence movements, with those being made during fixations being of a greater magnitude than those made during saccades (F_1 (1, 18) = 17.448, $p < 0.001$). Further, there was a significant interaction between dichoptic disparity, and whether the vergence occurred during a fixation or during a saccade (F_1 (4, 72) = 6.247, $p < 0.001$).

As can be seen from Fig. 7.8, the vergence that occurred during fixations was more strongly affected by the dichoptic disparity than was the vergence that occurred during saccades. Paired-samples t-tests showed that there were no significant differences in any of the comparisons when examining the magnitude of vergence movements during saccades (all ts ≤ 1, all ps > 0.4). In strong contrast, during fixations, all comparisons were significant (all ts > 2, all ps ≤ 0.01).

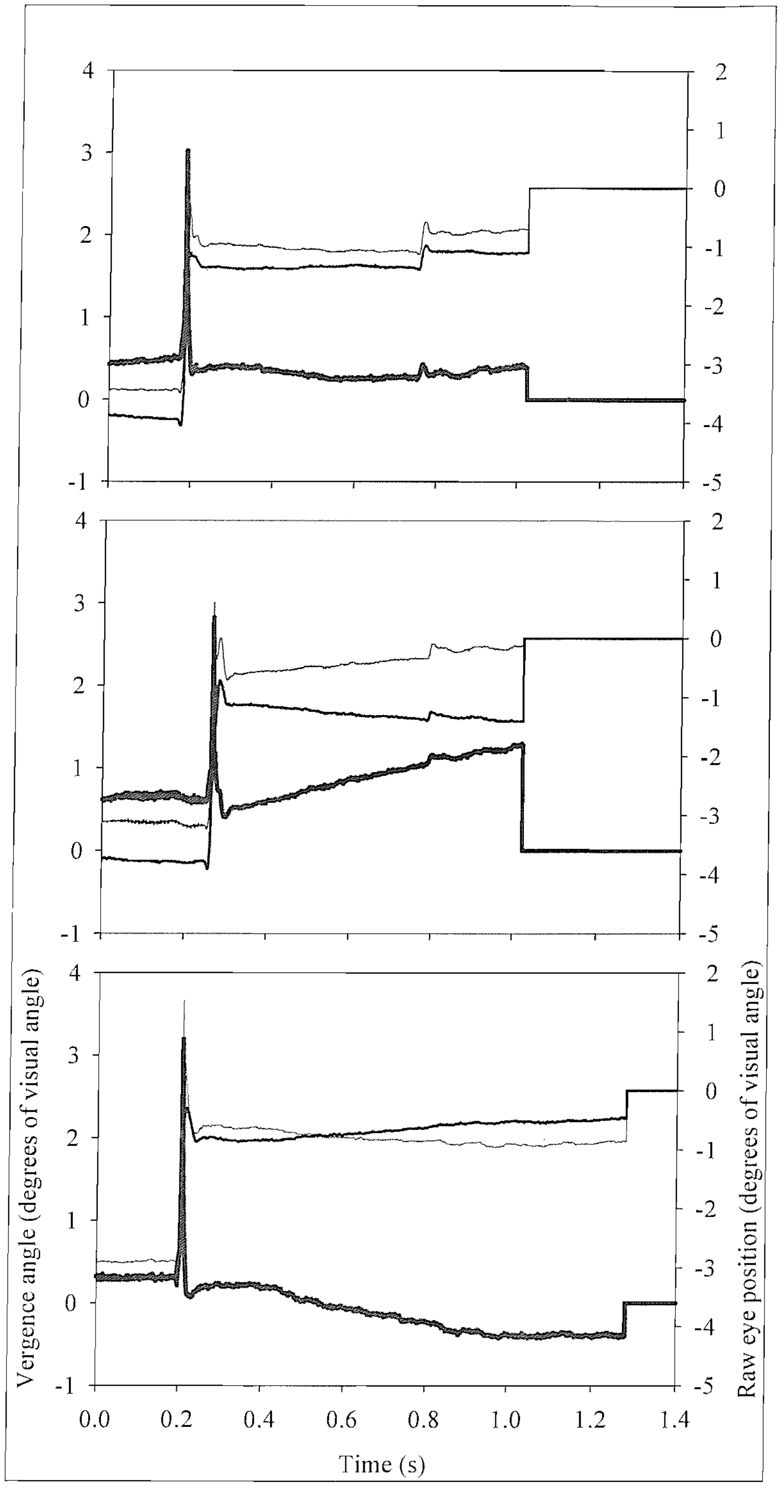

Fig. 7.7. The raw eye positions, and corresponding vergence angle, of one adult participant for three trials. The top panel shows a trial where the stimulus was aligned, the middle panel shows a trial where the stimulus was uncrossed by two character spaces and the bottom panel shows a trial where the stimulus was crossed by two character spaces. The heavy lines represent the vergence angle between the two eyes, the medium line represents the raw position of the left eye and the fine line represents the raw position of the right eye. The y-axis on the left side corresponds to the vergence angle (heavy line) and the y-axis on the right side corresponds to the raw eye positions (medium/fine lines).

Second, the proportions of convergent (as opposed to divergent) changes in vergence during either fixations or saccades are show in Fig. 7.9. These data indicate whether the direction of the vergence movements were appropriate for the dichoptic offset associated with the stimulus.

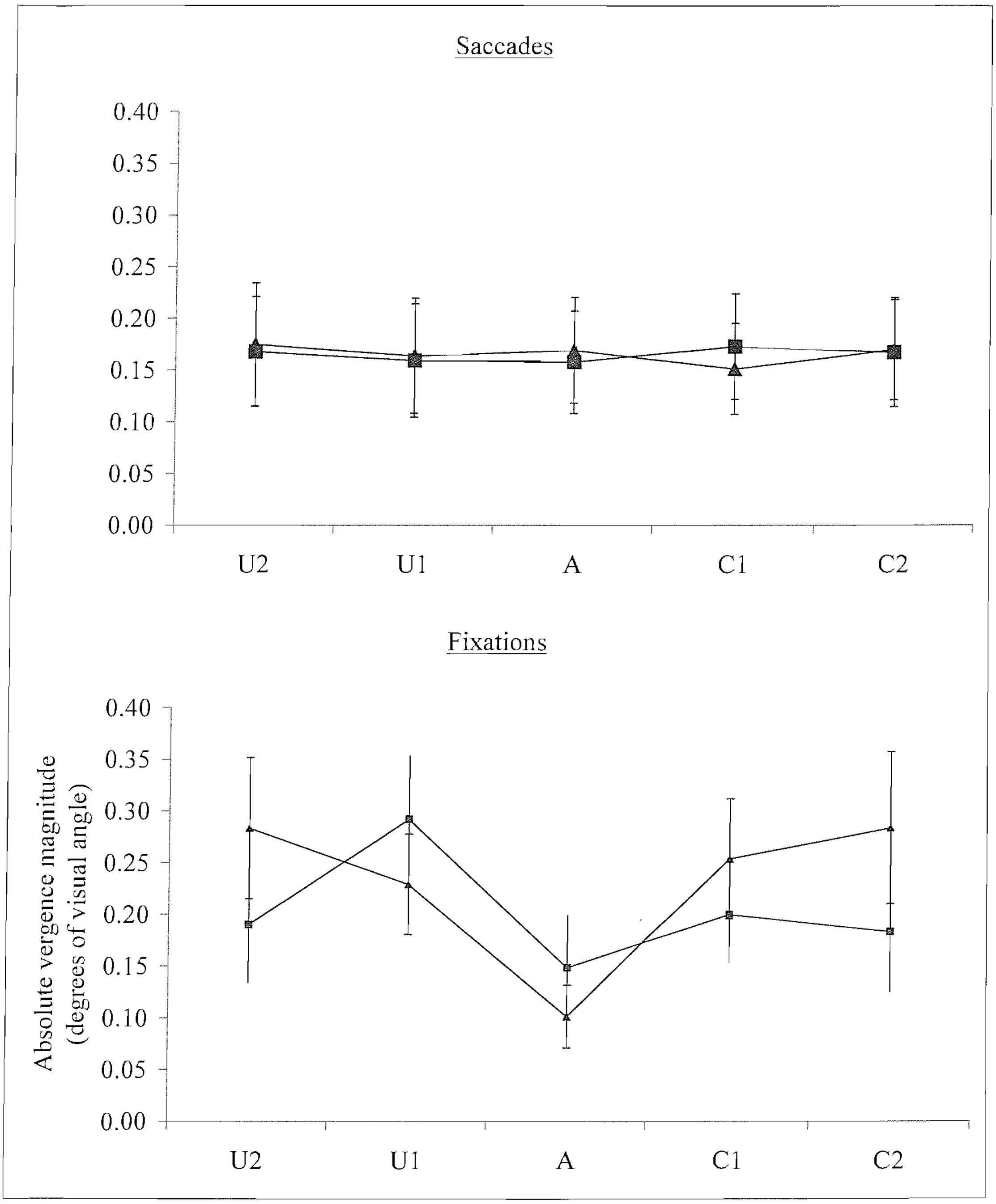

Fig. 7.8. Mean absolute change in vergence during the initial saccade onto the target (top panel) and during the initial fixation on the target (bottom panel). ▲symbols represent adult data and ■ symbols represent child data.

These data were analysed using a 2 (Participant group: adults vs. children) x 2 (Vergence type: fixation vs. saccade) x 5 (Stimulus dichoptic disparity: U2 vs. U1 vs. A vs. C1 vs. C2) repeated-measures ANOVA. Again, most of this analysis will not be reported here, as the results from these initial fixations are largely a duplication of the analyses in the preceding section of the results. However, the pertinent finding was that, despite there being no significant difference in the overall proportion of convergence made during fixations or saccades (F_1 (1, 18) = 0.33, $p = 0.57$), there was a highly significant interaction between the item disparity and whether the vergence occurred during a fixation or a saccade (F_1 (4, 72) = 25.61, $p < 0.001$).

As can be seen from Fig. 7.9, vergence movements were in the appropriate direction for the dichoptic stimulus during fixations, but not during saccades. For the analysis of vergence during fixations, all four retinal disparities lead to significantly different proportions of direction-appropriate vergence compared to the aligned condition (all ts > 3, all ps ≤ 0.001). Again, there were no significant differences between any of the comparisons for proportions of convergence during saccades (all ts ≤ 2, all ps > 0.05).

Therefore, during initial fixations on the stimulus, convergent movements were made for items presented with crossed dichoptic offsets and divergent movements were made for items presented with uncrossed dichoptic offsets. However, during initial saccades onto the target, the direction of the dichoptic disparity did not systematically affect the direction of vergence movements, or the magnitude of those vergence movements.

Summary. These data demonstrate clearly that the vergence system was responding to the disparity manipulated in the dichoptic stimuli very strongly during fixations on the stimulus. However, initial saccades onto the target do not appear to have been affected at all by the dichoptic nature of the stimuli.

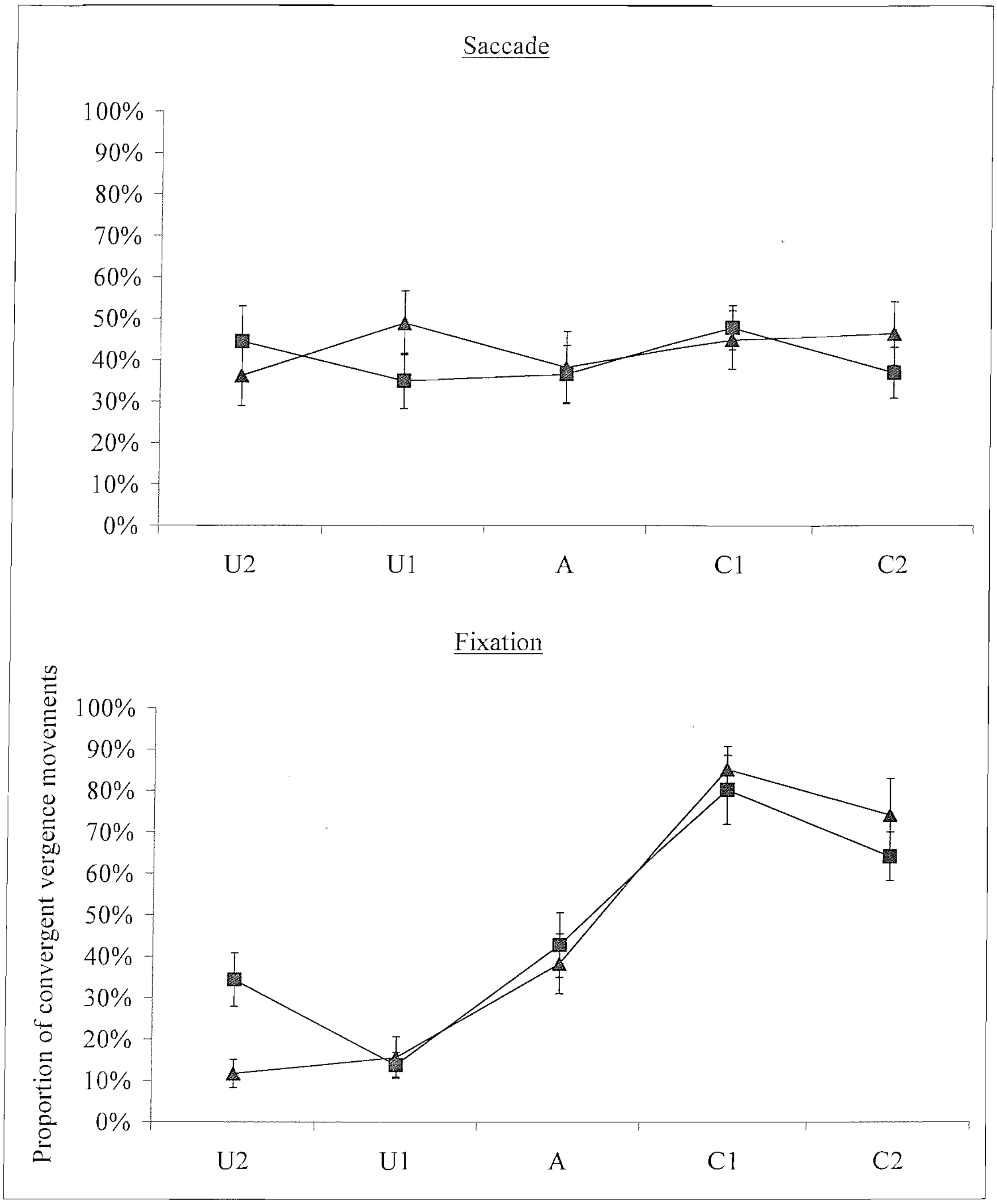

Fig. 7.9. The mean proportions of vergence movements that were convergent (as opposed to divergent) during initial saccades onto, or initial fixations on, dichoptic stimuli with different offsets. Data from saccades are represented in the top panel and data from fixations are represented in the bottom panel. ▲ symbols represent adult data and ■ symbols represent child data.

Fusion across multiple fixations. This section of the results considers total trial viewing times, and the number of fixations per trial as a function of the total retinal disparity at the end of the first fixation on the word, i.e. after the participant's saccade to and initial attempt to fuse the dichoptic stimulus. Figs. 7.10 and 7.11

show trial viewing times and number of fixations per trial across different retinal disparities.

A significant main effect of retinal disparity was found upon total trial viewing times (F_1 (4, 72) = 10.76, $p < 0.001$). For all participants, the trial viewing times were significantly longer for retinal disparities of two character spaces' in either direction, and one character space of crossed disparity compared to aligned retinal disparities (all ts > 2, all ps ≤ 0.01). The increase between aligned retinal disparities and those uncrossed by one character space was not reliable (t_1 (19) = 2.24, p = 0.04).

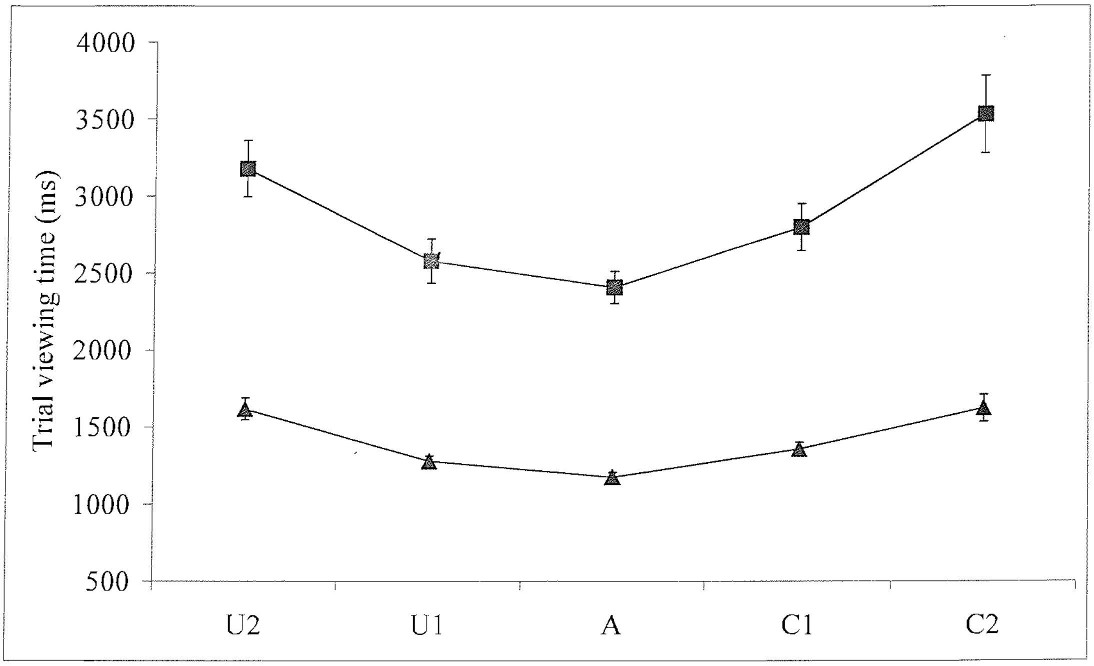

Fig. 7.10. Mean trial viewing times as a function of total retinal disparity. ▲ symbols represent adult data and ■ symbols represent child data.

Further, a significant main effect of participant group was found, where children had longer trial viewing times than adults (F_1 (1, 18) = 30.00, $p < 0.001$). There was also a significant interaction between participant group and retinal disparity (F_1 (4, 72) = 2.82, $p < 0.05$).

Paired-samples t-tests showed that there were significant increases in trial viewing times associated with all increases in retinal disparities for the adults (all ts > 3, all ps < 0.01). For the children, trial viewing times were significantly longer for retinal disparities of two character spaces in both directions (all ts > 2, all ps ≤

0.01), but there were no significant differences between aligned retinal inputs and disparities of one character space (both ts ≤ 2, both ps > 0.05).

Fig. 7.11 shows the number of fixations per trial at different retinal disparities. A significant main effect of retinal disparity was found upon the mean number of fixations per trial (F_1 (4, 72) = 8.70, $p < 0.001$). The number of fixations per trial was significantly higher for retinal disparities of two character spaces in either direction (both ts > 2, both ps < 0.01). However, the differences between aligned retinal inputs and disparities of one character space in either direction were not reliable (both ts ≤ 2, both ps > 0.05).

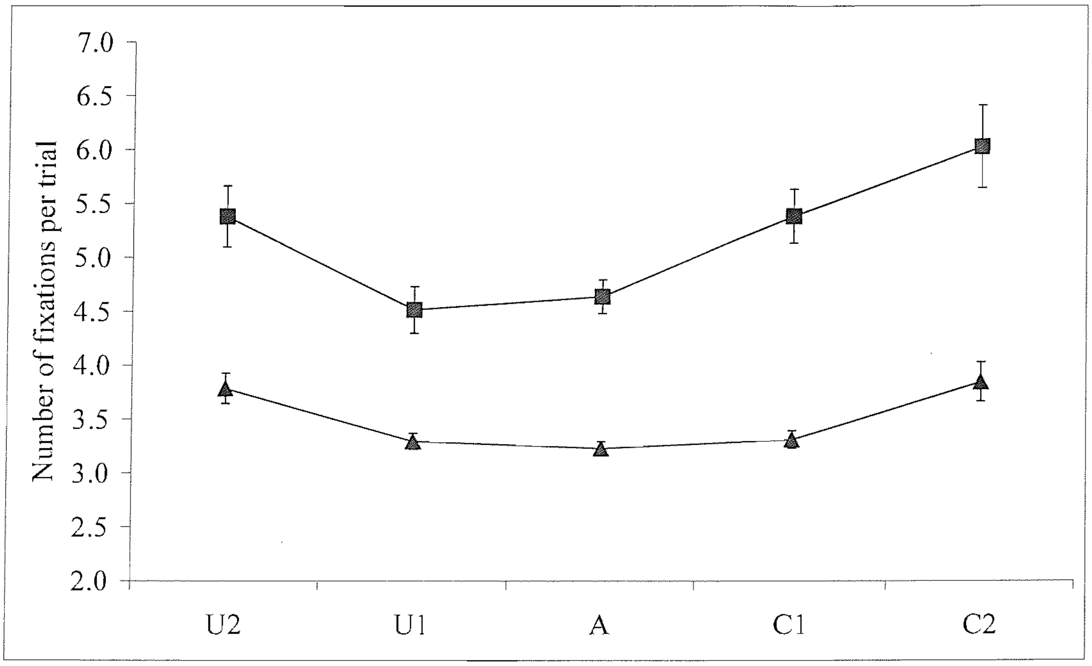

Fig 7.11. Mean number of fixations per trial as a function of total retinal disparity. ▲ symbols represent adult data and ■ symbols represent child data.

A main effect of participant group was also found, where children made more fixations per trial than adults (F_1 (1, 18) = 16.96, $p = 0.001$). However, there was no significant interaction between disparity and participant group (F_1 F_1 (4, 72) = 1.67, $p = 0.17$).

Summary. There were significant effects of disparity upon trial viewing times and the number of fixations per trial. These effects of retinal disparity reflect participants' increasing difficulty in fusing the two disparate retinal inputs. However, there were slight differences between these two measures – for all increases in retinal disparity, there was a corresponding increase in trial viewing times. However, there are potentially two different elements behind any increase in viewing time – the number of fixations made, and the durations of those fixations. For the number of fixations made per trial, there were more fixations made per trial for retinal disparities of two character spaces, but there was no increase in the number of fixations between aligned retinal disparities and those disparate by one character space in either direction.

Significant differences were found between adults and children on these measures, where children made more fixations per trial and had longer trial viewing times than adults. These differences reflect children's increased difficulty with the stimuli; this difficulty could either be related to age-related differences in the fusion process, or simply to differences in reading skill (i.e. adults' increased familiarity with the stimuli).

Response accuracy. Response accuracy is reported here as a function of retinal disparity from the end of the final fixation of each trial (i.e. the amount of binocular disparity experienced at the moment when the participant made their decision for that item).

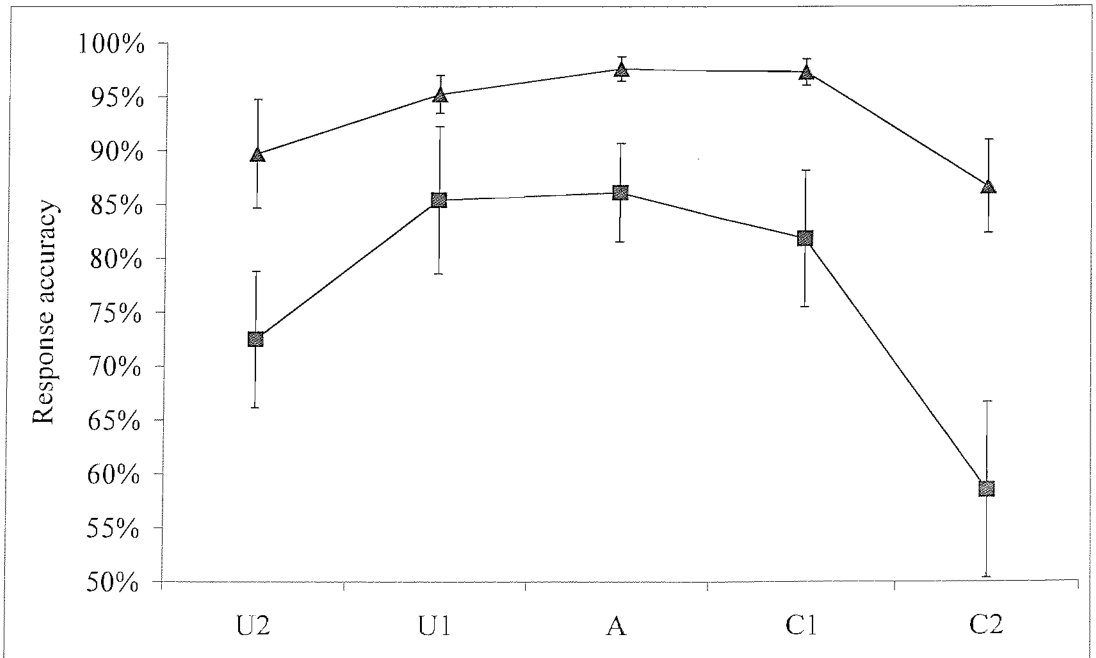

Fig 7.12. Mean response accuracy as a function of total retinal disparity. ▲ symbols represent adult data and ■ symbols represent child data.

A significant effect of disparity was found on response accuracy (F_1 (4, 18) = 2.53, p = 0.05). For all participants, more errors were made in detecting misspellings with larger retinal disparities. Response accuracy was poorer for retinal disparities of two character spaces, both crossed (t_1 (19) = 2.40, p = 0.03) and uncrossed (t_1 (19) = -2.22, p = 0.04); however, these effects were not reliable. The differences between retinal disparities of one character space in either direction compared to aligned fixations did not approach significance (both ts < 2, both ps > 0.1).

Again, there was a significant difference between adults and children, with children making more errors on the task than adults (F_1 (1, 18) = 6.66, p < 0.05). There was no significant interaction between participant group and disparity (F_1 (4, 72) = 0.50, p = 0.74).

Summary. The significant main effect of disparity clearly showed that there was a decrease in response accuracy when the participant was experiencing greater retinal disparity as they made the decision. In particular, response accuracy was poorer for retinal disparities of two character spaces. Overall, adults made fewer errors on the task than children did. Again, this may reflect either adults' increased familiarity with the stimuli as skilled readers, or adults' relative ease in viewing the dichoptic stimuli.

7.4 Discussion

Fusion or suppression? The first prediction for Experiment Five was that all participants would attempt to fuse the dichoptic stimuli, rather than suppressing one of the two retinal inputs. Previous research has demonstrated that, for adult readers, a unified visual percept is achieved through a process of fusion and not by suppression of one of the two retinal inputs (Liversedge *et al.*, 2006b). These data provided evidence that, when experiencing disparity, children also attempted to fuse the two retinal inputs.

If it were the case that, due to their poorer binocular coordination and subsequently increased retinal disparities in relation to adults, children simply suppressed one of the two retinal inputs then there ought to have been no effects of disparity upon the dependent measures in this experiment. If the children were suppressing information from one eye, then the disparity manipulation would only have served to slightly shift to the left or to the right the image presented to the non-suppressed eye. This would have had no effect whatsoever upon the children's ability to process the stimuli and carry out the task.

Therefore, the finding of effects of disparity upon the eye movement measures reported here is strong evidence that children between the ages of 7- and 11-years will attempt to fuse the two retinal inputs when experiencing disparity. Further, in support of Liversedge *et al.*'s data (2006b), the same argument holds for the adult data in the present experiment – the effects of disparity upon eye movement measures demonstrate the adults' attempts to fuse the dichoptic stimuli.

Parafoveal processing of the dichoptic stimulus. The most prevalent view of binocular eye movements is that the two eyes are under the control of a yoked command. In such a way, the two eyes can either both make a version or vergence movement, or both make a combined movement. Hering's Law states that any combined eye movement is the summation of vergence and version movements for each eye (Hering, 1977). Later work has demonstrated that the vergence and version components of a combined movement are not simply the summed version and vergence components. However, the combination of the two was argued to be a more complex interaction, a multiplication rather than a summation, but critically still a combination of two separate eye movement subsystems (version and vergence) which each control the two eyes through yoked neural signals (Ono, 1983; Zee *et al.*, 1992). There is a substantial body of literature examining binocular parameters of these combined eye movements, i.e. movements containing both version and vergence components (for a review, see Kirkby, Webster, Blythe & Liversedge, 2007). However, the idea that movements may be programmed independently for each of the two eyes has largely been dismissed as incorrect.

There has been a small body of more recent research that has considered the possibility that movements of the two eyes are programmed independently (Enright, 1996; 1998; King & Zhou, 2000). One question of interest for the present experiment was, therefore, whether landing positions on the dichoptically-presented target words would show any indication of independent saccadic targeting. Each eye would have been viewing a stimulus in the parafovea that was in a slightly different location to the stimulus being parafoveally viewed by the other eye. Therefore, a significant interaction between the direction of the dichoptic stimulus disparity and the relative landing positions of the left and right eyes would have indicated that each eye was targeting its independently-presented stimulus location. However, as can be seen in the results, this was not the case.

The results did show a main effect of dichoptic stimulus disparity, such that the larger the magnitude of the dichoptic offset between the two images, the further to the right within the word-space the two eyes landed. This is consistent with the idea that participants were not fusing the dichoptic stimulus in the parafovea but instead were targeting their saccades to a blurry object that became increasingly large with larger magnitudes of dichoptic disparity. Further, due to the manner in which the stimuli were programmed, the left edge of the non-fused stimulus always appeared in the same location. Increasing the dichoptic disparity would have made the target object appear larger by shifting the right edge of the object further right. This explains why saccadic landing positions were shifted increasingly further to the right as the dichoptic disparity increased.

As well as examining the landing positions, additional analyses were undertaken to investigate changes in vergence that occurred during those initial saccades onto the targets in comparison to the changes that occurred during fixations on the target. These results showed clearly that neither the direction nor the magnitude of the dichoptic stimulus disparity systematically affected the binocular characteristics of saccades onto the target. In contrast, once participants were directly fixating the words, the dichoptic stimulus disparity strongly affected the participants' binocular eye movement behaviour.

A second, related issue is that of depth perception – the successful fusion of a pair of images presented with dichoptic disparity typically gives rise to a sense of depth for that fused stimulus. Were the participants fusing the stimuli parafoveally, there ought to have been some systematic modulation of the binocular characteristics of those saccades to reflect the perceived depth of the stimulus. Note also that Ogle found that a sense of depth could occur for disparate stimuli that were not fully fused (1952). However, there is no evidence in the present data that participants were processing the depth of the dichoptic stimuli before directly fixating them.

Binocular disparity is measured at the depth of the screen. Therefore, an uncrossed binocular disparity of, for example, one character space measured at the depth of the screen would indicate that the participant's binocular point of fixation was at a depth beyond the screen. So, if participants were processing the depth of the stimuli in order to make their initial saccades onto the targets, then there ought to have been a systematic influence of the direction and magnitude of dichoptic disparity upon both the binocular saccade characteristics and landing positions. As discussed, this was simply not the case in the present data where there were no reliable interactions between the dichoptic stimulus disparity and the relative landing positions of the two eyes, nor the change in vergence angle during the saccade.

In summary, the analyses of binocular saccade characteristics provided clear evidence that participants were targeting their initial saccades to a non-fused stimulus, and that those saccades were yoked. There was no evidence in these data that saccades were programmed independently for each eye, or that there was any processing of the apparent depth of the stimuli as might have been caused by the dichoptic presentation before the participants directly fixated the targets.

The relationship between dichoptic stimulus disparities and retinal disparities. Some of these analyses have been presented with the independent variable being the dichoptic stimulus disparity (the disparity manipulated within the display through use of shutter goggles), while others have been presented across different retinal disparities (the combination of manipulated stimulus disparity and natural binocular disparity). It is necessary to consider carefully the relationship between these two variables before being able to draw conclusions from the analyses in their entirety.

With respect to the natural binocular disparity which occurs on a fixation by fixation basis, if the right eye is fixating a letter within the word which is further to the right than the letter fixated by the left eye then this is referred to as an uncrossed fixation. Consequently, the image that falls upon the retina of the right eye will be centred upon a letter that is further to the right within the word than the letter in the centre of the image that is falling upon the left eye. For example, when fixating the word, "MOTHER", if the right eye is fixating the letter, "H", and the left eye is fixating the letter, "T", then this would be referred to as an uncrossed fixation. The image falling on the right retina is centred on the letter, "H", while the image falling upon the left retina in centred upon the letter, "T", and so the uncrossed fixation results in an uncrossed retinal disparity. So, using this definition, an uncrossed fixation will lead to uncrossed retinal disparity while a crossed fixation will lead to crossed retinal disparity.

For the dichoptic stimulus manipulation, an uncrossed manipulation will lead to a crossed retinal disparity and vice versa. An uncrossed manipulation refers to the case where the image presented to the right eye is shifted further to the right on the screen than the image presented to the left eye. For example, in the simple case of an aligned fixation, the word, "MOTHER", might be presented such that in the same location on the screen the left eye might be fixating the letter, "T", but the right eye will be fixating the letter, "O" because the image presented to the right eye has been shifted to the right in the display. Thus, the image falling on the right retina will be centred on the letter, "O", while the image falling on the left retina will be centred upon the letter, "T". Therefore an uncrossed dichoptic stimulus disparity will lead to a crossed retinal disparity, while a crossed dichoptic stimulus disparity will lead to an uncrossed retinal disparity.

However, using the dichoptic disparity as an independent variable does not incorporate the participants' natural, binocular disparity. Therefore most of these analyses have been based around the measure of total retinal disparity which, as previously described, is a composite measure incorporating both the stimulus manipulation and any binocular disparity. Generally, there will be a strong correspondence between uncrossed dichoptic stimulus disparities and crossed "total" retinal disparities; however, there will be differences associated with binocular fixation disparity. It is important to note that the measure of total retinal disparity is, by far, the more reliable of the two as it takes into account the participants' binocular disparity.

The asymmetrical response to crossed and uncrossed disparities. These data showed, in several different cases, an asymmetrical oculomotor response to crossed and uncrossed retinal disparities. This asymmetry was seen in the likelihood of making a vergence movement during fixations, in the likelihood of any vergence movements made being direction-appropriate, in fixation durations, and in the overall change in proportion of retinal alignments from first to final fixations. Notably, there was no corresponding asymmetry in the response accuracy data.

Vergence movements were made in response to smaller crossed than uncrossed retinal disparities. Also, there was less direction-appropriate vergence for crossed retinal disparities (i.e. divergence) than there was to uncrossed retinal disparities, although this effect was clearer in the adult data than the children's data. In contrast, the durations of fixations made with uncrossed retinal disparities were longer than those with crossed retinal disparities. It was noted that this asymmetry was very clear in the main effect of retinal disparity on fixation durations, but less so in the separate analyses for each participant group. So, when the participant was not making a vergence movement, fixation durations were longer. A possible explanation may be that the vergence movements facilitated participants' fusion of the two retinal inputs and so, in turn, shortened fixation durations. When vergence movements were not made, fusion of the two retinal inputs would be more difficult and so fixations were longer.

When examining the relative proportions of different retinal alignments for first and final fixations of trials, a pattern was observed that sits well with the observed asymmetries in the likelihood of making vergence movements. In the case of uncrossed retinal disparities of either one or two character spaces, there were no significant decreases in their proportions from the first to the final fixations of each trial for either children or adults. In contrast, adults significantly reduced the proportions of crossed retinal disparities from first to final fixations. For the children, there were numerical trends to suggest that the proportions of crossed fixations decreased, but these were not significant.

Specific differences between the adults and the children with respect to this issue will be discussed in a later section. However, clearly participants' vergence systems were responding more strongly to crossed than to uncrossed retinal disparities. In relation to patterns of natural binocular disparity that occur during reading, as observed in Experiment Four, there is a prevalence of uncrossed fixations for both adults and children, although with noted developmental changes in the relative proportion of crossed fixations. Therefore these data indicate that the vergence system responds more strongly to the direction of disparity which is less commonly experienced on a day-to-day basis.

In contrast, there was no observed, corresponding asymmetry in the response accuracy data. Response accuracy was poorer for disparities, both crossed and uncrossed, of two character spaces. Given that vergence movements were less responsive to and less efficient in reducing uncrossed retinal disparities, this suggests that a residual, uncrossed retinal disparity can be fused more easily than a crossed retinal disparity. However, there are relatively few cases where there was a residual, crossed disparity at the end of the final fixation, due to the strong vergence response that occurred throughout the course of trials in order to reduce or eliminate the disparity.

Age-related changes in oculomotor behaviour. There were basic group differences observed on the probability of making a vergence movement during fixations, fixation durations, trial viewing times, and the number of fixations made. Children made a lower proportion of vergence movements overall during fixations, made more fixations, and had longer fixation durations and trial viewing times than adults. These differences reflect children's increased difficulty in processing the stimuli. A significant interaction between participant group and disparity would indicate some differential processing across the range of dichoptic disparities by children in comparison to adults; however, these main effects showing differences between adults and children simply reflect the children's increased processing difficulty for the stimuli overall. This difficulty could either stem from the dichoptic presentation of the stimuli, or the increased difficulty associated with lexical identification for children compared to adults.

Children may have found it more difficult to fuse the dichoptic stimuli than the adults did. While, ultimately, they may have been as successful in achieving a fused percept as the adults were, it may have been more difficult for them to achieve that fused percept so resulting in the described main effects.

Alternatively, adults are relatively skilled readers in comparison to children. Even though stimuli were controlled such that all the words used are typically known by children in the age group tested, those words will still be far more familiar and easy to read for adults than for children to whom they might be known but still relatively newly learned and difficult. It may, therefore, have been the case that the described main effects are a consequence of age-related differences in processing difficulty associated with reading, rather than binocular fusion.

In addition to the overall differences between adults and children, there were also a few measures on which there was an interaction between participant group and retinal disparity, thus showing some indication that children responded differently across the range of disparities than adults did. There were three different eye movement measures on which the interaction between participant group and retinal disparity showed a clear and consistent pattern – the probability of making a direction-appropriate vergence movement, the magnitude of vergence movements, and total trial viewing times.

For all three of these measures, children's response was poorer for retinal disparities of two character spaces compared to one character space. Children made lower proportions of direction-appropriate vergence movements to large retinal disparities, and the magnitude of those vergence movements was no greater than those vergence movements made in response to one character space disparities. Further, while trial viewing times did not increase for retinal disparities of one character space, there was a significant increase in trial viewing times for larger disparities indicating that the children were finding these stimuli more difficult to fuse.

In contrast, the adults made equally high proportions of direction-appropriate vergence movements for disparities of one character space as they did for disparities of two character spaces. Also, adults made larger vergence movements in response to these larger retinal disparities. Finally, adults showed a more gradual increase in trial viewing times as retinal disparity increased as opposed to the sudden increase observed in the children's data for disparities of two character spaces.

Overall, these interactions suggest that children's vergence response to large retinal disparities was poorer than that of adults, and that overall they found these disparities more difficult to fuse. It should be noted that there was no corresponding significant difference between adults' and children's response accuracy for these larger retinal disparities. Therefore, although children may have found it more difficult to fuse disparities of two character spaces, there is no evidence to suggest that they were, ultimately, less successful in doing so.

Panum's fusional area for linguistic stimuli. The overall aim of Experiment Five was to examine the limits of Panum's fusional area for linguistic stimuli. The second prediction was that disparity magnitudes that fell at least within the normal binocular range would be successfully fused. For adults, the mean binocular disparity during normal reading is 0.2° in adults and 0.3° in children. For this experiment, the behavioural measure of successful fusion was response accuracy.

Overall, there was a significant main effect of retinal disparity upon response accuracy, demonstrating that response accuracy decreased when participants were still experiencing retinal disparities at the end of final fixations of trials. However, in order to define a limit for Panum's fusional area for linguistic stimuli, it was necessary to examine the results from the t-tests to ascertain the magnitude of disparity that could be tolerated before there was a significant decrease in response accuracy. This decrease occurred for two character spaces of retinal disparity, both crossed and uncrossed, in adults and children (0.74° visual angle), although it was not reliable. Therefore the data indicated that the magnitude of disparity which could not be successfully fused was, unsurprisingly, greater than the magnitude of retinal disparity that occurs naturally as a result of binocular disparity.

However, response accuracy at retinal disparities of one character space (0.37°) was as good as response accuracy for aligned retinal inputs. This value is larger than that which occurs naturally both for adults and for children, suggesting that Panum's fusional area is larger than the disparities which are typically experienced during normal reading.

Overall, the response accuracy data, this being a behavioural measure of participants' success in fusing the retinal disparities, suggested that the limits of Panum's fusional area for linguistic stimuli lie between 0.37° and 0.74 °.

7.5 Conclusions

The first hypothesis was that both adults and children would tolerate disparity through a process of fusion. In support of this, the strong effects of disparity found upon the participants' eye movement behaviour during this experiment showed their increased difficulty with larger retinal disparities. This is strong evidence to support the view that participants were at least attempting to fuse the dichoptic stimuli, and certainly were not suppressing information from one of the two eyes.

The data showed an asymmetrical pattern of responses to crossed and uncrossed retinal disparities, suggesting that uncrossed disparities – those which more typically occur during natural reading – are more easily fused.

Second, it was predicted that the range of binocular disparities that normally occur during reading would be within the range of disparities that can be successfully fused. The response accuracy data showed that this was certainly the case; within the +/- 0.37° disparity range, response accuracy was extremely high for both the adults and the children.

The overall aim of this experiment was to examine the range of Panum's fusional area for linguistic stimuli in adults and children. The response accuracy data showed a significant decrease in participants' ability to successfully fuse retinal disparities between 0.37° and 0.74°. The lack of a significant interaction between disparity and participant group suggested that there is no difference in the range of disparities which can be fused by adults or by children. This suggests that the limits of Panum's area for linguistic stimuli, both for adults and children, lie between 0.37° and 0.74°.

Chapter Eight

General Discussion

In contrast to the wide literature on the eye movement behaviour of skilled adult readers, there is a surprisingly small literature on the development of oculomotor control during reading in children. The seminal review paper by Rayner (1998) had 802 references, the majority of which related to eye movements during reading. However, only four of these references concerned typically developing children's eye movements during reading. There have only been eight studies published, to date, which have examined typically developing children's eye movements during sentence reading.

These studies have established that there are age-related changes in eye movement behaviour during reading, such that younger readers make more fixations and regressions per sentence, have longer fixation durations, and make shorter saccades than skilled adult readers. Much of this developmental change has been attributed to the children's increased processing difficulty as beginning readers. However, there are still differences between adults' and children's eye movements, even when they are reading age-appropriate text.

Therefore, it seems possible that, in addition to reflecting the individual's reading skill, oculomotor control itself may be a skill which develops with age. The work presented in this thesis has examined two different characteristics of children's oculomotor control during reading in comparison to adults. First, data have been reported from three experiments which examined the time course of visual processing during fixations in reading, both of the fixated word and of the word to the right of fixation.

In the second half of this thesis, two experiments have been reported which examined the characteristics of children's binocular coordination during reading in comparison with that of adults. Each of these two strands of research will be discussed in turn.

8.1 The time course of processing during fixations in reading

Experiment One compared adults and children when reading text where each word disappeared 60 ms after fixation onset on that word. The results showed that children, both 7- to 9-years and 10- to 11-years, showed significant differences in their eye movement behaviour when reading disappearing text compared to normal text. In contrast, there were minimal differences in adults' eye movement behaviour across the two conditions. Specifically, children made fewer refixations but had longer fixation durations and total sentence reading times when reading disappearing text compared to normal text. There were no differences between the two text presentation conditions for adults.

Experiment Two investigated this finding further, manipulating the delay between fixation onset on a word and the disappearance of that word – either 40 ms, 80 ms, or 120 ms disappearing text, or normal text. The results of Experiment Two provided strong evidence that any differences between adults' and children's reading of disappearing text was attributable to their reading skill. The critical finding was that the main difference in eye movement behaviour when reading disappearing text was a reduction in the proportion of refixations made, and a related effect on fixation durations. This would appear to be more of a strategic change in eye movement control, given that refixations become redundant once the fixated word has disappeared.

There did not seem to be general disruption, as measures such as regression probabilities were not affected. Further, the effects of refixation probabilities were only observed in the case where the reader was presented with age-appropriate text, i.e. in the case where they might normally be expected to make a higher proportion of refixations. When reading easy text, where the refixation probability was quite low for normally presented text, there were no effects of the disappearing text manipulation upon adults' eye movement behaviour.

The finding that there were no significant interactions between the reader's age group and the duration after which the fixated words disappeared (except for the critical measure of refixation probability) showed that younger readers were no more disrupted by the disappearing text than were the adults. Therefore, these data provided no evidence to support the suggestion that there is a developmental change in the speed with which readers can take up visual information during fixations in reading.

Experiment Three manipulated the temporal availability of the word to the right of fixation (N+1) rather than the fixated word (N). Word N+1 disappeared 60 ms after fixation onset on word N, thus restricting parafoveal pre-processing of word N+1 to the initial 60 ms of fixation on word N. Despite previous evidence showing that children make less use of information to the right of the fixated word during reading, the results showed that children were no more disrupted by the disappearing text manipulation than the adults. In fact, there was some indication in the data that the opposite case may be true – non-reliable trends on several eye movement measures suggested that children were, at least numerically, more disrupted by the disappearance of word N+1 than the adult readers.

These data were argued to be consistent with serial lexical identification models of eye movement behaviour during reading. If readers process multiple words in parallel during fixations in reading then, given that the extent of children's parafoveal pre-processing is limited in comparison to adults, children ought to be less disrupted by the disappearance of word N+1 than adults. However, this was clearly not the case.

Further, the data from Experiments One and Two showed that children were just as quick as adults in the uptake of visual information. Therefore, the disruption observed in their eye movement behaviour when word N+1 disappeared cannot be attributed to the speed of their visual processing, where it might have been argued that children's pre-processing was interrupted at an earlier stage due to their slower uptake of visual information. Rather, the data across Experiments One to Three suggested that adults begin pre-processing of word N+1 at an earlier moment during the fixation on word N than children do. Consistent with a theoretical position of serial lexical identification, there may be a developmental change in the timing of the shift of processing from word N to word N+1 during fixations.

One account that is developed in this thesis is that the reader's cognitive processing of the fixated word determines when the reader begins to pre-process word N+1, and so skilled adult readers begin pre-processing earlier during the fixation than beginning readers. Specifically, a certain stage of lexical processing must be achieved before the reader can begin to pre-process the word to the right of fixation. Adults are somehow faster or more efficient in their lexical processing than are children, and so achieve this stage at an earlier moment during fixations than do children. In this way, adults gain slightly more preview than children when word N+1 disappears 60 ms after the onset of fixation on word N. Therefore, it was argued that the effects observed in the children's data suggest there is an age-related change in the timing of the shift of visual processing from the fixated word to word N+1 during fixations on word N. Further experimental work is clearly necessary to establish this finding reliably, and to investigate it further.

In summary, Experiments One to Three show a clear pattern, considering two different mechanisms underlying eye movement behaviour during sentence reading – the speed of visual processing, and the timing of serial processing of multiple words within a sentence. The data showed no evidence for an age-related change in the speed at which readers can take up visual information from the printed page. The observed differences between adults and children were determined by the relative difficulty that readers of different ages were experiencing, associated with their cognitive processing of the reading material. However, the data do suggest that there is an age-related change in the timing of sequential processing of words during fixations. It seems likely that the speed and efficiency of the reader's processing and identification of the fixated word determines when they shift their processing from word N to word N+1.

8.2 Binocular coordination during reading

In Experiment Four, binocular eye movements were recorded as participants read through sentences. The aim was to characterise children's binocular coordination during sentence reading in comparison to that of adults. While previous research had compared children's and adults' binocular coordination in non-reading tasks, the data from Experiment Four were the first measurement of typically developing children's binocular coordination when reading sentences. The main results from this experiment are summarised below:

1. Children have greater magnitudes of disparity between the fixation positions of the two eyes than adults do.

2. Children make a higher proportion of crossed fixations than adults do, and this decreases with age.

3. Word length does not affect binocular coordination during reading, either in children or in adults.

These data were, largely, consistent with the literature on children's binocular coordination in non-reading tasks. Here, children made a higher proportion of crossed fixations than did adults, but the proportion of uncrossed fixations was still higher than the proportion of crossed fixations for both groups. However, numerical trends in the data from Experiment Four, in context with previous research, suggested that younger readers may actually make a higher proportion of crossed than uncrossed fixations altogether. The data across several other studies suggest that up to the age of 9-years, crossed fixations are predominant and that for children aged 10-years and above, the pattern changes such that uncrossed fixations become predominant.

The finding that younger children make more crossed fixations, either in relation to the proportion of uncrossed fixations, or in relation to the low proportion of crossed fixations that adults make, has been found now in studies using both LEDs and linguistic stimuli. The pattern of differences in binocular coordination across adults and children does not, therefore, seem to be affected by the cognitive processing demands of the task; rather, the developmental changes in binocular coordination seem to be a consequence of the maturation of the visual system, with either muscular or neural causes. However, the large magnitudes of disparity that were recorded for the children in particular raised the question of how children tolerate these binocular disparities without experiencing diplopia.

Experiment Five was designed to examine the mechanism underlying the experience of a unified visual percept during fixations in reading, despite binocular disparity. The aims were to determine whether children achieved a single percept, rather than diplopia, through a mechanism of fusion or suppression, to measure Panum's fusional area for linguistic stimuli, and to examine whether there is a developmental change in the size of Panum's fusional area.

Shutter goggles were used to create horizontal disparity between the images of single words presented to the two eyes, whilst binocular eye movement recordings were taken. The combination of the stimulus manipulation and the participants' binocular disparity gave an overall measure of retinal disparity. The binocular eye movements reflected participants' attempts to fuse the disparate stimuli. Further, participants' ability to fuse the stimuli, with varying directions and magnitudes of retinal disparity, was assessed using a lexical decision task. The main findings from these two studies were as follows:

1. Children, as well as adults, fuse disparate retinal inputs when reading rather than suppressing one of the two eyes.

2. Children's vergence response to large retinal disparities is poorer than that of adults, but there does not appear to be a consequence of this in terms of a decreased ability to fuse these larger retinal disparities.

3. Panum's fusional area for linguistic stimuli extends up to 0.37° in children and in adults.

4. The response to and tolerance of crossed and uncrossed retinal disparities is not symmetrical. Uncrossed disparities, which are experienced more commonly as a consequence of normal binocular coordination, are tolerated more readily than crossed retinal disparities.

With respect to the adult data, the pattern of results was very clear. Uncrossed fixations occurred frequently when reading, and adults seemed to fuse these disparities very easily without necessarily making vergence movements to compensate. For the children, the pattern was slightly less clear. Considering the data from Experiment Four in which normal binocular disparity was measured as participants read through sentences, children made a higher proportion of crossed fixations than adults.

The characteristic, increased proportion of crossed fixations in younger children, along with the observed asymmetry in fusion of crossed and uncrossed disparities in Experiment Five, lead to the a posteriori expectation that the fusion of retinal disparities might also have showed developmental changes in asymmetry such that crossed disparities are tolerated more readily by younger children.

However, this was not evident in the data from Experiment Five. The asymmetry observed in the likelihood of making a vergence response was the same for the children as for the adults, where a larger magnitude of uncrossed retinal disparity was necessary to elicit a vergence movement in comparison to crossed retinal disparities.

It is possible that the age range of the children tested is the reason why stronger developmental changes in binocular fusion asymmetries were not observed. In Experiment Five, the age range of the child sample was 7- to 9-years-old. Within this, there were five children aged 7- to 9-years and five children aged 10- to 11-years. Therefore, it may still be plausible that there is a developmental change in the asymmetrical vergence response to crossed and uncrossed disparities that would be apparent if different age groups of children were directly compared.

8.3 Statistical analysis of children's eye movement data

Throughout the analyses reported in this thesis there have been a number of instances where effects were reliable across items but not across participants. There are two possible reasons why this may have been the case. First, it may be a difference in the relative power associated with the two types of analyses. For example, in the 3 x 2 repeated-measures ANOVAs that were used in Experiments One and Two, there were typically 240 data points contributing to each items analysis (40 items giving data in each of six different, within-item conditions). In contrast, for the analysis across participants, there were between 48 and 72 data points contributing to the analysis (between 24 and 36 participants giving data in two within-participant conditions).

Second, there may be a more theoretically interesting reason for this difference across the two types of analysis – these patterns may be showing that while all of the items in the stimulus set produce consistent effects, not all the of the participants within any particular group are behaving in a consistent way. An inspection of the standard deviations for the eye movement measures in each of the three groups supports this latter interpretation of the patterns of data.

When examining the data from Experiments One to Three, typically, standard deviations for the younger readers' data are much larger than those associated with the older readers' data. For three of the six eye movement measures analysed, total sentence reading times, the number of fixations made and the number of regressions made per sentence, both the older and younger children's groups had much higher standard deviations than the adults. For fixation durations, it was the younger children's group that had the noticeably higher standard deviation while the older children's group was more comparable to the adults. For refixation and word skipping probability, there were no clear differences when inspecting the numerical differences.

These differences in the standard deviations of the three age groups raise the question of whether there was genuinely more variance in the children's data, or whether there were some individual children who were outliers and so affected the group data disproportionately. Table 8.1 compares the standard deviations and inter-quartile ranges for the data from three different eye movement measures from Experiment Three. Inter-quartile ranges are far less affected by the presence of outliers than standard deviations, and a comparison of the two measures provides some indication of whether the variance in these data is attributable to the samples as wholes, or to particular individuals within the samples.

		Standard deviation	Inter-quartile range
Total sentence reading time	Adults	833	1048
	10- to 11-years	1491	1781
	7- to 9-years	1945	2548
Number of fixations per sentence	Adults	2.8	3
	10- to 11-years	4.7	6
	7- to 9-years	5.5	6
Number of regressions per sentence	Adults	1.4	2
	10- to 11-years	2.2	3
	7- to 9-years	2.7	4

Table 8.1. Standard deviations and inter-quartile ranges for the data from three eye movement measures from Experiment Three.

As can be seen from this comparison, the ratios between the groups in terms of their variance are extremely similar for both standard deviations and inter-quartile ranges, for all three eye movement measures examined. This strongly suggests that the large standard deviations seen in the children's data across Experiments One to Three do represent the variance within the group as a whole, and are not due to outliers.

The next issue that must then be considered is whether these eye movement data represent continuous developmental trajectories which simply have more variance at younger ages, or whether they represent categorical differences in eye movement control between adults and children? The experimental work that has been reported in this thesis was designed to determine whether or not there were specific differences between adults and children in terms of their eye movement behaviour during reading. To this extent, this was achieved in the experiments reported in the thesis. A question that goes beyond the data reported is that of the nature of the change in eye movements with development. However, in order to closely examine the nature of any developmental change, it would be necessary to employ a very different approach to experimental design than that reported in this thesis. For example, a longitudinal study measuring the eye movement behaviour of children on a regular basis from when they first begin reading to when they become relatively fluent, skilled readers would be essential. In addition to chronological age, variables such as reading and language skills and IQ would also have to be measured and analysed alongside the eye movement data to begin to understand the developmental trajectory of oculomotor control during reading in relation to higher-level cognitive abilities.

To reiterate, the aim of the work reported in this thesis was to determine whether specific age-related changes existed, and this has been achieved. The children's data reported here are some of the first of their kind, and thus the issues raised are important ones that must be considered in future research in this area. The variation observed in children in their reading behaviour across different sentences may be related to chronological age, reading age, or the relative difficulty and age-appropriateness of the stimuli to name but a few possible causal factors. Clearly, further experimental investigation is required to more fully understand the relationship between oculomotor control and the cognitive development of children from beginning to skilled readers.

8.4 Age-related changes in oculomotor control during reading

The results from these five experiments comparing children's oculomotor control to that of adults' can be divided into two groups – those experimental observations which showed age-related changes, and those which did not. There was no age-related change in the speed of visual information uptake during fixations in reading, nor was there a difference between adults and children in their ability to fuse the range of retinal disparities examined. However, there were age-related changes in the timing of parafoveal pre-processing, and in the characteristics of binocular coordination that occurred during normal sentence reading, as well as in the vergence response made to manipulated retinal disparities.

8.5 Conclusions

The results from Experiments One to Three showed that the primary factor underlying children's oculomotor behaviour during reading is their cognitive processing of the text. The ease with which a child of a given age can process and identify the fixated word has been shown to determine very low-level characteristics of their eye movement behaviour; specifically, when processing shifts from the fixated word to the word to the right of fixation, and the strategy according to which the reader maintains fixation on the fixated word until they are ready to move their eyes to a new word in the sentence.

Experiments Four and Five showed that there are developmental changes in binocular coordination, suggested to be under either muscular or neural control, which are not specific to the task of reading. However, when viewing lexical stimuli, there were clear differences between adults' and children's vergence response to large retinal disparities. Despite this, children's ability to fuse retinal disparities appears to be equal to that of adults.

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<u>Appendices</u>

Appendix A: Materials for Experiments One, Two and Three

Target words in each sentence frame are shown in italics. For each item, the sentence frame labelled "a" contains the high frequency target word and the sentence frame labelled "b" contains the low frequency target word.

1a) The old broken *window* caused a real problem this morning.
1b) The old broken *hammer* caused a real problem this morning.

2a) The nice kind *worker* went swimming with his children today.
2b) The nice kind *banker* went swimming with his children today.

3a) The sudden *threat* was a shock and I forgot what I was doing.
3b) The sudden *bother* was a shock and I forgot what I was doing.

4a) The dusty *mirror* was by the door where you said it would be.
4b) The dusty *armour* was by the door where you said it would be.

5a) The bitter *coffee* that you gave me tasted really unpleasant.
5b) The bitter *cherry* that you gave me tasted really unpleasant.

6a) The nasty *leader* walked slowly along the street by himself.
6b) The nasty *beggar* walked slowly along the street by himself.

7a) The fluffy *animal* was very cute but it made me sneeze a lot.
7b) The fluffy *kitten* was very cute but it made me sneeze a lot.

8a) The gentle *lawyer* has really beautiful long, curly red hair.
8b) The gentle *maiden* has really beautiful long, curly red hair.

9a) The folded *letter* was used to light a fire when I was cold.

9b) The folded *napkin* was used to light a fire when I was cold.

10a) That strong *cheese* changed the taste of the pizza entirely.

10b) That strong *pepper* changed the taste of the pizza entirely.

11a) Her lovely *speech* was spoiled by the unexpected rain shower.

11b) Her lovely *outfit* was spoiled by the unexpected rain shower.

12a) The noisy *cattle* stood in the centre of the town square.

12b) The noisy *pigeon* stood in the centre of the town square.

13a) The special *school* helped them to pass their exam after all.

13b) The special *lesson* helped them to pass their exam after all.

14a) The sudden *danger* made us all really scared and we ran away.

14b) The sudden *scream* made us all really scared and we ran away.

15a) I listened to your *advice* but I was not very happy about it.

15b) I listened to your *excuse* but I was not very happy about it.

15a) He saw the young *driver* sitting next to the road all alone.

16b) He saw the young *damsel* sitting next to the road all alone.

17a) I thought my secret *effort* yesterday was very impressive.

17b) I thought my secret *escape* yesterday was very impressive.

18a) The pretty *island* has lots of different plants and animals.

18b) The pretty *meadow* has lots of different plants and animals.

19a) Yesterday your *mother* was angry and shouted at all of us.

19b) Yesterday your *cousin* was angry and shouted at all of us.

20a) The special *effect* was so impressive when we finally saw it.

20b) The special *chapel* was so impressive when we finally saw it.

21a) He immediately noticed the lovely large *garden* this morning.

21b) He immediately noticed the lovely large *bubble* this morning.

22a) He really wanted to wait and see our group *result* yesterday.

22b) He really wanted to wait and see our group *finish* yesterday.

23a) She laid down and put her head on the clean *cotton* to sleep.

23b) She laid down and put her head on the clean *fleece* to sleep.

24a) She lay awake thinking about the cold *church* she had seen.

24b) She lay awake thinking about the cold *kennel* she had seen.

25a) They were all a bit scared of the grumpy *fellow* at the park.

25b) They were all a bit scared of the grumpy *keeper* at the park.

26a) He thinks the colour of my hair is quite *silver* without dye.

26b) He thinks the colour of my hair is quite *normal* without dye.

27a) She shouted at the maid to go and quickly *answer* the door.

27b) She shouted at the maid to go and quickly *polish* the door.

28a) They were all working hard on the special *design* from Spain.

28b) They were all working hard on the special *puzzle* from Spain.

29a) The toddler played with the pretty *marble* you gave her.

29b) The toddler played with the pretty *rattle* you gave her.

30a) I tripped and had an accident in the dark *forest* last night.

30b) I tripped and had an accident in the dark *cavern* last night.

31a) I was excited to discover the old broken *record* yesterday.

31b) I was excited to discover the old broken *shield* yesterday.

32a) Yesterday we all spotted the very large *insect* in the wood.

32b) Yesterday we all spotted the very large *bridge* in the wood.

33a) My mum bought me a jumper with a yellow *square* on the front.

33b) My mum bought me a jumper with a yellow *button* on the front.

34a) She spends lot of time talking to the nice *people* next door.

34b) She spends lot of time talking to the nice *tailor* next door.

35a) When he finally went inside the empty *palace* it was so cold.

35b) When he finally went inside the empty *cellar* it was so cold.

36a) She tripped and fell onto the hard *ground* and hurt her back.

36b) She tripped and fell onto the hard *barrel* and hurt her back.

37a) She went to the new shop and bought a blue *pencil* yesterday.

37b) She went to the new shop and bought a blue *jersey* yesterday.

38a) In one of the cupboards, I found that *ticket* which you lost.

38b) In one of the cupboards, I found that *kettle* which you lost.

39a) Inside an old can they found a strange *object* that was blue.

39b) Inside an old can they found a strange *liquid* that was blue.

40a) There were a lot of visitors at the local *market* this month.

40b) There were a lot of visitors at the local *stable* this month.

Appendix B: Children's materials for Experiment Four

Sentences one to 28 contain a target word manipulated for frequency. For each item, the sentence frame labelled "a" contains the high frequency target word and the sentence frame labelled "b" contains the low frequency target word. Sentences 29 to 56 contain a target word manipulated for length. Target words in each sentence frame are shown in italics. For each item, the sentence frame labelled "a" contains the long frequency target word and the sentence frame labelled "b" contains the short frequency target word.

1a) The old broken *window* nearly hurt someone yesterday morning.
1b) The old broken *hammer* nearly hurt someone yesterday morning.

2a) The nice kind *worker* went swimming with his children today.
2b) The nice kind *banker* went swimming with his children today.

3a) The sudden *threat* was a shock and I forgot what I was doing.
3b) The sudden *bother* was a shock and I forgot what I was doing.

4a) The dusty *mirror* was by the door where you said it would be.
4b) The dusty *armour* was by the door where you said it would be.

5a) The bitter *coffee* that you gave me tasted really unpleasant.
5b) The bitter *cherry* that you gave me tasted really unpleasant.

6a) The gloomy *leader* walked slowly along the street by himself.
6b) The gloomy *beggar* walked slowly along the street by himself.

7a) The fluffy *animal* was very cute but it made me sneeze a lot.
7b) The fluffy *kitten* was very cute but it made me sneeze a lot.

8a) The lovely *lawyer* has really beautiful long, curly red hair.
8b) The lovely *maiden* has really beautiful long, curly red hair.

9a) Your torn *letter* was used to light a fire when we were cold.

9b) Your torn *napkin* was used to light a fire when we were cold.

10a) That strong *cheese* changed the taste of the pizza entirely.

10b) That strong *pepper* changed the taste of the pizza entirely.

11a) I tripped and had an accident in the dark *forest* last night.

11b) I tripped and had an accident in the dark *cavern* last night.

12a) We couldn't stop looking at the lovely *garden* in the sun.

12b) We couldn't stop looking at the lovely *bubble* in the sun.

13a) He really wanted to wait and see the grand *result* yesterday.

13b) He really wanted to wait and see the grand *finish* yesterday.

14a) She laid down and put her head on the soft *pillow* to sleep.

14b) She laid down and put her head on the soft *fleece* to sleep.

15a) The mean man had left his dog in the cold *church* all night.

15b) The mean man had left his dog in the cold *kennel* all night.

16a) They were all a bit scared of the nasty *fellow* at the park.

16b) They were all a bit scared of the nasty *keeper* at the park.

17a) I think the colour of her hair is quite *silver* without dye.

17b) I think the colour of her hair is quite *normal* without dye.

18a) He shouted at the maid and told her to *answer* the door now.

18b) He shouted at the maid and told her to *polish* the door now.

19a) We were all working hard on the special *design* from France.

19b) We were all working hard on the special *puzzle* from France.

20a) The baby played all day with the pretty *rattle* you gave her.

20b) The baby played all day with the pretty *marble* you gave her.

21a) Her lovely *speech* was ruined by the unexpected rain shower.

21b) Her lovely *outfit* was ruined by the unexpected rain shower.

22a) The noisy *cattle* got plenty of attention from the big crowd.

22b) The noisy *pigeon* got plenty of attention from the big crowd.

23a) The special *lesson* helped him to ride really well yesterday.

23b) The special *saddle* helped him to ride really well yesterday.

24a) The sudden *danger* made us all really scared and we ran away.

24b) The sudden *scream* made us all really scared and we ran away.

25a) Yesterday morning I found an old broken *record* in our shed.

25b) Yesterday morning I found an old broken *shield* in our shed.

26a) During the night we heard a really loud *insect* in the room.

26b) During the night we heard a really loud *shriek* in the room.

27a) My mum bought me a jumper with a yellow *button* on the front.

27b) My mum bought me a jumper with a yellow *stripe* on the front.

28a) She spends lot of time talking to the nice *people* next door.

28b) She spends lot of time talking to the nice *tailor* next door.

Appendix C: Adults' materials for Experiment Four

Sentences one to 20 have the target word being manipulated for frequency as high frequency and the target word being manipulated for length as short in the sentence frame labelled a. In the sentence frame labelled b, the target word being manipulated for frequency as low frequency and the target word being manipulated for length as long.

These combinations are reversed in sentences 21 to 40, where high frequency target words are paired with long target words in sentence frame a and low frequency target words are paired with short target words in sentence frame b.

1a) Once he saw the retired *worker* in the local *pool* looking very sad indeed.
1b) Once he saw the retired *healer* in the local *restaurant* looking very sad indeed.

2a) He showed the famous *leader* his secret *drug* quickly before they were seen.
2b) He showed the famous *sheikh* his secret *photograph* quickly before they were seen.

3a) They ran from the remote *church* to the hidden *cave* as fast as they could.
3b) They ran from the remote *chalet* to the hidden *laboratory* as fast as they could.

4a) At school the broken *window* caused too much *harm* during the lunch break.
4b) At school the broken *sledge* caused too much *excitement* during the lunch break.

5a) Because of the sudden *threat* he lost his written *poem* that was so special.
5b) Because of the sudden *hustle* he lost his written *invitation* that was so special.

6a) The boy found the giant *flower* in the private *sale* at the rich man's home.
6b) The boy found the giant *python* in the private *collection* at the rich man's home.

7a) He poured a very big *coffee* for the company *boss* as he wanted a pay rise.
7b) He poured a very big *cognac* for the company *specialist* as he wanted a pay rise.

8a) There is no obvious *answer* for this *jury* which makes things quite tricky.
8b) There is no obvious *simile* for this *phenomenon* which makes things quite tricky.

9a) He followed the young *artist* into the posh *hall* and was amazed by it all.
9b) He followed the young *vandal* into the posh *department* and was amazed by it all.

10a) Sadly, having the wrong *doctor* gave people *lung* problems after treatment.
10b) Sadly, having the wrong *dosage* gave people *depression* problems after treatment.

11a) They used the old rusty *pump* the whole *summer* holiday without a problem.
11b) They used the old rusty *helicopter* the whole *annual* holiday without a problem.

12a) They had a very good *game* with the local *police* who happened to be there.
12b) They had a very good *experience* with the local *jogger* who happened to be there.

13a) In the normally serious *firm* a sudden huge *change* made the workers laugh.
13b) In the normally serious *parliament* a sudden huge *hiccup* made the workers laugh.

14a) He saw the nervous young *maid* with your *sister* in the garden shed earlier.
14b) He saw the nervous young *inhabitant* with your *rifles* in the garden shed earlier.

15a) It was a very pretty *path* with a beautiful *forest* over to the left of it.
15b) It was a very pretty *background* with a beautiful *cobweb* over to the left of it.

16a) She threw the vile purple *sock* onto the dirty *ground* and then stormed off.
16b) She threw the vile purple *decoration* onto the dirty *pallet* and then stormed off.

17a) For many days the kind *monk* went to the local *market* every day by himself.
17b) For many days the kind *technician* went to the local *hanger* every day by himself.

18a) He lifted the large *tyre* away from the dark *corner* as it was quite light.
18b) He lifted the large *typewriter* away from the dark *podium* as it was quite light.

19a) Luckily their honest *lord* listened to their *scheme* and made a good choice.
19b) Luckily their honest *councillor* listened to their *tirade* and made a good choice.

20a) He chose the very biggest *jeep* in that *moment* because he really wanted it.
20b) He chose the very biggest *microscope* in that *raffle* because he really wanted it.

21a) It has been an awkward *matter* due to their *assumption* about being in control.
21b) It has been an awkward *finale* due to their *talk* about being in control.

22a) A bird sat on the highest *branch* is a common *indication* that it will rain later.
22b) A bird sat on the highest *thatch* is a common *myth* that it will rain later.

23a) The storm caused a huge *effect* and the whole *university* was very badly flooded.
23b) The storm caused a huge *deluge* and the whole *town* was very badly flooded.

24a) Following the sudden *demand* she saw the quiet *journalist* behind the old church.
24b) Following the sudden *detour* she saw the quiet *port* behind the old church.

25a) Today they ate a huge *dinner* and forgot their *appearance* despite their promise.
25b) Today they ate a huge *gateau* and forgot their *diet* despite their promise.

26a) The mean and grumpy *farmer* wanted some *discipline* bringing to his workshop soon.
26b) The mean and grumpy *potter* wanted some *rope* bringing to his workshop soon.

27a) I sat and read a very long *report* about *literature* being cheaply available here.
27b) I sat and read a very long *advert* about *fuel* being cheaply available here.

28a) The audio tape in your *pocket* is for their *experiment* which will go ahead soon.
28b) The audio tape in your *stereo* is for their *joke* which will go ahead soon.

29a) He gave an excellent *speech* in the windy *conditions* just outside our local town.
29b) He gave an excellent *eulogy* in the windy *park* just outside our local town.

30a) She placed the old green *bottle* with your *spectacles* on top of the large table.
30b) She placed the old green *beaker* with your *disc* on top of the large table.

31a) They offered him all their *assistance* to start *action* but he refused their help.
31b) They offered him all their *gear* to start *paving* but he refused their help.

32a) They found the burnt *settlement* by following their *father* through the woodland.
32b) They found the burnt *flag* by following their *captor* through the woodland.

33a) Yesterday the special *instrument* in the locked *centre* went missing for a while.
33b) Yesterday the special *bell* in the locked *casing* went missing for a while.

34a) Afterwards the foreign *ambassador* became a valued *member* of the whole household.
34b) Afterwards the foreign *cook* became a valued *mentor* of the whole household.

35a) He found the old dusty *manuscript* in the private *office* late one night at work.
35b) He found the old dusty *lock* in the private *annexe* late one night at work.

36a) There was a bright shiny *motorcycle* in the next *street* that we went to look in.
36b) There was a bright shiny *coin* in the next *casket* that we went to look in.

37a) It was quite an unusual *exhibition* but your *friend* said that he really liked it.
37b) It was quite an unusual *dish* but your *suitor* said that he really liked it.

38a) They sold the old broken *television* to the strange *person* passing through town.
38b) They sold the old broken *seat* to the strange *pedlar* passing through town.

39a) At his big house the rich *chancellor* wrote a lovely *letter* about his new niece.
39b) At his big house the rich *poet* wrote a lovely *sonnet* about his new niece.

40a) In September at the busy *conference* the latest *theory* became extremely popular.
40b) In September at the busy *farm* the latest *trowel* became extremely popular.

Appendix D: Materials for Experiment Five

	Correct	Incorrect		Correct	Incorrect
1	NOTICE	NOTNCE	30	PUZZLE	PUIZLE
2	HAMMER	HAQMER	31	HUNGER	HUWGER
3	GROWTH	GROVTH	32	WILLOW	WILQOW
4	COTTON	COJTON	33	KEEPER	KEHPER
5	EXCUSE	EXCDSE	34	NORMAL	NORZAL
6	POETRY	POCTRY	35	SEASON	SEJSON
7	WORKER	WORHER	36	SINGER	SINWER
8	POISON	POQSON	37	JINGLE	JIUGLE
9	GARDEN	GARXEN	38	MINUTE	MINRTE
10	SHOWER	SHFWER	39	RATTLE	RACTLE
11	SECOND	SECHND	40	ANIMAL	ANIOAL
12	THREAD	THWEAD	41	REPORT	REKORT
13	SELLER	SELCER	42	CHAPEL	CHSPEL
14	MOTHER	MOJHER	43	MOMENT	MOMWNT
15	SQUARE	SQUTRE	44	TERROR	TECROR
16	LIQUID	LIOUID	45	FLEECE	FLESCE
17	SLEEVE	SLEKVE	46	GROUND	GRNUND
18	REASON	REZSON	47	PILLOW	PILUOW
19	WINTER	WINQER	48	STABLE	STZBLE
20	CHEESE	CHGESE	49	HORROR	HORQOR
21	NUMBER	NUMAER	50	KETTLE	KEVTLE
22	PEPPER	PEIPER	51	FOREST	FORVST
23	WEAPON	WEAUON	52	SUPPER	SUKPER
24	NAPKIN	NAZKIN	53	MINNOW	MINQOW
25	BUTTON	BUTUON	54	LENGTH	LEBGTH
26	COFFEE	COHFEE	55	ESCAPE	ESCRPE
27	WINDOW	WINXOW	56	ISLAND	ISXAND
28	KENNEL	KECNEL	57	LEADER	LEAQER
29	RUBBER	RUBJER	58	VALLEY	VAKLEY

	Correct	Incorrect
59	COUSIN	COUOIN
60	JUNIOR	JUEIOR
61	RECORD	RECCRD
62	AMOUNT	AMXUNT
63	REPAIR	REPIIR
64	FAMILY	FAAILY
65	HEAVEN	HEAQEN
66	BRIDGE	BRFDGE
67	BUBBLE	BUBNLE
68	SCHOOL	SCGOOL
69	SHIELD	SHIHLD
70	CELLAR	CEKLAR
71	THREAT	THRMAT
72	SPIRIT	SPJRIT
73	CIRCLE	CIRFLE
74	PRAYER	PRZYER
75	SORROW	SORYOW
76	MARKET	MAQKET
77	BOTHER	BOTCER
78	FIDDLE	FIWDLE
79	PEOPLE	PEOVLE
80	REWARD	REUARD
81	SEARCH	SEABCH
82	SIGNAL	SIWNAL
83	HUNTER	HUNXER
84	CHERRY	CHDRRY
85	SHADOW	SHAUOW
86	BUTTER	BUCTER
87	ANSWER	ANSKER
88	WIGGLE	WIBGLE
89	SAVAGE	SAVZGE
90	REFUSE	REIUSE
91	DANGER	DANQER
92	BANKER	BAVKER
93	RACKET	RACJET
94	LETTER	LEVTER
95	PALACE	PALTCE
96	JERSEY	JEZSEY
97	LESSON	LESAON
98	FINISH	FICISH
99	RIBBON	RIBKON
100	RESCUE	REQCUE