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FACULTY OF MEDICINE, HEALTH AND LIFE SCIENCES

School of Psychology

Binocular Coordination and Dyslexia

By

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ABSTRACT

FACULTY OF MEDICINE, HEALTH AND LIFE SCIENCES
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Developmental dyslexia is suggested to affect approximately 5-10% of the population (Habib, 2000). The most influential theory of dyslexia is the phonological-deficit theory of dyslexia (Liberman, 1973; Stanovich, 1988; Snowling, 2000). An alternative explanation is that visual deficits can lead to reading difficulties (e.g. Stein & Walsh, 1997). To date the findings are mixed regarding the extent of visual deficits within the dyslexic population. Whether these problems represent a cause, correlation or consequence of the reading difficulty also remains highly controversial.

The data presented throughout this Thesis examined the possibility that reading difficulties, associated with dyslexia, are linked to poor binocular coordination. In three experiments binocular eye movements of adults, typically developing children and children with dyslexia were measured while they read sentences or scanned dot string targets. In these experiments findings of previous binocular studies were replicated. Specifically, fixation disparity was modulated by the amplitude of the preceding saccade and the fixation position on the screen regardless of whether fixations and saccades were targeted to dots or words.

Additionally, during the dot scanning task adult's binocular coordination was improved in relation to children's, but no reliable differences were found between the three groups. Critically, a significantly greater magnitude of fixation disparity was found for dyslexic children compared to typically developing children and adults during the reading task alone. The existence of linguistically modulated differences in binocular coordination for dyslexic children is a novel finding. The patterns of results from the three experiments indicate that poor binocular coordination in dyslexic children is restricted to reading linguistic material. Clearly, this represents a stimulus specific deficit in regard to binocular coordination, for children with dyslexia.

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DECLARATION OF AUTHORSHIP

I, Julie A Kirkby declare that the thesis entitled Binocular Coordination and Dyslexia and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- This work was done wholly while in candidature for a research degree at this University;
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- Where I have consulted the published work of others, this is always clearly attributed;
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- Parts of this work have been published as:

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Chapter One

Adult's binocular coordination during reading and non-reading tasks

Over the last forty or so years, the study of eye movements has become an extremely valuable tool for scientists interested in investigating aspects of human cognitive processing. A substantial body of research has accumulated exploring the basic characteristics of eye movement behaviour during reading (see Rayner, 1978b; 1998). But despite the depth of this research and its implications, comparatively few studies have investigated how the two eyes move in relation to each other; that is to say, binocular coordination. The principal reason for this lack of binocular research is probably a prevalent assumption amongst reading researchers that two precisely coupled retinal inputs were essential for visual encoding and lexical identification. In fact, what is apparent, from the now increasing body of research is that disparity between the two lines of sight is frequent, although the visual system normally tolerates such disparity during reading.

It will be clear from the review of the literature below that researchers became interested in binocular coordination for quite different reasons. Some have focused on investigating whether binocular coordination affects reading fluency. Others are interested in examining what (if any) factors influence binocular coordination. Two lines of research have therefore arisen with regard to binocular coordination. On the one hand, to investigate factors which may influence binocular coordination during reading, various visual and linguistic aspects of text have been manipulated. On the other hand, there is a considerable literature detailing the human binocular coordination system during non-reading tasks. These two lines of research are frequently motivated by distinct theoretical questions and practical objectives, and they often measure quite different aspects of oculomotor behaviour. Interestingly however, both lines of enquiry have tended to substantiate one another. By correlating the findings of studies that have used non-reading tasks with those using linguistic text as experimental stimuli, general conclusions about the binocular coordination system and the factors that influence binocular behaviour are beginning to emerge.

The next section provides a brief initial review of studies into the basic characteristics of eye movements in adults while subsequent sections in this Chapter discuss studies of binocular coordination in reading and non-reading tasks. The following Chapters then report and compare the outcomes of studies investigating binocular coordination for adults, typically developing children and children with dyslexia.

1.1 Eye movement techniques

It is perhaps a good point to evaluate the strengths and weaknesses of the method used to record binocular eye movements during the current studies; therefore, the most typical eye movement recording techniques currently in use are discussed and compared. These techniques are: (1) electro-oculogram (EOG), (2) infrared reflection devices, (3) scleral search coil, and (4) video-oculography. Each of these techniques have relative strengths and weaknesses with respect to the system's parameters, i.e. spatial resolution, temporal resolution, the ease with which eye movements are recorded and the sensitivity to detect small changes in ocular alignment.

(1) Electro-oculogram (EOG). This technique requires the placement of a pair of electrodes at the outside of the two eyes (outer Canthi) to track binocular eye movements. These electrodes measure the change in corneoretinal potential as participants move their eyes in response to instructions given to view a visual display or scene. During calibration the participant is required to oscillate between two fixation points, which are positioned at locations with an angle of separation known to the experimenter, and then the recorded EOGs are related to these calibration angles. While temporal accuracy (1ms) is comparable to other forms of eye tracking technologies the spatial accuracy is poor, typically within the range of ±2°. It is the systems spatial inaccuracy that makes it unsuitable to use for reading research, where the precise position of the eyes on a particular letter within a word is frequently analysed. Another disadvantage of this technology is that the corneoretinal potential is not static; rather it is affected by light and fatigue. Therefore, the procedure needs continual calibrations (Carpenter, 1988). However, an advantage in the use of this technique is that participants are unaffected by the device and tasks are performed

with minimal interference. EOGs are mainly used in the diagnosis of neurological disorders.

(2) Infra-red oculography. A number of commercially available eye trackers use infra-red oculography, this includes the Dual Purkinje eye tracking system used throughout this Thesis to collect eye movement data from the two eyes simultaneously. Using this technique eye movement recordings are obtained by measuring the amount of light reflected back to a detector when a small fixed (infra-red) light source is focussed on the eyes (see Figure 7.1). Infra-red light is used as it is undetectable to the eyes. This means that eye movement parameters for different tasks are unaffected by the beam, and eye movements can be recorded in the dark to obtain a strong signal from the fourth reflection. The spatial resolution of this technique is very high (<0.1°), as is the temporal resolution (<1ms) of the system. Therefore, this technique is possibly the most desirable system to record the precise positions of the eyes during reading. There are disadvantages to this system however, in as much as it does not permit for any head movements; therefore, participants are securely positioned in the trackers by the use of head straps and bite bars. This means that sitting very still while in head restraints can be quite arduous for very small children. Another disadvantage is the limited range in which eye position can be measured; the fourth reflection is occluded by the iris when a participant makes an eye movement in excess of 10 to 15 degrees of visual angle from a central fixation point. This disadvantage however, was not an issue during the current series of experiments, since the calibration range used during the experiments was 11.42° therefore, a deviation of only 5.71° was required in both directions from a central fixation point; the calibration range represents the maximum horizontal extent of the stimuli during the experiments.

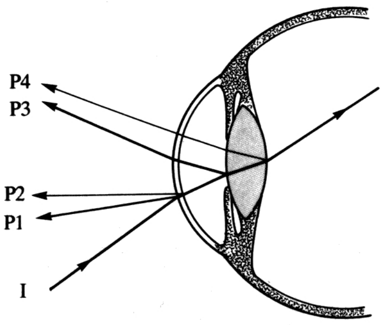

Figure 1.1
Dual Purkinje Image The first reflection occurs at the front surface of the cornea and the fourth is a virtual image found at the back of the lens. The DPI eye trackers obtain highly accurate eye movement data from the relative positions of the two images.

(3) Scleral search coils. This technique involves coils of wire embedded in a silicon annulus that is placed in the eye (or in the case of the Yarbus-type lens, Yarbus, 1967, are held in place by suction cups). When the coil of wire moves in a magnetic field (a magnetic field is generated by two field coils either side of the head) this movement induces a voltage which is then converted into eye movement data using the appropriate software. This method of eye movement recording provides very high temporal (<1 ms) and spatial resolution (<0.1°). However, the main disadvantage is the invasive nature of the technique. Therefore, it is used less often than the other methods described here and more than often the main participants in these studies are the authors themselves.

(4) Video-oculography. Video and image analysis eye trackers have been developed which automatically record the position of the eyes. Some of the video and image based systems also use an infrared light source to produce images from the surface of the eye (cornea and lens) which are then recorded by an infrared camera. Tracking the movement of these images is then used to calculate the position of the pupil and its centre. The advantage of these trackers is the ease with which data is collected; however, the main disadvantage has been, in the past at least, that image based methods tended to have lower temporal and spatial resolutions than those achieved with infra-red oculography. However, more recently the Eyelink 2000 is now able to record binocular eye movements at 1000 HZ with a spatial accuracy of <0.5°.

Recently in the eye tracking lab at the University of Southampton binocular eye movements were recorded from participants using both the Eyelink 2000 and the DPI trackers. It was demonstrated that the DPI trackers obtained less variability in the data and increased sensitivity to detect very small changes in binocular alignment that did not occur in the data obtained with the Eyelink 2000. Therefore, all things considered, the eye tracking technology used in the current work was the most suited to the nature of the experimentation.

1.2 Basic characteristics of eye movements during reading

Reading involves a highly stylised oculomotor behaviour where the two principal, defining features of eye movements are saccades and fixations. Saccades are rapid, ballistic eye movements of up to 500° per second. They vary in their amplitude and duration, with small saccades having shorter durations than longer ones (e.g., a 2° saccade will be of approximately 30 ms duration, and a 5° saccade will be of approximately 40-50 ms duration; Abrams, Meyer & Kornblum, 1989; Rayner, 1978a). On average, saccades tend to be shorter when reading than during scene perception. Saccade lengths are measured in character spaces rather than absolute distances during reading because saccade lengths are the same (in terms of the number of characters) regardless of whether the text is presented close or distant from the reader, or at different visual angles (Morrison, 1983; Morrison & Rayner, 1981; O'Regan, 1983; O'Regan, Levy-Schoen & Jacobs, 1983). Between the saccades the eyes are relatively still. These periods are called fixations, the duration of which are within the range of 150-500 ms (though the majority are on the order of 200-250 ms). The saccadic eye movements serve the purpose of rotating the eyeball such that light from newly fixated text falls on the fovea (Rayner, 1998).

The human retina is not uniform with respect to visual acuity; instead, it is comprised of three regions. These regions are not categorically distinct, separate portions of the retina, but rather regions across which visual acuity varies continuously. The three regions are the fovea, the parafovea, and the periphery (Rayner, 1978b; Balota & Rayner, 1983). The fovea is the central 2° of our vision within which visual acuity is highest. The parafovea is the region that extends outwards from the fovea to 5° either side of fixation; the periphery, as the name suggests, is the region extending beyond this. The further away from the foveal region of the retina that light from a visual stimulus falls, then the poorer the acuity with which that stimulus will be perceived. Thus, to see something clearly, it is necessary to orient the eyes such that light from a target stimulus falls on the high acuity region of the fovea.

It is virtually impossible to read if the text is visible only in the parafovea or periphery due to acuity limitations (Rayner & Bertera, 1979; Rayner, Inhoff, Morrison, Slowiaczek & Bertera, 1981); nonetheless, not all words are fixated. Readers fixate content words (words that have a definable lexical meaning) on about 85% of occasions and function words (words that serve to express grammatical relations with other words in a sentence) on about 35% of occasions (Just & Carpenter, 1980; Rayner & Duffy, 1988). The probability of a word being fixated is further dependent on word length, the longer the word, the more likely it is to be fixated (Rayner & McConkie, 1976). Words consisting of 2-3 characters are fixated about 25% of the time; words consisting of 8 characters or more are nearly always fixated and may often require more than one fixation.

Most saccades are made from left to right when reading English. However, approximately 10-15% of saccades are made from right to left. Two types of right to left movements occur during English reading: return sweeps and regressions. Return sweeps are saccadic eye movements that are made after a reader has fixated the furthest point on the right of a line of text. These saccades are made in order to fixate the next line of text. In contrast, regressive eye movements occur at any point during reading and are usually made in order to refixate material that has already been fixated at least once. Small regressions of a few character spaces in length are usually within-word regressions that ordinarily occur when the reader makes a saccade that positions the point of fixation non-optimally on a word. In such situations, a regression is often made in order to compensate. Other regressions, usually between words, often occur with disruptions in lexical, syntactic, or semantic processing. It follows then that processing difficulty and regressions are related. When a text becomes conceptually difficult, the frequency of regressions increases as does fixation durations, whereas saccade length consequently decreases (Jacobson & Dodwell, 1979; Rayner & Pollatstek, 1989).

Readers are unable to acquire new visual information during a saccade since the velocity of the eye movement results in smearing of the visual information (Uttal & Smith, 1968). Blur is not perceived during a saccade because the visual information that is sampled at the beginning and end of a saccade masks the visual input that occurs during a saccade (Brooks, Impelman, & Lum, 1981; Campbell & Wurtz, 1978; Chekaluk & Llewellyn, 1990). Sensitivity to visual stimuli is reduced during a saccade since readers are unable to acquire new information. This phenomenon is referred to as saccadic suppression (Matin, 1974).

A saccade is a motor movement; thus, a certain amount of time is needed to plan it. Whenever a saccade is generated, two important metrics can be computed: where the saccade is targeted and when the saccade will be executed. Some researchers have argued that "when" to move the eyes (reflected in fixation durations) and "where" to move the eyes (reflected in fixation locations) are determined via independent processes (see Aslin & Shea, 1987; Becker & Jürgens, 1979; Findlay & Walker, 1999; Rayner and McConkie, 1976; Rayner & Pollatsek, 1981; 1987; 1989). A large number of visual and linguistic factors influence both where and when readers make fixations during reading, though for brevity's sake, these will not be discussed in detail here (see Rayner, 1998 for a review). Having provided a brief synopsis of some basic characteristics of eye movements based on studies employing monocular recordings, the attention in the next two sections of the literature review will focus on binocular coordination of the eyes.

1.3 Binocular coordination in non-reading tasks

As one would expect when discussing binocular vision, both the direction and the distance of a visual object in relation to the observer are important factors in oculomotor control. Information regarding the distance and direction of an object relative to the observer is utilized such that each eye can accurately fixate an object. Accurate fixation is achieved by utilizing disjunctive saccades (saccades in which the point of fixation changes in both depth and direction), conjugate saccades (saccades that involve movement exclusively in the same direction), and pure vergence movements (a depth only movement). Note that some researchers refer to conjugate saccades as pure version movements, those that occur when the eyes are seemingly yoked and move in the same direction, maintaining a constant angle of sight between them. Vergence eye movements are the opposite, in that the eyes move in different directions so that the angle of sight between them changes.

Disjunctive eye movements are combined movements in which the eyes move in the same direction but by different amounts.

Binocular vision extends our field of vision and allows us to perceive and move around our environment with greater accuracy than monocular vision would permit (Jones & Lee, 1981). Although humans have binocular vision, they perceive the world as a single, unified, cyclopean percept. The visual system is required to coordinate the input of the two eyes precisely and systematically; the issue of binocular coordination is central to this process.

As mentioned earlier, many researchers assumed until recently that the eyes fixated on the same letter within a word during reading. Similarly, it was often assumed that human saccadic eye movements were entirely conjugate during scanning of non-linguistic material. Specifically, when making eye movements to change either the horizontal or vertical fixation location but not the depth location, it is generally assumed that a binocular saccade is perfectly conjugate. However, it has become apparent with advances in binocular experimentation that this is not always the case and saccade metrics for each eye frequently have different characteristics.

Collewijn, Erkelens, and Steinman (1988) developed a technique to investigate how target direction and depth within the oculomotor range influence saccadic parameters such as peak velocity, amplitude, and duration of saccades. They used a revolving magnetic field-sensor coil technique (Collewijn, Martin & Steinman, 1981) to record absolute horizontal and vertical eye positions of both eyes in space. Participants were required to make saccadic eye movements between two LEDs. The LEDs were temporally dictated by the pace of a metronome. Pairs of LED targets appeared in two conditions. In one, the LEDs were positioned symmetrically around an iso-vergence circle (in which eye movements between any two points required only a horizontal change in position without a vergence component). In the second condition, the central LED was illuminated in combination with an LED in the periphery, potentially requiring movements in both horizontal and depth planes. The target direction and the plane on which the target was placed were determined in a pseudo-random sequence.

LEDs are used as stimuli as they demand a real depth change in fixation position. The two main stimuli that drive vergence eye movements are the disparity between the locations of stimulation on the two retinas. However, there are other factors that drive vergence movements, the awareness of the proximity of an object;

vergence can also be under attentional control when attending to a 3-dimensional visual scene. LED targets change in 3-dimensional space, therefore the distance between the target and the observer changes; this change modulates disparity vergence, also with a change in accommodation. When stimuli are presented on a screen the accommodative component is isolated and only the fixation disparity modulates vergence movements.

Collewijn et al. (1988) found that saccades were unequal in the two eyes when the eyes made horizontal saccades between stationary targets located on the iso-vergence circle. Saccades of the abducting eye (the eye moving temporally) relative to the adducting eye (the eye moving nasally) were significantly larger in size, had higher maximum velocities, and had shorter durations. Moreover, saccades of the abducting eyes were more skewed than those of the adducting eye. (Skewness refers to the time between saccade onset and peak velocity (acceleration period) as a fraction of the total saccade duration.) These differences resulted in the eyes becoming transiently diverged during a saccade. Furthermore, Collewijn et al. (1988) established a relationship between saccadic amplitude and the magnitude of disparity between the two lines of sight during a saccade.

Bains, Crawford, Cadera, and Vilis (1992) investigated when the oculomotor system becomes non-conjugate during a saccade. In particular, they were interested in whether a single saccade generator guides oculomotor control of the two eyes or whether separate saccade generators exist for each eye. Binocular measurements of five adult participants were taken using a three-dimensional implementation search coil technique (Tweed, Cadera, & Vilis, 1990). Participants were seated at a distance of two metres from a target board. This was a distance that would necessitate no significant changes in the angle between the two eyes when fixating different positions on the board. The vergence angle between the eyes at the central target was 1.718º, whereas the angle was 1.703º at the peripheral target. Target positions were indicated by a 0.23º red dot on a yellow background and were continuously visible. Participants were seated in a position such that the central target was displayed straight ahead and at eye level. Twelve targets (hour labels) were placed 30º eccentrically around the centre target, spaced as on a clock. Consecutive saccades were made from the centre target to each of the eccentric targets. Approximately 15 saccades were made to each target as binocular recordings were taken.

The results indicated that successive saccades of the same direction and amplitude showed variations in velocity, duration, and curvature. Peak saccadic velocity varied systematically with saccade direction. The mean peak velocities of the two eyes were extremely similar, although small differences between the two eyes were noted. The abducting eye had a higher peak velocity during horizontal saccades and also started to saccade earlier than the adducting eye. These findings are consistent with Collewijn et al.'s (1988) findings reported above, demonstrating transient divergence of the two eyes during the saccade. Bains et al. (1992) suggested that these differences might be attributed to differences in synaptic delays and/or mechanical dynamics of the muscles controlling the two eyes. They, therefore, inferred that transient divergence did not necessarily result from lack of yoking between the two eyes (here yoking refers to a single neural signal controlling both the left and right eyes).

Disjunctive saccades (combinations of vergence and version, driven by a stimulus which requires movements in both the horizontal and vertical planes and in depth) differ in their characteristics to conjugate saccades (pure version) in that they have a lower velocity and longer duration. Some researchers have argued that the two are generated in different ways. Zee, Fitzgibbon, and Optican (1992) recorded binocular eye movements in four adult participants who were asked to saccade between targets. The task involved various combinations of version and vergence movements. Their results also supported findings from Collewijn et al., (1988), showing transient changes in horizontal alignment during both horizontal and vertical version movements in the absence of a required depth movement. The eyes generally became divergent during the initial stage of a saccade, and subsequently became convergent. Alignment changes tended to be divergent during upwards-vertical version movements and convergent during downwards-vertical version movements. More generally, their results showed that the velocity of vergence movements was greater when they were part of a combined vergence-version movement than when they were pure vergence movements.

Collewijn, Erkelens and Steinman (1995) examined the interaction between vergence and version. They studied the dynamics of voluntary, horizontal, binocular gaze-shifts between pairs of continuously visible three-dimensional targets. Target angle differed in depth only (pure vergence), direction only (pure version; conjugate saccades), or in both depth and direction (combined vergence/version movements;

disjunctive saccades). Their experiments focused on gaze-shifts between targets that were located in what they referred to as the manual working space; that is, the area in which the majority of human visuo-motor activity occurs. Natural gaze-shifts that occur in this area require alterations in version and vergence. Their manipulations required interactions of vergence and version during disjunctive gaze shifts.

Version and vergence were well integrated for the purpose of achieving three-dimensional binocular gaze-shifts with speed and efficiency in a large part of manual working space. This is an important aspect of binocular vision as it enables stereopsis (3D vision) and precise coordination of prehension (Epelboim et al., 1995; Loftus, Servos, Goodale, Mendarozqueta & Mon-Williams, 2004). Collewijn and colleagues found that binocular gaze-shifts between locations within manual working space were mostly disjunctive. Furthermore, stimuli that were designed to elicit pure vergence still induced disjunctive movements because participants made small version movements even though these were not required. Gaze behaviour at further distances necessitated little vergence and gaze-shifts were usually conjugate. These results were again in agreement with those of Collewijn et al. (1988) and Bains et al. (1992) mentioned previously, all of which indicate a degree of disconjugacy with respect to binocular control during saccades in non reading tasks.

Erkelens and Sloot (1995) found results similar to those described above. The objective of their study was to quantify the spatial variability in trajectories of binocular saccades. Self-paced saccades were made between a number of stationary visual targets located in the frontal plane. In excess of 75 saccades were made to each target. Binocular measurements of horizontal and vertical eye movements were recorded using the scleral coil technique. The effective direction was defined as that from the starting position to the end position of each primary saccade. The initial direction of the saccade was defined as the direction from the starting position to the eye position when the saccade had covered a distance of 2.5º. Erkelens and Sloot found that variability was between 2 to 7 times larger in initial directions than in effective directions. The curvedness of the saccades appeared to result from a purposeful control strategy, whereby, initially, the eyes accelerated in roughly the direction of the target after which they were guided specifically to the target. However, these irregular patterns of saccadic direction were highly correlated between the eyes, indicating that the variability for the two eyes was very similar.

Erkelens and Sloot suggested that saccades, for both eyes, were generated from a common source or spatial map.

Collewijn et al. (1995) provided important information about eye movements during non-reading tasks; however, their data was confined exclusively to descriptions of gaze-changes as a function of time. In a later study, Collewijn, Erkelens, and Steinman (1997) focused on the spatial trajectories of the binocular fixation point (i.e., the intersection point of the two lines of sight) associated with various conjugate and non-conjugate gaze shifts within a horizontal plane of regard. The trajectories of conjugate and convergent gaze-shifts were highly curved; whereas divergent gaze-shifts produced relatively straight trajectories (see also Doyle & Walker, 2001 for evidence of curved saccades in both eyes). Collewijn et al. (1997) also noted that Collewijn et al. (1995) found unique dynamic characteristics that were associated with version, vergence, and disjunctive saccades. Their results suggested that control of the vergence and version components of the gaze-shift could be, to a degree, dissociated for targets that differed in both depth and direction. These results are inconsistent with models of binocular oculomotor control claiming that each eye responds to its own target. Rather, target depth and target direction can be processed and responded to separately by ocular vergence and version, and this does not have to occur at exactly the same time. If it were such that only one system, vergence or version, was active at a given moment then respective, discernible, velocity characteristics would be displayed. At all other times, when both systems operate simultaneously (i.e., when the head is free and targets are within a range that relies heavily on vergence), a strong interaction would occur with an acceleration in vergence, and the movement would become disconjugate.

Another relevant study was conducted by Kloke and Jaschinski (2006). They described the extent of individual variability in binocular transient asymmetry. Their stimuli consisted of red points of light, 2 mm in diameter, presented by laser diodes. Participants were asked to make eye movements of 5° to the left or the right of a centrally presented fixation point. Eye movements were recorded by an infrared reflection technique (Reulen et al., 1988). Transient divergence resulting from binocular latencies and/or velocity asymmetry resulted in a maximum divergence of 1°. The effect of saccadic direction was negligible in relation to latency and divergence differences, accounting for less than 0.3% of variance. Kloke and

Jaschinski demonstrated that the degree of divergence occurring during a saccade was accounted for by the asymmetry of saccadic velocity rather than latency differences or fixation disparities prior to saccade onset. Individual divergence variability correlated strongly with asymmetric binocular velocity. Although they used non-linguistic stimuli in their study, Kloke and Jaschinski suggested that individual differences in transient asymmetries of the two eyes may be related to normal and abnormal reading abilities. This possibility will be discussed later in Chapter 3.

On the basis of the seven non-reading binocular studies that have been reviewed, it is apparent that saccades are not temporally and spatially conjugate. Note that these studies have used two different eye tracking mechanisms (scleral coils and infrared reflections) to measure binocular saccades across a range of similar tasks, and have all found transient divergence between the two eyes during saccades. Saccades between targets differing in direction, but not in depth, are actually non-conjugate. Subtle differences in the timing of binocular saccades may modulate the coordination of the eyes, with the abducting eye (the eye moving temporally) initiating a saccade slightly in advance of the adducting eye (the eye moving nasally). Differences in the peak velocity, duration, and skewness of abducting and adducting saccades have also been demonstrated. Furthermore, inequalities in spatial dimensions have been observed, with saccades of the abducting eye having larger amplitudes than those of the adducting eye. However, note that the divergence that occurs within the saccade may not necessarily result from a lack of yoking between the eyes. Instead, such divergences may be attributed to synaptic transmission differences or differing muscular control between the eyes.

To summarise, binocular coordination studies have demonstrated two dissociated systems responsible for version and vergence components of eye movements, which operate within distinct temporal frameworks. These systems are highly interactive. The vergence component of the oculomotor system becomes temporally similar to the version component during combined eye movements. One final point is that people have no perceptual experience of the transient divergence that occurs during saccades. There are at least two reasons for this. First, saccades are very fast, and ordinarily short in duration; hence, there is little opportunity for detection. Second, as described in the previous section, saccadic suppression occurs during a saccade. Consequently, transient disparity of retinal inputs would not be detected.

The studies described above have focused on saccade metrics; few studies, however, have investigated fixation disparity. Perhaps this is not too surprising since it is primarily during fixations that visual information is extracted and processed. Therefore, it is perhaps reasonable to assume that it would be more likely to observe alignment of the points of fixation during fixations than during saccades. In the following section, studies that have looked specifically at disparity during fixations in reading are reviewed. Again, these studies have used a variety of methods to record eye movements, but have used stimuli that were always linguistic in nature (words, sentences, texts). The results are highly consistent with those already reviewed despite differences in theoretical and methodological approaches.

1.4 Binocular coordination during reading

Comparatively few studies have specifically examined binocular coordination during reading in adults. Early monocular eye movement studies suggested good binocular coordination and exact synchrony (e.g., Tinker, 1958; Yarbus, 1967). Smith, Schremser and Putz (1971) used real-time computer methods to investigate the extent to which the eyes were coordinated in directional motion. They measured the difference in timing of saccade initiation between the two eyes during reading of texts that differed in difficulty and orientation (the text was or was not rotated clockwise or anticlockwise from the horizontal). Smith et al.'s main finding was a time difference between saccade onsets for each eye; these seemed to cluster around three values. In each case, the left eye led the right eye (by either 1 ms, 7-9 ms or by 14 ms). Saccade initiation asymmetry was also affected when the reading display was rotated by 15° from the horizontal direction, but was not influenced by the difficulty of the text. The Smith et al. results conflict with the view that the eyes are exactly conjugate in saccadic motion. Instead, they indicate that very small differences in the timing of binocular saccadic initiation administrate the coordination of the eyes. Smith et al. suggested that the neurons of the cortex and midbrain (which govern eye motion) may be time and direction specific when determining the guidance and coordination of the eyes. Note, however, that Smith et al. reported precise data for the timing of differences in peak saccadic velocities.

From the peak saccadic velocity data they inferred differences in saccade onset latencies for the two eyes. Also, the saccade onset asymmetries reported by Smith et al. were of considerable magnitude and the direction of the asymmetry was opposite to that reported in subsequent research (e.g., see discussion of Collewijn et al. 1988). Another aspect of Smith et al.'s data that deserves mention is their failure to find a text difficulty effect on the magnitude of binocular coordination asymmetries, a finding that is consistent with Juhasz, Liversedge, White and Rayner (2006, see below).

Recent studies have investigated the degree to which disparity exists during fixations in reading. Hendriks (1996) examined post-saccadic vergence velocity during fixations in adults. She monitored the binocular eye movements of 12 participants while they read words in context (prose passages) or in a list of unrelated words. Participants were asked to read normally while attending to the meaning of the word or to read the words in order to sound them out sub-vocally. She found that passage reading produced a higher vergence velocity during fixations than reading unrelated words. Also, vergence velocities were higher when reading for meaning than when making subvocal pronunciations. Hendriks attributed this latter finding to the fact that readers must rely solely on visual information when words appear in unrelated lists because a helpful context is unavailable. She argued that, under such circumstances, saccades are smaller in amplitude and fixations more stable than they are when words are read in passages. Vergence velocity during fixations was increased more after long preceding saccades than short preceding ones (Collewijn et al., 1988; Zee et al., 1992). Therefore, readers tended to make large saccades when processing difficulty was reduced, (i.e. while reading for meaning) this in turn, lead to faster vergence velocities during fixations. Note that this finding is consistent with studies using LEDs rather than text as stimuli.

Heller and Radach (1999) reported three experiments to examine different aspects of binocular coordination in reading. They investigated how binocular fixation disparity was influenced by fixation position on a page of text; specifically, whether or not the residual disparity remaining at the end of a fixation accumulates as the reader progresses through multiple lines of text. Heller and Radach also examined differences in fixation disparity magnitude between binocular and monocular reading conditions and the influence of text difficulty on binocular parameters. Their results regarding fixation disparity were consistent with findings from Collewijn et al. (1988). The saccade amplitude asymmetries that were observed in the simple scanning paradigm were also present in reading. In contrast to Collewijn et al.'s scanning data, however, vergence movements in reading were notably slower and a residual disparity at the end of each reading fixation was common (see also Hendriks, 1996). In order to determine whether this residual disparity would lead to an accumulation of fixation error over several lines of text, 7 participants were asked to read 20 short passages, each consisting of 6 lines. Participants were asked to read fluently without resting at the beginning of each new line. The results showed different disparity magnitudes for the first line of each passage than for the remaining lines. Fixation error accumulated over the first line, with an average value of approximately 2 character spaces. This trend, however, then slowed and reversed over the remaining lines, leading to a reduced mean fixation error of approximately 1.5 character spaces. Heller and Radach suggested that the visual system does not tolerate the accumulation of disparity beyond a certain point. Note, however, that these data are descriptive and no formal statistical analyses were conducted; therefore, the findings should be treated with some caution.

Heller and Radach (1999) designed a second experiment to examine differences between monocular and binocular reading. Eight participants were asked to read 200 lines of text under normal binocular conditions and then read 200 lines with one eye occluded and 200 with the other eye occluded. When participants read monocularly, fixation durations, the proportion of regressive saccades, and the number of fixations per line increased, suggesting that reading monocularly was more difficult than reading binocularly (see also Jones & Lee, 1981). A substantial and unexpected increase in the amplitude of progressive saccades under monocular viewing was also found. Heller and Radach speculated that the field of view may be somewhat reduced under monocular conditions and that the saccadic system might be unable to adapt easily to this change. Importantly, however, as with Collewijn et al. (1988), no differences were found between saccade amplitudes for monocular left and right eye saccades. Despite the occlusion of one eye, the movement amplitude of the non-occluded eye during the fixation remained comparable to that observed under binocular viewing conditions. Further, no differences between the monocular and binocular viewing conditions were observed in the slow vergence movements that occurred during fixations (see also Inhoff, Solomon, Seymour & Radach, 2008).

This suggests that the slow vergence movements during fixations are reflex-like and pre-programmed, rather than a specific response to the current visual stimuli.

The final question that Heller and Radach asked was whether task demands modulate binocular saccade metrics during reading. They predicted that differences in saccade amplitudes between the two eyes would be reduced under difficult reading conditions, consistent with the view that reduced fixation disparity might occur when reading is difficult. To test this hypothesis, they compared binocular coordination during reading when text was presented in normal case to text presented in MiXeD cAsE (since mixed case text is known to cause increased processing difficulty during reading, e.g. Coltheart & Freeman, 1974). Basic oculomotor measures (e.g. fixation durations, number of fixations, etc.) showed that reading mixed case text was more difficult than reading text presented normally. Critically, they also reported that differences in binocular saccade amplitudes were reduced for mixed case relative to normal text. Subsequently, vergence velocity during fixations was slower for mixed case than for normal text. These effects held for the entire range of saccades. Heller and Radach (1999) concluded that the visual system is able to tolerate larger binocular fixation errors in normal reading compared to difficult reading. Heller and Radach interpreted these results, along with the finding that vergence movements remain similar under monocular and binocular viewing conditions, as indicating that fixational vergence is reflexive and does not require binocular visual input in order to manifest. It appears that task demands primarily influence saccade coordination, the vergence movements being largely a consequence of the binocular saccade metrics.

Kliegl, Nuthmann and Engbert (2006) further demonstrated a systematic disparity between the points of fixation of the two eyes during reading. They found that the eyes fixated different letters within a word on 41% of fixations. The dataset in their study was large, in that 222 participants read 144 sentences. Although binocular coordination during reading was not the primary focus of their study, they did investigate whether fixation disparity affected the duration of first-pass, single fixations and saccade amplitudes. Their data showed no influence of disparity on fixation durations or on the amplitude of the incoming or outgoing saccades. Kliegl et al.'s (2006) finding that left and right eye saccade amplitudes did not differ may initially appear somewhat puzzling, given that the majority of studies investigating binocular saccade metrics have shown differences in saccade amplitudes for the adducting and abducting eyes. One would suspect that this null effect may be due to correlations between saccade amplitude and disparity that arose from how the measures were computed. Disparity was assessed as mean disparity during a fixation rather than computing saccade amplitudes on the basis of disparity that exists at the beginning and end of a saccade. Perhaps a more important point to note from Kliegl et al.'s data concerns the null effect of disparity on fixation durations. This strongly suggests that the ease with which linguistic processing could proceed was uninfluenced by fixation disparity. This point is interesting in regard to the suggestion that for some individuals with dyslexia, the cause of their reading difficulties may be related to their binocular alignment. This issue will be considered later in Chapter 3 (section 3.6 *Dyslexic individual's binocular coordination in non-reading tasks*).

Another noteworthy aspect of Kliegl et al.'s (2006) data concerns the prevalence of fixations on which the lines of sight were crossed (with the left point of fixation to the right of the right point of fixation by more than one character). Kliegl et al. found that the eyes were more likely to be crossed than uncrossed on disparate fixations. This result is notable in that several other studies have found the opposite pattern such that the prevalent disparity was uncrossed rather than crossed.

In a recent study Nuthmann and Kliegl (2009) reported analyses based on the Potsdam-Sentence-Corpus of binocular data. Their findings are very similar to those reported in other studies, in that small disparities occurred during fixations and these accumulated through successive fixations made along a line of text. Interestingly, Nuthmann and Kliegl found that during fixations disparities were predominantly crossed (i.e., the point of fixation of the left eye was to the right of that of the right eye), the opposite pattern to that obtained in several other studies (e.g., Blythe et al., 2006; Juhasz et al., 2006; Liversedge, White, Findlay and Rayner, 2006; Liversedge, Rayner, et al., 2006). As yet, it is unclear why different experiments have yielded different patterns of disparity; clearly, further research is required in order to elucidate this issue (see Chapter 2 section 2.4 *Discussion*).

Another study that examined binocular coordination during reading was conducted by Liversedge, White, Findlay and Rayner (2006). They investigated the magnitude and nature of fixation disparity, attempting to replicate and extend the findings of Heller and Radach (1999) by determining how frequently fixation disparity occurred and its direction. Additionally, they compared precise fixation positions at fixation onset with those at fixation offset to examine the vergence movements made throughout fixations. They analyzed the movements of the eyes during fixations *per se* and the movements in relation to the nature and magnitude of fixation disparity at fixation onset. They found that the points of fixation were disparate by one character space or more at the end of a fixation on 47% of fixations made across the entire sentence. These results were in agreement with those reported by Heller and Radach (1999). On the basis of these findings, Liversedge, White et al. disputed the widely held assumption that both eyes always fixate the same character during reading. Liversedge, White et al. also reported that the proportions of aligned (53%), crossed (8%) and uncrossed (39%) fixations were approximately constant for all 15 participants. Moreover, they showed that the magnitude of fixation disparity was not modulated by eye dominance, nor were the proportions of aligned, crossed and uncrossed fixations.

In answer to the question of whether disparity alignment and magnitude change during a fixation, Liversedge, white et al. (2006) compared the proportions of fixations that were aligned at the beginning and the end of a fixation. At the end of a fixation the proportion of aligned fixations was greater (53%) than at the beginning of a fixation (48%). Fixation disparities had greater magnitudes at the beginning of a fixation than at the end of one. These findings support those of Hendriks (1996). Vergence movements do occur during fixations in reading and, on average, vergence movements aid in reducing disparity during a fixation. Liversedge, White et al. also clarified the nature of the vergence movements that were recorded. This was achieved by grouping qualitatively different movements into categories. Convergence movements occurred with the most frequency (52% of fixations), whereas divergence movements occurred only half as often (25% of fixations). Drift movements, in which the two eyes moved in the same direction by an equal amount (13% of fixations) and stable fixations (10%) occurred in roughly in the same proportions. Note that drift movements are slow movements of both eyes by an equal amount in the same direction. Importantly, however, drift movements are not the same as version movements since drift movements occur during a fixation, whereas version movements occur during saccades. Note also that the two types of movement have very different temporal characteristics. The vergence data reported by Liversedge, White et al. illustrate that convergence movements usually predominate during fixations, but other types of eye movements and stable fixations also occur. Further, the occurrence of movement during fixations was partially dependent on the alignment of the fixation. Vergence was more likely to occur during unaligned than aligned fixations and its direction tended to be corrective in relation to the direction of the disparity.

It may be helpful at this point to make explicit the close relation between studies that have focussed on disparity during fixations and studies that have focused on convergence or divergence of the eyes during saccades. Clearly, the terminology and the manner in which the analyses were conducted have been quite different in these two bodies of work. It is important to realise, however, that data from both sets of studies are entirely complementary.

Recall that studies of adult saccadic binocular coordination have demonstrated a transient divergence of the eyes during a saccade. That is to say, the two eyes move apart from each other such that the eye moving outwards becomes further ahead than the eye moving in a nasal direction. This divergence of the eyes is comparable to what reading researchers have defined as uncrossed (although this terminology has always been applied to the state of the eyes during fixations). Note, though, that this divergent state is temporary in that prior to saccade completion, the eye moving nasally starts to catch up with the outward moving eye. Recall, however, that several studies in which saccadic divergence has been analysed reported that residual divergence between the two eyes persisted even at the end of a saccade. Collewijn et al. (1988) reported that the residual divergence was, on average, 0.3° in magnitude. The clear implication of this finding is that some uncrossed disparity between the positions of the eyes should occur at the beginning of fixations; indeed, this is what Liversedge et al. (2006) found. The mean disparity between the eyes at the beginning of fixations was 1.3 character spaces, which equated to 0.38°. Thus, findings showing saccadic divergence in non reading tasks and those showing prevalence for uncrossed fixation disparity during reading are consistent with each other. Note also, that this holds despite the use of different types of eye tracking systems, different theoretical motivations, and different approaches to the analyses.

Now the discussion will turn to the experimental work investigating reading, specifically focusing on linguistic and visual processing of text in relation to binocular coordination. As reported earlier, Heller and Radach (1999) proposed that the visual system tolerates less fixation disparity when presented with MiXeD cAsE than normal text. Juhasz, et al. (2006) investigated whether properties of the text affect binocular coordination during reading. Readers' eye movements were tracked binocularly as they read sentences containing high and low frequency words or trials containing horizontal rows of equally spaced Xs. Half of the sentences were presented in normal case and half in mixed case. The inclusion of high and low frequency words allowed Juhasz et al. to determine whether word processing difficulty influenced disparity since high frequency words are easier to process than low frequency ones (Inhoff & Rayner, 1986; Rayner & Duffy, 1986). Additionally, the horizontal rows of Xs provided an opportunity to examine disparity during scanning under conditions in which language processing did not occur. Finally, mixed case text is more difficult to visually process than normal case text; thus, Juhasz et al. could determine whether visual processing difficulty reduced disparity.

The results were very similar to Liversedge White et al.'s (2006) findings. Three types of fixation patterns were found: aligned, uncrossed, and crossed, with 55% of fixations belonging to the aligned category. Average fixation disparity magnitude was not different for uncrossed than crossed fixations and fixation durations were not affected by the nature of the binocular fixation pattern. More importantly, however, fixation disparity was not affected by the nature of the text, sentences or Xs, nor was it affected by the case or frequency manipulations. There was, however, a standard frequency effect (Rayner, 1998) in which fixations were longer on low frequency than on high frequency words.

The findings of Juhasz et al. were inconsistent with those obtained by Heller and Radach (1999). However, there are several important differences between the two studies. There are differences in the stimuli; Juhasz et al.'s study used unrelated single sentences where the stimuli used in the Heller and Radach study were passages of 200 lines. With this in mind, it may well be the case that presenting an entire passage in alternating text would make the display harder to read than when single sentences were presented. It may also be the case that passage reading, compared to reading unrelated sentences, may induce greater top-down cognitive influence on reading behaviour; these differences in the stimuli may have contributed to the different pattern of results found. Furthermore, the two studies were conducted in different languages (German and English).

It is also important to point out that monocular calibrations were performed by Juhasz et al. (e.g., when calibrating the left eye the right eye was occluded and vice versa) while Heller and Radach (1999) performed binocular calibrations. Monocular calibrations are considered the most reliable method of calibration when recording binocular eye movements (Liversedge White et al., 2006; c.f., Nuthman & Kliegl. 2009). Furthermore, Juhasz et al. reported that calibration accuracy was checked for each eye after every two trials throughout the experiment; Heller and Radach on the other hand provide no details as to the frequency of calibration checks during their study. Finally, the manor in which they measured fixation disparity was also inconsistent. Heller and Radach used the difference in binocular saccade amplitude as their measure of disparity; Juhasz et al. reported disparity as the difference between the fixation position of the two eyes at both the start and end of fixation. Therefore, these differences in experimental conditions and the fact that no formal statistics are reported in the Heller and Radach paper, prevent a direct comparison between the studies.

The studies of binocular coordination during reading discussed prior to this point have, largely, been descriptive in nature; in the sense that they have largely offered a description of binocular coordination under different experimental conditions. The final study considered in this section is one by Liversedge, Rayner, White, Findlay, and McSorley (2006). This was theoretically motivated work that attempted to actively drive the binocular eye movements of participants. This work related to the classic debate during the 19th century between Ewald Hering and Hermann von Helmholtz regarding the neural control of coordination between the two eyes. Helmholtz believed that the two eyes were driven by independent neural signals, and through experience the two eyes learn to move in coordination with one another (Howard, 2002). He argued that, once learnt, this binocular coordination could not be overridden at will; however, independent control did remain anatomically possible. This, he suggested, was demonstrated by the oculomotor system's response to the separation of the visual axes when induced with prisms. Therefore, Helmholtz's theory assumed that eye movements were unyoked and independent neural signals control each eye. Each single independent signal, thus, represents the required eye movement for each eye in relation to a movement in both direction and depth.

In contrast, Hering's law held that equal innervation, in the form of a single neural signal, controls both eyes (Hering, 1977). Furthermore, he argued that binocular coordination was innate and not altered by learning. He proposed that the two eyes should be considered as one organ, incapable of independent movement. Hering believed that binocular eye movements were yoked and driven by two systems (vergence and version). The vergence and version systems each issue independent commands but, critically, each sends a single neural signal to both eyes. Although Hering was seen to "win" the argument, researchers have continued to be polarized over these issues (see King & Zhou, 2000). Recent neurophysiological data have revealed that premotor neurons encode monocular commands and motoneurons encode binocular commands (King and Zhou, 2000). King and Zhou concluded on the basis of this new evidence that both theories are partially correct. (See also the discussion of Bains et al., 1992; Collewijn et al., 1995, 1997; Erkelens & Sloot, 1995; in Section 1.3.)

Liversedge et al. investigated how readers program saccadic eye movements and were particularly interested in whether saccades for each eye are programmed independently (e.g., Helmholz, 1910, as cited in Howard, 1999), or if they are driven by a single neural signal (e.g., Hering, 1868, as cited in Howard, 1999). Experimental sentences were constructed containing a target compound noun (e.g. *cowboy*) that was 6, 8 or 10 characters long (each morphological constituent was the same length). Shutter goggles were used to block visual input to each eye alternately every 8 ms. These alternations were synchronised with changes in the display screen such that all words in the sentence other than the target word were presented in their entirety to both eyes, whereas a different portion of the target word was presented alternately and separately to each eye. Additionally, the movements of each eye were precisely measured. Three target word presentation conditions were employed: congruent (*cowb* to the left eye and *wboy* to the right eye); incongruent (*wboy* to the left eye and *cowb* to the right eye) and a binocular control condition (*cowboy* to both eyes). Importantly, participants perceived the whole target word regardless of the particular presentation condition. Also, the two character overlap served to anchor the word portions together in the vertical plane.

Liversedge, Rayner et al. made three predictions. First, if saccade metrics were computed for each eye independently on the basis of each eye's unique retinal stimulation, then different saccade sizes and different landing positions on the word would be expected for each eye (since each eye would target a different portion of the word). Second, if the input from one of the two eyes was suppressed, and saccade metrics computed on the basis of one or other visual input, then saccades would be of different lengths (depending on whether the right or the left part of the word was being suppressed). Finally, if saccade metrics were computed on the basis of a representation that is unified from the two different retinal signals, then the mean saccade lengths and fixation positions on the target word should be uninfluenced by the different dichoptic presentation conditions.

Fixation durations on the target word were significantly increased under the dichoptic presentation conditions compared to the control condition; nonetheless, landing positions on the target word were uninfluenced by dichoptic presentation. Thus, Liversedge, Rayner et al. concluded that saccade metrics for a non-foveal target word were computed on the basis of a unified perceptual representation obtained from distinct retinal signals (note that Collewijn et al. 1997 formed a similar conclusion on the basis of independent evidence). Liversedge, Rayner et al. also proposed that this unified visual percept is achieved through a process of fusion rather than suppression.

An important conclusion that follows from Liversedge, rayner et al., it that a crucial function of the oculomotor system is to coordinate binocular eye movements in order to position the points of fixation sufficiently close to one another that a single, unified visual percept of the text may be achieved. Nonetheless, several studies indicate that fixations are disparate by more than one character space (but seldom by more than 2 characters) in just under half of the fixations made during reading.

1.5 Summary

Based on the results of studies which have acquired data from both reading and non-reading tasks, it appears that significant magnitudes of disparity, both foveal and non foveal, between the two retinal inputs are tolerated on a fixation-by-fixation basis. The deviation from the intended state of vergence (fixation disparity) during fixation goes unnoticed; however, disparate images that fall outside of Panum's fusion area lead to a steady state vergence error feedback signal. Small vergence movements frequently occur during fixations and these are often in a corrective direction, in that they typically reduce disparity, though residual fixation disparity does remain immediately prior to the following saccade. Vergence movements are similar under monocular and binocular viewing conditions; thus, it seems plausible that vergence movements are pre-programmed and reflexive rather than determined by specific visual input. Researchers are beginning to piece together an understanding of how the visual system accomplishes a unified cyclopean percept based on differing retinal inputs using dichoptic presentation techniques (e.g. Blythe, Joseph, Findlay & Liversedge, 2008). A unified representation appears to be achieved through a process of fusion rather than suppression of one retinal image. Fusion seems to occur at an early stage in visual processing and binocular saccade metrics are computed on the basis of this unified percept.

Several empirical reading studies have investigated which (if any) aspects of text processing may modulate binocular coordination (e.g., Blythe et al., 2006; Heller & Radach, 1999; Hendriks, 1996; Juhasz et al., 2006; Liversedge, White, et al., 2006; Liversedge, Rayner, et al., 2006). Only one study reported above has shown a significant influence of processing difficulty on binocular coordination (Hendriks, 1996), and this may be at least partly due to a confounding variable (preceding saccade amplitude). While, Heller and Radach (1999) argued that processing difficulty affected binocular coordination a more thorough examination (Juhasz et al., 2006) failed to replicate their findings. Therefore, it appears that adult binocular coordination is not affected by manipulations of processing difficulty, such as case or frequency. Fixation disparity seems to be largely visually based, reflecting fundamental, low level aspects of oculomotor behaviour.

The characteristics of binocular coordination in adults are relatively well documented across a range of laboratory based viewing situations and tasks. A clear relationship has been established between the preceding saccade amplitude and the velocity of vergence movements which occur during fixation (Collewijn et al., 1988; Zee et al., 1992). With these conclusions in mind the following series of experiments were designed. Experiment One aimed to investigate the suggestion that binocular coordination is largely visually based, and asked which (if any) aspects of the visual stimuli affected binocular coordination. This was examined in relation to both the magnitude and the direction of fixation disparity and saccadic disconjugancy.

Chapter Two

Experiment One: adult binocular coordination during scanning simple dot stimuli

2.1 Introduction

The aim of Experiment One was to examine the characteristics of adults' binocular coordination during saccades and fixations while scanning simple dot stimuli. More specifically, the study was designed to investigate whether the visual characteristics of non-reading stimuli influences binocular coordination. A proportion of research investigating binocular coordination during reading has focused on investigating what (if any) aspects of linguistic processing influence the characteristics of fixation disparity (e.g., Blythe et al., 2006; Bucci & Kapoula, 2006; Heller & Radach, 1999; Hendriks, 1996; Juhasz et al., 2006; Liversedge, White, et al., 2006; Liversedge, Rayner, et al., 2006; Yang & Kapoula, 2003).

Simple non-reading, visual stimuli have been regularly used in studies that have investigated saccade disconjugancy and post-saccadic vergence (e.g., Collewijn, et al., 1988; Collewijn, van der Mark & Jansen, 1975; Erkelens, Collewijn, & Steinman, 1989). Typically, these studies are solely concerned with moment to moment oculomotor control during saccades to simple light point targets, and do not assess the influence of higher order cognitive (and specifically linguistic) factors on binocular coordination. Also, the intrinsic visual characteristics of the stimuli are not usually manipulated. Such studies have shown that binocular saccades display temporal and spatial disconjugacy (Erkelens et al. 1989; Zee et al., 992). Transient divergence between the two eyes has been demonstrated to occur during saccades across a range of saccadic tasks and temporal and spatial differences between the parameters of binocular saccades may, or may not, be due to a lack of yoking between the two eyes (Bains et al., 1992; Collewijn et al., 1988; Hering, 1977; cited in Howard, 1999; King & Zhou, 2000; von Helmholtz, 1962; as cited in Howard, 1999; see Chapter 1, for a full discussion). More specifically, such effects have been argued to reflect neural connections independently activating the muscles controlling rotation of the eyeballs (King & Zhou, 2000; von Helmholtz, 1962, as cited in Howard, 1999), or differing synaptic delays, or even differences in the mechanical dynamics of the muscles that control the two eyes (Bains et al., 1992).

As described in Chapter 1, there have been two distinct and largely independent approaches to the investigation of binocular coordination; one in which linguistic stimuli (and sometimes non-linguistic stimuli for comparison) are employed to examine binocular eye movement control during fixations, and the other employing simple visual stimuli to assess the coordination of the eyes during saccades. These approaches are not only motivated by different objectives and interests in relation to oculomotor behaviour, but also adopt different techniques in the analyses of the eye movement data. Despite this, however, it is increasingly apparent that the findings generated by the two approaches are both consistent and complimentary (see Chapter 1). For present purposes, note that, to date, there have been very few, studies that have been carried out to investigate how binocular coordination is affected by the manipulation of the visual characteristics of non-reading stimuli. Therefore, Experiment 1 was designed to investigate such influences on binocular coordination.

Whilst it is the case that very few experiments have manipulated visual characteristics of stimuli in relation to binocular coordination, there are two experiments in which the influence of viewing distance has been assessed in adult participants (Collwijn et al., 1997; Yang & Kapoula, 2003). In both these investigations the same simple dot stimuli (LEDs) were presented to participants either at near viewing distances (~15cm and 20cm respectively) or far viewing distances (~75cm and 150cm respectively). Although the visual stimulus characteristics remained the same under the different viewing conditions, the change in the physical proximity of the target to the observer affected the size of the image falling on the retina. To this extent, Collwijn et al.'s, and Yang and Kapoula's manipulations involved a change in the visual characteristics of the retinal stimulus under the different experimental conditions. Perhaps unsurprisingly, these subtle changes in the visual characteristics of the stimuli produced very limited effects. Collwijn et al. found a very small effect of viewing distance on binocular coordination, and Yang and Kapoula found no reliable effects.

The aim of the current investigation was to assess the influence of a variety of different visual characteristics of stimuli on binocular coordination. In several of the conditions in the present experiment the size of the saccade target was manipulated to assess its influence on binocular coordination whilst viewing distance was held constant. In other experimental conditions, the aim was to create situations that produced eye movement behaviour that was analogous to that observed during reading, but during which no linguistic processing occurred. In this way the magnitude of any observed fixation disparities in relation to the magnitude of similar effects observed during reading could be assessed (e.g., Blythe et al., 2006). Note also that in the present study identical hardware and software for the acquisition and analysis of the data to those used by several preceding studies was used (e.g., Blythe et al. 2006; Liversedge, White, et al., 2006; Liversedge, Rayner et al., 2006), thereby precluding the possibility that any differences obtained might be caused by such factors. Finally, the data from the present study were examined to assess binocular coordination both during fixations and during saccades (c.f., Kapoula, Vernet, Yang, & Bucci, 2008).

There were three experimental tasks in the present experiment. In the dot string condition (Task 1) participants were presented with horizontal arrays of dot stimuli that were grouped into strings of the same length (i.e., strings of 2, 4, or 6 dots, as well as a condition in which single dots formed the stimuli). These stimuli were designed to appear visually similar to horizontal arrays of words but, obviously, did not contain any linguistic content and omitted fine grained letter features such as ascenders and descenders. Participants were required to scan from left to right fixating each of the dot strings in the horizontal array in turn. Under these conditions participants were required to perform patterns of highly stylised saccades and fixations similar to those that occur during reading. Therefore, this situation provides an opportunity to investigate the influence of the visual stimulus characteristics while eliminating the influence of linguistic factors. Grouping the dots into strings and gradually increasing the horizontal spatial extent of the unit of visual information (i.e., from single dots to 2, 4 and then 6 dots) provided an opportunity to investigate the influence of target size on binocular coordination. Also, using strings of dots rather than words allowed the construct of horizontal arrays of stimuli that were all of the same size. Uniformity across dot strings meant that any variability in saccade metrics was not caused by differences in the horizontal spatial extent of the stimuli comprising the array. Quite clearly, it would have proved much more difficult to manipulate target size consistently over each trial if we had used linguistic stimuli, since sentences are very rarely composed exclusively of words that are all the same length.

The first experimental task (Task 1, horizontal rows of dot targets) provided a very valuable opportunity to examine variability in binocular landing positions on horizontal dot strings of different lengths. With respect to the stimuli in the present study, there is the opportunity for increased variability in landing positions for dot strings that are longer than for those that are shorter since there is a wider range of possible landing positions for targets of greater compared to smaller horizontal extent. Such increased variability would be consistent with the rationale underlining Helmholtz's theory of binocular coordination, indicating that saccades are independently targeted for each eye. Conversely, and consistent with Hering's law of equal innervation, if a unified signal does drive saccadic targeting then binocular coordination would not be influenced by the horizontal extent of the target.

The experimental conditions in the first testing session, therefore, allowed the assessment of whether there is increased variability in binocular landing positions, in terms of increased fixation disparity for longer compared to shorter dot strings. On the assumption that greater precision of saccadic targeting will occur for smaller compared to larger targets, then one might expect reduced disparity for short than long dot strings. Alternatively, if disparity is not influenced by the size of the target to which the saccade is made, then one should observe little, if any, relationship between target size and fixation disparity for fixations on the target. These were the primary experimental hypotheses examined during Task 1.

The second task (Task 2, two simultaneously presented single dot targets) investigated binocular coordination during a series of successive saccades made between two single dot stimuli presented horizontally apart on the computer screen. Participants were required to make saccades between the two dots in time with a metronome. This procedure is very similar to that employed by Lemij and Collewijn (1989) who found that participants' saccadic accuracy was enhanced when looking back and forth between two stationary, continually visually available dot targets, compared to when they were required to follow a dot that was presented at locations randomly such that it was not clear where the target would appear. However, note that Lemij and Collewijn considered only monocular eye movements, and no examination of binocular coordination under these conditions was undertaken.

In the third task (Task 3, randomly presented single dot targets) single dots were presented at one of four bi-lateral horizontal locations, at near or far eccentricities from a centrally presented cross. The central cross disappeared, after which the target dot immediately appeared either to the left or to the right. Participants were simply required to saccade from the cross to the dot. Thus, the experimental conditions in the third task were designed to allow the systematic examination of the influence of saccade amplitude and direction, on binocular coordination during fixations. While the studies reported in Hendriks (1996) and Heller & Radach (1999) have found that the velocity of fixation vergence movements is positively correlated with incoming saccade amplitude during reading, these studies did not include analyses of the absolute magnitude or the direction of fixation disparity in relationship to the amplitude of the preceding saccade. Furthermore, while several studies have investigated how the magnitude of fixation disparity changes across the line of text (e.g. Heller & Radach, 1999; Liversedge, White et al., 2006; Nuthmann & Kliegl, 2009), to date, in binocular research during reading there has been no specific investigation of the influence of the direction of the preceding saccade on the magnitude or direction of fixation disparity. This is somewhat surprising given regressive saccades from right-to-left, and return sweeps (when the eyes move from the end of a line of text to the beginning of the next line of text) are typical (during reading of English). Furthermore, less proficient (i.e. dyslexic readers) or beginner readers are found to make more regressive eye movements than skilled readers (Rayner, 1998). It is, therefore, a very pertinent question in relation to binocular research in reading, as to whether the direction and magnitude of the preceding saccade influences the alignment characteristics of the two eyes during the subsequent fixation.

2.2 Methods

Participants. The nine participants were all students from the University of Southampton (Mean age = 23.25, SD = 3.28; age range = 19 – 29 yrs). All had English as their first language with normal, uncorrected vision. Participants were either paid in cash or earned course credits for volunteering to take part.

Apparatus. Two Dual Purkinje Image eye trackers were used to record binocular eye movements. The resolution accuracy of the dual-Purkinje system is less than 1 minute of arc. Eye positions were monitored every millisecond. A Pentium® 4 computer interfaced with the eye trackers and all the visual stimuli were presented on a Philips 21B582BH 24″ monitor. The stimuli (dots) were presented at a viewing distance of 1000 mm. Each dot covered .29° of a visual angle and was presented in white on a black background. The room was dark except for a small dim indirect light source. To minimise participants' head movements during the experiment, they were required to bite on a sterilised bite bar, which was covered with dental wax, to lean into two forehead rests, and to have a Velcro strap secured behind their head. This allowed for accurate oculomotor data to be obtained from both the right and left eyes.

Stimuli. The study employed three separate eye tracking tasks. In Task 1, (Figure 2.1) horizontal rows of dot targets (diameter .29˚) were presented simultaneously and remained visible throughout the trial. The rows of dots consisted of, five single dot targets, or dots grouped into strings of two, four and six dots. Strings of two dots were presented as a row of 12 targets, strings of four dots were presented as a row of eight targets and strings of six dots were presented as a row of six targets. In Task 2, (Figure 2.2) two single dot targets, (again, of diameter .29˚) were presented on the horizontal axis about the screen centre. The dots were presented simultaneously and separated by 5.5˚ of visual angle. In Task 3, (Figure 2.3) single dot targets were presented in isolation at four possible locations along the horizontal axis. Presentation was randomly assigned to a position that corresponded to 5.5˚ or 2.1˚ either to the left or right of a central cross.

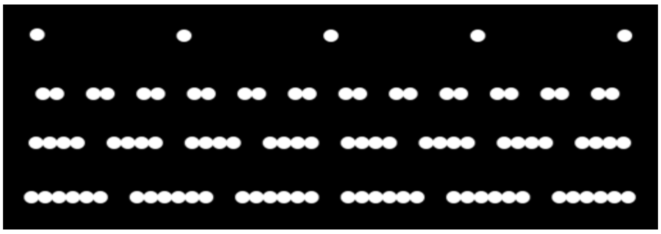

Figure 2.1

Non-linguistic stimuli, for task 1, only one row of dots was presented during a trial; a dot covered .29˚ of visual angle.

Figure 2.2

Stimuli for Task 2. Two simultaneously presented single dots 5.5° of visual angle separated the two dots.

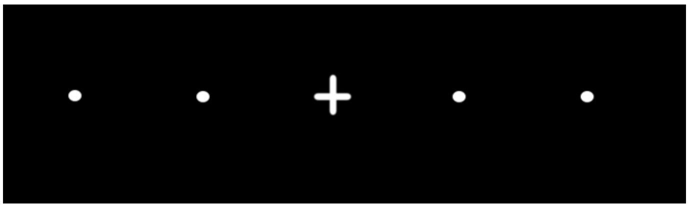

Figure 2.3

Stimuli for Task 3. In a single trial only one dot was presented; 2.1° and 5.5° to the left and to the right of the centrally presented fixation cross.

Procedure. In Task 1 (the presentation of a horizontal row of dot targets), participants were instructed to fixate on a cross, presented on the left side of the screen for one second. The fixation cross was then replaced by a row of dot targets with the leftmost dot of the first target in the row replacing the cross. Participants were required to scan the rows from left to right treating each dot string as a target, rather than making repeated fixations on each individual dot of a string (i.e., to treat each string as if it were a word in a sentence). Participants were required to hold fixation on the final dot string in the row until it disappeared. The displays remained on the screen for a period that easily allowed each of the strings to be fixated once or twice (5000 ms for single dots; 10000 ms for two dot strings; 8000 ms for four dot strings; 5000 ms for six dot strings). After the row of targets disappeared, a fixation cross reappeared on the left side of the screen indicating the start of a new trial. The task consisted of six trials for each dot string size (i.e. one, two, four and six dots).

In Task 2 (the presentation of two single dots), participants were instructed to fixate the centrally present cross. The cross was then replaced by two dots one on either side of the screen. Participants were instructed to make a saccade between the two dots, which was temporally dictated by the pace of a metronome (set at 60 beats per minute) until the targets disappeared. After this, a central cross appeared again, indicating the start of the next trial.

During Task 3 (the presentation of single dots in isolation), a central cross appeared and the participants were requested to fixate the cross until it was replaced by a target dot. The presentation location of the target was randomly allocated to one of four possible positions along the horizontal axis. Participants were instructed to make a saccade to the target and hold fixation until the target disappeared. After the target disappeared it was replaced by the central cross which indicated the start of a new trial. The entire task consisted of six trials in the four positions, a total of 24 trials. All instructions were given both verbally and in writing prior to calibration. Participants were allowed to ask questions at that point if they did not understand any of the instructions.

Calibration. Left and right eye calibrations were performed monocularly (e.g. when calibrating the left eye, the right was occluded and vice versa). During calibration the participant was instructed to stare at one of three fixation points presented horizontally in the middle of the screen to the left, centre and right of the vertical midline. Monocular eye positions were recorded for each of these fixation points and then checked for accuracy. This was then repeated for the other eye. When calibration was completed the experimental stimuli were presented. Following every three trials the calibration accuracy was checked and, if necessary, the eye trackers were recalibrated.

Analysis. Fixations were manually identified in order to avoid contamination by dynamic overshoots (see Figure 2.1; Liversedge, White et al., 2006; Deubel & Bridgeman, 1995). A custom-designed software package was utilised to analyse all data. The analyses are based on all valid fixations and saccades recorded during the experiment. Disparity was calculated at fixation onset and offset so that any vergence movements observed could be compared across conditions. Furthermore, calculating disparity at the start and end of fixation provided a method of investigating the influence of the visual characteristics of the stimuli at different time periods during the fixation. Blinks were excluded from the data stream in the initial stage of analysis, during the segmentation of data into fixations and saccades.

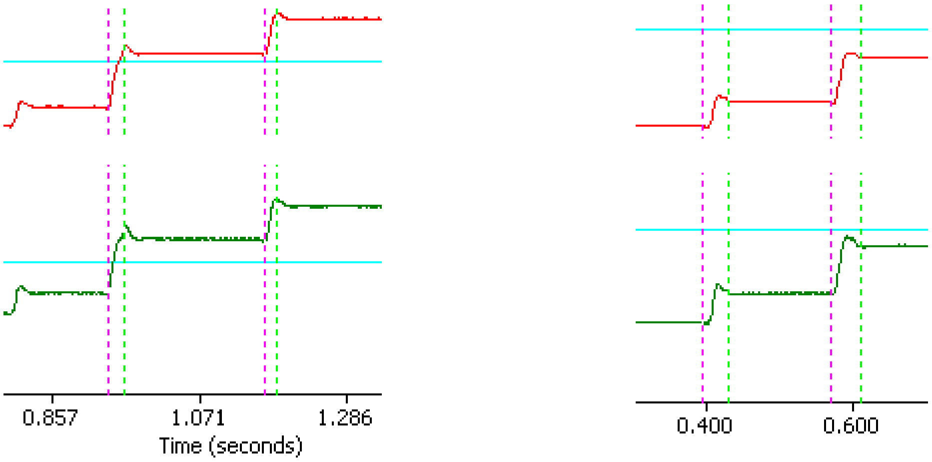

Figure 2.4

Right panel shows manually selected saccades and fixations where all dynamic overshoot is excluded from the fixation durations. Left panel shows automated selection of saccades and fixations where the start and end of a saccade is selected by a velocity above (below) threshold of 10% of the maximum velocity. (Vertical axis represents horizontal eye position (in degrees) left to right eye movements running from the bottom to the top of the graph.)

Fixations with durations of more than 80 ms were considered valid; no upper cut-off was applied due to the experimental instructions to maintain a long fixation at the end of trials. Additionally, fixations were deleted if the absolute disparity during that fixation was more than 2 standard deviations from the mean for that individual participant (discarding all fixations with a mean fixation disparity greater than M+ 2SD is standard procedure see Liversedge, White et al., 2006: Blythe et al., 2006). Thus, all fixations of more than 80 ms with a disparity within 2 standard deviations of the mean were included in the analysis. Fixations with durations of less than 80 ms, along with the subsequent saccade, that were excluded from the analyses represented 3.8% of the data. A further 4.1% of the data were excluded from the disparity analyses due to an absolute end of fixation disparity greater than 2 SD from the mean for each participant. A further 4.7% of the data were excluded due to an absolute disparity of greater than 2 SD from the mean for each participant at fixation onset.

Fixation disparity was calculated by deducting the horizontal start of fixation position for the right eye from that of the left eye. This procedure was repeated for the end of fixation positions for the two eyes. Similar to Liversedge, White et al. (2006), fixations were categorized as aligned or unaligned. To be considered as an aligned fixation, the fixation points of the two eyes were required to be within one dot space of each other (.29°). Therefore an unaligned fixation represented an absolute disparity of more than one dot (greater than .29°). Unaligned fixations were further categorized into those that were uncrossed and those that were crossed. A crossed fixation was defined as one where the point of fixation of the left eye was to the right of the point of fixation of the right eye. An uncrossed fixation was defined as the converse of this.

2.3 Results

What are the basic characteristics of binocular coordination during scanning of horizontal rows of dot stimuli?

One of the primary questions under investigation was whether the basic characteristics of binocular coordination during left-to-right horizontal scanning of dot strings (when no linguistic processing was required), were similar to those observed during reading (e.g., Blythe et al., 2006; Juhasz et al., 2006; Liversedge, White et al., 2006; Nuthmann & Kliegl, 2009). Fixation disparity was calculated at both fixation onset and offset to provide both a static measure of binocular coordination and an index of the vergence movements that occurred during fixation. Also computed, was the mean difference in saccade amplitude for the two eyes. These are shown in Table 2.1.

At fixation onset the mean disparity between the points of fixation for the two eyes was .24°, and by fixation offset this had reduced to .22°. These disparities are consistent with those reported by Blythe et al. (2006), who reported disparity magnitudes of .24° at fixation onset and offset for adults during a reading task. For seven of the nine participants that were tested, there was a small reduction in fixation disparity through the course of a fixation, though for two participants a small increase in fixation disparity occurred. In addition to fixation disparity, the mean absolute difference in the saccade amplitude for the two eyes was also computed, which was .1°. Thus consistent with previous studies (e.g., Collwijn et al., 1988) it was shown, that all participants demonstrated a degree of asymmetry in their binocular saccade amplitudes.

Table 2.1

Average fixation duration, absolute disparity magnitudes at fixation onset, absolute disparity magnitudes at fixation offset and saccade amplitude differences between the two eyes for each of the nine participants tested during scanning of horizontal arrays of dots. Standard deviations are provided in parentheses.

Participant	Fixation duration	Absolute Disparity magnitudes at Fixation onset	Absolute Disparity magnitudes at Fixation offset	Absolute Differences in Saccade Amplitudes for the Two Eyes
1	391 ms (315)	.16° (.15°)	.15° (.10°)	.18° (.43°)
2	504 ms (560)	.45° (.26°)	.38° (.23°)	.12° (.22°)
3	432 ms (271)	.25° (.17°)	.27° (.17°)	.13° (.13°)
4	461 ms (278)	.16° (.17°)	.15° (.13°)	.11° (.13°)
5	465 ms (362)	.20° (.15°)	.19° (.15°)	.08° (.09°)
6	554 ms (479)	.17° (.13°)	.15° (.11°)	.07° (.27°)
7	504 ms (485)	.23° (.15°)	.18° (.13°)	.09° (.09°)
8	618 ms (227)	.19° (.14°)	.16° (.11°)	.14° (.23°)
9	677 ms (715)	.22° (.16°)	.23° (.14°)	.11° (.12°)
Mean	511 ms (446)	.24° (18°)	.22° (.17°)	.11° (.20°)

Next the alignment proportions of all valid fixations were considered. The mean proportions of aligned, uncrossed and crossed fixations at the start and end of fixations are presented in Table 2.2.

Table 2.2

Mean fixation alignment proportions, at fixation onset and fixation offset during scanning of horizontal arrays of dots (Note that percentages have been rounded to the nearest whole number)

	All start data (%)	End Aligned (%)	End Uncrossed (%)	End Crossed (%)
All end data		73%	16%	11%
Start aligned	70%	91%	2%	7%
Start uncrossed	21%	35%	64%	0%
Start crossed	9%	21%	0%	79%

During the majority of fixations the eyes were aligned, were uncrossed less often, and crossed least often of all. A one-sample *t*-test comparing the proportion of aligned fixations to chance (50%) showed that eyes were aligned significantly more often than chance both at the start (*t* (8) = 4.12, *p* < .01) and the end (*t* (8) = 4.48, *p* < .01) of fixation. For 27% of fixations made across the horizontal arrays of dot strings the eyes were disparate by the horizontal extent of one dot or more at the end of fixation. Similarly, Liversedge, White et al. (2006) and Blythe et al. (2006) both found that the eyes were not always aligned by the end of a fixation during reading.

Recall that all the unaligned fixations were further categorised as either crossed or uncrossed. Again, since these two categories are dependent, comparisons of the probability of making an uncrossed fixation against chance (50%) were conducted. A one-sample *t*-test showed that for the start of fixation data, when the two eyes were not aligned, fixations were significantly more often uncrossed than chance, (*t* (8) = 2.52, *p* = .04); however, by the end of a fixation unaligned fixations were no more often uncrossed than chance (*t* (8) = 1.11, *p* = .30). Thus, overall for the unaligned fixations, the eyes were more likely to be uncrossed than crossed at fixation onset; however, no such difference existed by the end of a fixation. While this pattern is similar to that obtained by Liversedge, White et al. (2006), in that the points of fixation were diverged at fixation onset and small vergence movements reduced the disparity throughout fixation, they are also different in that Liversedge, White et al. observed residual uncrossed disparity at the end of fixation, and this was not the case here.

Previous research has demonstrated that the two eyes make asymmetric saccades during reading (Hendriks, 1996; see also Heller & Radach, 1999), and the present results were again consistent with this finding. In Task 1, the disconjugacy between the two eyes accounted for between 8 and 10% of the absolute total saccade amplitude (see Table 2.3), with larger amplitudes for the abducting eye (the eye moving temporally, $\mu = 1.19$, SD = 1.13) than the adducting eye (the eye moving nasally, $\mu = 1.13$, SD = 1.12; *t* (8) = 16.99, *p* < .01).

Table 2.3

The mean saccade amplitude for the abducting and adducting eyes, the mean amplitude of the disconjugacy of saccades (absolute values in degrees) and the disconjugacy expressed as a percentage of saccade amplitude for each of the dot strings.

	Saccade Amplitude for the Adducting Eye	Saccade Amplitude for the Abducting Eye	Difference in the two eyes' saccade amplitudes	Percentage of saccade
Five, single dot targets	1.64°	1.70°	.13 °(.03)	8%
Twelve, two dot strings	.86°	.91°	.09° (.03°)	11%
Eight, four dot strings	1.05°	1.09°	.09° (.03°)	9%
Six, six dot strings	1.23°	1.30°	.12° (.04°)	9%

The proportion of saccade amplitude accounted for by disconjugacy is in line with the findings of Heller and Radach (1999). They reported asymmetry between the saccade amplitudes of the two eyes (5% for saccades of 10-12 characters and 15% for saccades of 2-3 characters), values similar to those that were obtained here. Thus, the data presented in Table 2.3 indicate that the absolute magnitude of saccade disconjugacy is similar during normal reading and when targeting dot strings during the scanning task. The present data contrast in one respect with those data reported by Heller and Radach, in that the present data indicate that saccade disconjugacy is larger for saccades of greater amplitude (the opposite pattern to that observed by Heller & Radach). Note, however, that the observed disconjugacy between the eyes during movements arises due to differences in saccade amplitude and peak velocity rather than any temporal difference in saccade onset.

Is binocular coordination affected by the horizontal extent of the target?

In the next set of analyses the influence of the horizontal extent of the target (one dot, two dot, four dot and six dot strings) on binocular coordination are considered. In the current analyses, it was of particular interested to determine whether fixation disparity was increased for targets with a greater horizontal spatial extent than for those with reduced horizontal extent. To reiterate, the reasoning was as follows: the smaller and more spatially localised the stimulus, potentially, the greater the binocular precision required during saccadic targeting and orienting, resulting in a reduced horizontal disparity at fixation onset. Thus, in line with this rationale, increased fixation disparity was predicted with larger horizontal extent of the target.

To examine the effect of target extent, fixation durations, absolute fixation disparities, and differences in the absolute saccade amplitude for the two eyes were computed for all target extent conditions. Here all the fixations made as participants scanned the arrays of dots were considered (regardless of whether these followed a rightward or a leftward saccade). One-way repeated measures ANOVAs were conducted. In regard to fixation durations there was no reliable influence of the extent of the dot string (for targets consisting of one dot μ = 561ms, SD = 106; two dots μ = 498ms, SD = 92; four dots μ = 517ms, SD = 145; and six dots μ = 489ms, SD 95; *F* (3, 24) = 2.15, *p* = .12). This result is not particularly surprising given that the stimuli in the present experiment were simple arrays of dot strings and variability in fixation duration has frequently been shown to be related to underlying cognitive processes (see Chapter 1, section 1.1 *Basic characteristics of eye movements during reading*). Thus, it appears that visuo-cognitive processing was no more difficult for stimuli formed from groups of dots than for those formed of single dots.

Then absolute disparity magnitudes were examined as a function of the horizontal extent of the target. Contrary to the predictions, there was no significant effect of target extent on disparity at the start of fixations (*F* (3, 24) = 1.35, *p* = .28; one dot μ = .30, SD .18; two dot μ = .20, SD .05; four dot μ = .24, SD .16; six dot μ = .27, SD .12) or at the end of fixations (*F* (3, 24) = .82, *p* =.50; one dot μ =.25, SD .15; two dot μ = .19, SD .06; four dot μ = .22, SD .13; six dot μ = .24, SD .10). Indeed, the numerical trends that exist within the data are in the opposite direction to that expected. The smaller the target extent, the greater the magnitude of disparity found, though again, these effects were not significant. In addition to these analyses, ANOVAs were computed to examine whether there was any modulatory influence of target extent on the proportions of alignments. These analyses also failed to reveal significant effects (all *F*s < 1.11). These results indicate that binocular coordination remained consistent over all the horizontal target extents investigated.

The present manipulation in Task 1 also provided an opportunity to investigate whether fixation disparity was significantly reduced between the start and the end of fixation and whether the degree to which any vergence movements differed was related to the horizontal extent of the target. To address these questions the data for absolute disparity magnitudes at the start and the end of fixations were examined using a four (Target extent: one/ two/ four /six dots) x two (Sample point of fixation: start vs. end) repeated measures ANOVA. No reliable effects in these analyses were obtained (all *F*s < 1.5). By the end of fixation there was a numerical decrease in the magnitude of disparity, but this was not significant (*F* (1, 8) = 3.21, *p* = .11). This numerical difference, although not reliable, is consistent with that reported by Liversedge, White et al. (2006), and numerical differences reported by Blythe et al. (2006).

Table 2.2 shows the patterns of alignment (aligned, uncrossed and crossed) at the start and the end of all valid fixations and the proportion of fixations in each alignment category as a function of their alignment at fixation onset. In these analyses the aim was to determine whether, as is the case during reading, the alignment of the two eyes altered during fixations, and whether the horizontal extent of the target under fixation influenced any such vergence movements. Again, repeated measures ANOVAs were conducted, comparing the proportion of fixations in each of the alignment categories at fixation onset and offset for the targets of different extents (one/ two/ four /six dot strings). For the aligned fixations there were no reliable effects (all *F*s < 2.94); for the uncrossed fixations there was a main effect of sample point (fixation onset vs. offset) with fewer uncrossed fixations at fixation offset than onset (*F* (1, 8) = 13.33, *p* < .01). These analyses showed no reliable effect of target extent or any interaction (*F*s < 1); for crossed fixations there was no reliable effect of target extent (*F* < 1), however, there was a significant effect of sample point in fixation, (*F* (1, 8) = 6.91, *p* = .03) where the proportion of crossed fixations increased during fixation. Thus, the prevalence of uncrossed disparity at fixation offset was reduced relative to that at fixation onset and target extent did not affect vergence movements. Again, these data indicate that vergence movements of the eyes during fixation are small but corrective and reduce the disparity in fixation prior to a saccade.

What is the nature of vergence movements during fixations on dot strings?

Previous research has described vergence eye movements that occur during fixation; the current aim was to precisely categorise the nature of the movements. Four main categorises were identified (based on those of Liversedge, White et al., 2006). 1) Stable fixations, where both eyes moved less than (or equal to) 10% of a dot's diameter (.03°). 2) Drift movements, where the eyes move in the same direction for an equal amount and the difference in the movement of both the two eyes was less than .03°. 3) Convergence, where the point at which the two eyes' lines of sight cross moves nearer to the viewer. This can be due to either both eyes moving in different directions (left eye moves right, right eye moves left), or due to one eye only moving (the left eye moves right or instead the right eye moves left) or result from both eyes moving in the same direction (i.e. drift) but where one eye moves further (if drifting to the left then the right eye moves further and conversely for a rightwards drift the left eye moves further). The final category, 4) Divergence, where the point at which the eyes' lines of sight cross moves away from the viewer. This can be due to both eyes moving in the same direction with one eye moving further, or when one eye moves and the other remains stable (the left eye moves left, or right eye moves right), or due to both eyes moving in different directions (the right eye moving right and the left eye moving left).

Detailed analyses revealed that only 9% of all fixations made to dot targets presented along a horizontal array were stable. These fixations were shown to have a mean disparity of .23° at fixation onset. Further analyses found that while scanning horizontal dot targets, the extent of the target had no significant effect on the percentage of stable fixations (F (3, 24) = 1.14, $p = .35$). For all target extent conditions it was significantly more likely that the eyes moved during fixation rather than remaining stable throughout fixation. Due to the dependent nature of the two categories (stable fixation vs. movement during fixation) one sample t-tests compared the percentage of stable fixations with chance (all ts > 2). During 10% of all fixations made to dot targets along a horizontal array, the disparity between the two eyes' line of sight remained constant while both the eyes' line of sight made drift movements in the same direction. These fixations were also, on average .23° disparate at fixation onset.

While scanning horizontal arrays of dot groups, 60% of all fixations were found to demonstrate convergent movements, where the focal points of one eye, or both eyes, converge to decrease retinal disparity. This was the most frequently occurring movement during fixation. A reduction of fixation disparity is consistent with the findings in reading research (Blythe et al., 2006; Liversedge, White et al., 2006; Nuthmann & Kliegl, 2009). Here a reduction of disparity was evident even in the absence of any cognitive or linguistic processing necessary to complete the task, thus indicating that disparity reduction is a visually mediated behaviour rather than being cognitively driven. Further analyses were conducted to determine the nature of the convergence movements. As mentioned above, convergence can be achieved through the combination of one stable eye and one converging eye. Forty five percent of convergent fixations demonstrated this oculomotor pattern; the mean magnitude of disparity was .25° at fixation onset when this pattern of eye movement occurred. Convergence due to both eyes moving in the same direction with one eye moving further than the other accounted for 20% of convergent fixations. Finally, both eyes moving in opposite directions to reduce retinal disparity constituted a further 35% of convergent movements. This pattern of convergence was found to occur in cases where the most retinal disparity was recorded at fixation onset (magnitude = .30°).

Further analyses were conducted to investigate the divergent movements during fixation. Twenty one percent of all fixations were found to include a divergence between the two lines of sight; here, retinal disparity ranged, on average, between .19° and .22° at fixation onset. The precise nature of the divergent movements also consisted of three distinct oculomotor patterns. Here, 24% of the divergent fixations were achieved through unequal drift movements. Fixations where only one eye moved accounted for 57% of divergent fixations, and in 19% of the divergent fixations both eyes moved in different directions.

Does the direction of alignment at fixation onset affect the vergence movements that occur during fixation?

To address this question, the probability of making a vergence movement (either convergent or divergent) contingent upon start of a fixation alignment (aligned vs. unaligned) was initially investigated. The data showed that when the eyes were aligned, vergence movements occurred during 80% of all fixations; similarly vergence movements occurred during 78% of all unaligned fixations. In a second stage of analyses the probability of making a convergent movement during fixation, contingent on whether the eyes were aligned, crossed or uncrossed at fixation onset were compared. These analyses showed that the probability of making a convergent movement was modulated by the alignment characteristic at the start of fixation. Participants were found to converge their eyes during 74% of all fixations where the eyes were initially uncrossed at the start of fixation, 36% on those fixations when the eyes were crossed and 58% of those where the eyes were aligned. Further analyses compared the probability of making a divergent movement during fixation contingent on whether the eyes are aligned, crossed or uncrossed at fixation onset. The analyses showed that the probability of making a divergent movement was again modulated by the alignment characteristic of the eyes at the start of fixation. It was found that the two eyes made divergent movements during 34% of all fixations when the lines of sight were initially crossed at the start of fixation, 11% of those fixations when the eyes were uncrossed and on 22% of those fixations when the eyes were aligned. These data indicate that vergence movements were not random (see Figure 2.5) when participants were scanning the simple dot stimuli. Instead, to some extent, these movements were made in response to the alignment of the eyes at the start of fixation. In line with the data presented by Liversedge, White et al. (2006), it appears that when the two eyes are uncrossed at fixation onset, convergent movements serve to reduce the residual disparity that has occurred during the preceding saccade. Further when the two eyes are initially crossed at fixation onset divergent movements serve to align the eyes and reduce disparity.

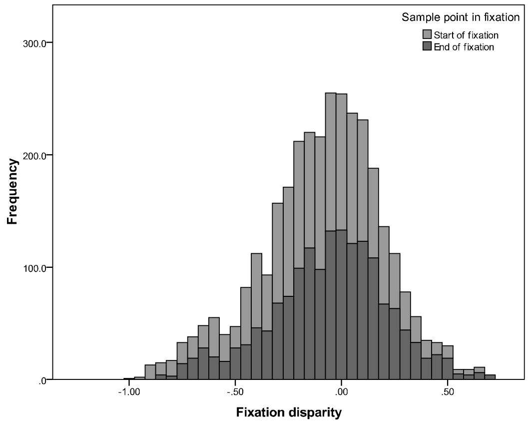

Figure 2.5

Distribution of start and end of fixation disparity, obtained during Task 1. A negative number represents an uncrossed fixation.

Does the horizontal extent of the target affect vergence movements that occur during fixation?

In all conditions, during fixation the two lines of sight were significantly more likely to converge (*Fs* > 25.0) than remain stable, drift or diverge. Further analyses determined that the horizontal extent of the target did not significantly affect the proportion of fixations where either a convergent movement was recorded (*F* (3, 24) =1.98, *p* = .14), or a divergent movement (*F* (3, 24) = 1.18, *p* = .34).

There were correlations between fixation duration and the left eye drift r = .18 (significant at .01 level) and the right r = .29 (significant at .01 level). These correlations indicate that rather than the amount of disparity at fixation onset driving these vergence movements it appears that the longer a target is fixated (regardless of the targets' horizontal extent) the greater the amount of vergence that occurs during fixation. Again these findings are consistent with Liversedge, White et al. (2006).

Is fixation disparity or the proportion of alignment affected by the preceding saccade amplitude or direction?

Recall that the third testing session (Task 3) involved the random presentation of a single dot task, and participants were required to fixate a dot presented along the horizontal axis at different degrees of eccentricity from the central fixation cross (5.5° or 2.1°). Further, these targets were presented to either the left or the right of the screen. There were, therefore, four possible positions in which the single dot target could appear and the spatial location of the presentation was randomised between trials. In line with the observed saccade asymmetry in the previous scanning task, the data acquired during presentation of single dot stimuli (see Table 2.4) show that the amplitude of the abducting eye was significantly greater than that of the adducting eye in relation to all target eccentricities (*F* (1, 8) = 1.84, *p* = .01). Thus, the pattern of saccade asymmetry was constant regardless of saccadic direction or distance.

To investigate the effect of saccade direction and distance on both fixation disparity and the direction of alignment, fixations on targets in each of four possible positions (far left, near left, near right and far right targets) were categorised. Far target fixations were preceded by a 5.5° amplitude saccade; near target fixations were preceded by a 2.1° amplitude saccade. The analyses were conducted on fixation onset data on the assumption that any influence of saccade amplitude upon fixation disparity would be more pronounced at fixation onset. The preceding saccade amplitude was found to significantly modulate the magnitude of disparity; the greater the amplitude of the preceding saccade the greater the magnitude of fixation disparity (*F* (1, 8) = 6.17, *p* = .04). However, the analysis showed that the direction of the preceding saccade had no reliable influence on fixation disparity (*F* (1, 8) = .10, *p* = .76).

Table 2.4.

Mean absolute fixation disparity and mean preceding saccade amplitude (in degrees).

Saccade direction	Distance to centre of target	Abducting eye saccade amplitude	Adducting eye saccade amplitude	Start of fixation absolute disparity
Left	5.5°	4.90°	4.83°	.26°
Left	2.1°	1.94°	1.87°	.21°
Right	2.1°	1.95°	1.80°	.22°
Right	5.5°	4.84°	4.56°	.27°

The influence of saccade direction and distance on the nature of fixation alignment was also assessed. The proportion of fixations that were aligned at the onset of a fixation were compared with the proportions of unaligned fixations. Further those fixations that followed a leftward or rightward saccade to a target that required a saccade of different amplitudes (5.5˚ or 2.1˚) were categorized. Perhaps unsurprisingly, given the previous findings, neither the proportions of aligned vs. unaligned fixations, nor the nature of the unaligned fixations (uncrossed vs. crossed) were modulated by the direction of the preceding saccade (*F*s < 1). However, there was a numerical trend in the data for a modulatory effect of saccade amplitude on fixation onset alignment proportions, where the proportion of aligned fixations was reduced following larger (5.5˚), than smaller (2.1˚) saccades (*F* (1, 8) = 4.77, *p* = .06). However, the proportion of those fixations categorized as unaligned was not affected by the increased saccade amplitude required to fixate the target (*F* (1, 8) = .10, *p* = .76); here, proportionally more unaligned fixations were uncrossed in comparison to crossed following either a large or small saccade. Again these findings are consistent with Liversedge et al. (2006).

Does parafoveal availability of a target during repeated saccadic movements influence binocular coordination?

In the second experimental task (Task 2, simultaneous presentation of two single dot targets), the aim was to assess whether binocular coordination was different for saccades that were repeated, and made to targets that were continually visually available in the parafovea (as contrasted to the saccades of a similar amplitude made to targets presented with sudden onset in various locations in Task 3). In this Task, participants were required to make repeated saccades between two dots to the beat of a metronome. Importantly, the two target dots were positioned horizontally 5.5° apart about the midline of the computer screen. This distance was selected to allow the direct comparison of binocular coordination under circumstances in which repeated saccades of similar magnitude were made between targets that remained on the screen at all times and binocular coordination that occurred after the 5.5° saccades to target onsets in the previous testing session. It was hypothesised that repeated saccades of similar magnitude between omnipresent targets may well result in reduced fixation disparity relative to saccades of similar magnitude made singularly to targets that appeared shortly before saccades were initiated. All valid fixations were included in the analyses.

Table 2.5

Mean alignment proportions at the start and end of fixation in both the parafoveal preview condition (where repeated saccades were made between two dots) and the target elicited saccade (where saccades were made to targets presented with sudden onset in various locations). Note all data is rounded to the nearest whole number.

		Aligned	Uncrossed	Crossed
End of fixation	Parafoveal preview	86%	13%	1%
	Target elicited	83%	9%	8%
Start of fixation	Parafoveal preview	73%	26%	0%
	Target elicited	80%	14%	5%

The analyses presented here compare the disparity magnitudes and the proportions of alignment at fixation onset. Fixation onset data were again used as it was anticipated that effects would be maximal at this sampling point. Analyses showed that the magnitude of fixation disparity was comparable regardless of whether saccades were made to single target onsets (μ= .23˚ SD = .14˚), or were directed repeatedly between targets that were continually available in the parafovea (μ = .22 SD .16˚) (*t* (8) = .90, *p* = .39). Furthermore, the proportion of aligned fixations at fixation onset (shown in Table 2.5) was not reliably different regardless of whether saccades were made to single target onsets, or were repeated between targets that were continually available (*t* (8) = 1.26, *p* = .25). Furthermore, for the unaligned fixations, the proportion of uncrossed fixations did not differ across these conditions either (*t* (8) = 2.09, *p* = .07; though the effect was marginal). Thus, it appears that binocular coordination was very largely constant under these different experimental conditions.

2.4 General discussion

During all the tasks and conditions, at the start of fixation all participants had, on average, .24° of disparity between the points of fixation of the two eyes. The eyes were more often aligned than unaligned (within one dot space, measuring .29°). However, if the eyes were unaligned during fixation they were more often uncrossed than crossed. This pattern of alignment is consistent with the reading data reported by Liversedge, White et al. (2006), Juhasz et al. (2006) and the adult data reported by Blythe et al. (2006). It was also found that during fixation, vergence eye movements frequently occurred, and these were typically in a corrective direction such that the average disparity between the positions of the two eyes was reduced to .20° at the end of a fixation. A key point arising from the current data is that, broadly speaking for adult skilled readers at least, patterns of fixations were not at all chameleon-like (c.f. King & Zhou, 2000). Such (consistent) patterns occurred even during these non-reading tasks where encoding of fine grain detailed visual information was not necessarily required in order to perform the task.

Despite there being a number of null effects in the current set of results[1], the findings are still informative for a number of reasons. Examining binocular coordination using novel manipulations in non-reading tasks provided an opportunity to ascertain the degree to which four basic visual characteristics of the stimuli

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modulated fixation disparities. The particular paradigms were chosen as they allowed for the examination of typical eye movement behaviour that occurs during scanning more generally, irrespective of cognitive influences. The experimental stimuli were manipulated in respect of four basic visual characteristics, namely, the horizontal spatial extent of the saccadic target, the direction and distance of target location from fixation, and the parafoveal availability of the target. It was of particular interest to examine whether binocular coordination during fixation was influenced by these factors as a systematic investigation during a general scanning task had not been conducted prior to the current study and, based on previous work, such factors were likely to modulate fixation disparity. Each one of these factors will now be discussed in turn.

The influence of the horizontal extent of the visual stimuli was examined. By increasing the horizontal spatial extent of the dot strings, the number of potential landing sites for each eye on the target was increased. Thus, potentially, there would be greater variability in the landing positions of each eye for targets with greater horizontal extent compared to those that were more horizontally localised. Consequently, it was reasoned that disparity, on average, would be greater for dot strings that were longer than for those that were shorter.

However, no evidence to suggest that the horizontal extent of the target influenced the magnitude or alignment (aligned, uncrossed or crossed fixations) of fixation disparity during scanning of simple dot stimuli was found. The disparity was comparable regardless of the horizontal extent of the string of dots to which the saccade was made. This finding tends to suggest that participants targeted saccades to one of the constituent dots within a multi dot string, rather than to the dot string as a whole (note that this is particularly likely since in one of the conditions, strings were comprised of just two dots). Furthermore, because disparity was similar regardless of the horizontal extent of the dot string to which the saccade was made, it appears that the specificity of saccadic targeting was similar in both eyes and the granularity of the precise saccade target remained constant regardless of the horizontal extent of the whole dot string. Clearly, if it had been the case that saccades in each eye were targeted independently to different sites within the dot string, then given that there are more potential landing sites on a long than a short target dot string, disparity at fixation onset would be greater for long dot strings than for short dot strings. This was not the case.

The influence of the parafoveal availability of the visual target along with the fact that participants were required to perform repeated saccades to these visual targets was also examined. Prior to the examination it had been considered likely that greater binocular coordination (i.e., reduced disparity) would be observed during saccades made repeatedly between two targets that were continually available within the parafovea, compared to saccades that were elicited by single targets that appeared at randomly allocated locations, such that parafoveal availability of the target was limited prior to a saccade. In a monocular eye tracking study, Lemij and Collewijn (1989) showed that repeated saccades between continually available targets were more spatially accurate than saccades made to target onsets with limited parafoveal availability. Analyses were conducted that assessed whether there was increased saccadic accuracy in terms of binocular coordination when targets were continuously available (and repeated saccades made between these) compared with single target onsets made to the same locations. No evidence was found to suggest that the magnitude of disparity at the start of fixation was any more reduced when repeated saccades were made to continuously available parafoveal targets, compared to saccades made to single target onsets. Fixation disparity metrics appear to be consistent across single target availability, and recurrent oculomotoric responses associated with repeated saccadic targeting of continuously available targets.

Presenting a saccadic target at one of four possible positions along the horizontal axis (a near or far target to either the left or the right of a centrally presented fixation cross), provided the opportunity to examine the influence of the target's location; specifically the direction and the distance of the stimulus from a given saccadic launch site. Given that findings have suggested that there is a positive relationship between saccade amplitude and the magnitude of fixation disparity at fixation onset (Collewijn et al., 1988, Liversedge, White et al., 2006; Nuthmann & Kliegl, 2009), the manipulation allowed for the assessment of the extent to which this effect occurred both for saccades made in a leftward as well as those made in a rightward direction. Any modulatory influence of saccade direction on disparity measures was deemed to be potentially very relevant to eye movement research in reading. The direction of saccades in reading can vary across languages; English is read from left to right and saccades are predominantly rightward, whereas, in Hebrew, where readers move from right to left, saccades are predominantly leftward. Note, however, saccades do also occur in the direction counter to that which predominates in a language (i.e. return sweeps and regressions). Furthermore, the frequency of regressive eye movements is somewhat increased for beginning readers and for those that find reading more challenging than skilled readers (e.g., dyslexic readers). Clearly, if fixation disparity is influenced by the direction of a saccade then this could mean that there would be systematic differences in binocular coordination both between different languages, as well as in relation to disrupted reading behaviour.

It was found that the amplitude of the preceding saccade consistently influenced binocular coordination; more specifically, that the greater the amplitude of the preceding saccade, then the greater the magnitude of subsequent fixation disparity. This was the case for single saccades to single dot targets and consecutive saccades made between multiple dot targets. The direction of the preceding saccade (i.e. whether to the left or right) did not influence binocular coordination. The current data demonstrate a clear relationship between the preceding saccade amplitude and the magnitude of the subsequent fixation disparity. This result is consistent with the findings of Collewijn et al., 1988, Liversedge, White et al., 2006 and Nuthmann & Kliegl, 2009, suggesting that fixation disparity during reading is visually based and reflects fundamental, low level, aspects of oculomotor control.

In the dot string scanning task (Task 1), the stimuli were specifically designed to require oculomotor control analogous to that which occurs during reading. The task required participants to make a series of rightward saccades and fixations on each of the dot strings in turn. Note, however, that since the stimuli were non-linguistic, the processes associated with written language comprehension were not engaged during fixation in the way that they are during reading. Thus, this particular task allowed for the examination of reading-like eye movement behaviour in the absence of linguistic processing. Furthermore, during the current experiments hardware and software were used for the acquisition and analyses of the eye movement data that were identical to those used in previous reading research (e.g. Blythe et al., 2006; Juhasz et al., 2006; Liversedge, White et al., 2006; Liversedge, Rayner et al., 2006). Thus, the consistency of experimental set up readily allows for comparison of the findings. Despite other differences across experiments (e.g., differing font sizes and viewing distances), the magnitude of fixation disparity demonstrated during the present non-reading tasks was quite similar to that observed in the reading research (Juhasz et al., 2006; Liversedge, Rayner et al., 2006;

Liversedge, White et al., 2006), and, in fact, identical to the adult data reported by Blythe et al. (2006).

Given the robust nature of fixation disparity observed during reading and during the current non-reading tasks, it appears that binocular coordination is strikingly similar, irrespective of whether saccades are programmed in relation to words during reading, or to dot strings during a simple horizontal scanning task. Again, the results are consistent with the suggestion that binocular coordination is not modulated by linguistic or higher level cognitive processing (Juhasz et al., 2006; Bucci & Kapoula, 2006).

However, although there is considerable agreement concerning the basic characteristics of binocular coordination across a number of reading studies (see Chapter 1, section 1.2 *Binocular coordination in non-reading tasks*), there is one aspect of these binocular findings that demands further discussion. In several studies different proportions of crossed and uncrossed fixations have been reported. Some studies have found crossed disparities to be prevalent (e.g. Kliegl et al., 2006; Nuthmann & Kliegl, 2009), while others have obtained a majority of uncrossed disparities (e.g. Blythe et al., 2006; Juhasz et al., 2006; Liversedge, Rayner et al., 2006; Liversedgee, White et al., 2006). However, it is clear that further investigation is required to determine the cause for the observed inconsistencies in the pattern of unaligned fixation data reported in the literature. To date, several suggestions have been proposed to account for this 'anomaly'. These have included issues of methodology such as the precise nature of the calibration procedure (See Chapter 1, c.f., Nuthmann & Kliegl, 2009), characteristics of the visual stimuli (e.g., the colour of the targets relative to the background; Kliegl et al. 2006), and individual differences (Jaschinski, Svede, & Jainta, 2008). Discussion of this issue will be deferred until the final Chapter of the Thesis.

In summary, the data reported here clearly show that basic visual characteristics of the stimuli have limited influence on binocular coordination in general saccadic scanning behaviour. Changes in disparity were associated with horizontal saccades for all participants and residual disparity was observed even at the end of a fixation. Thus, binocular fixation disparity (of a limited degree) is regularly tolerated during reading and non-reading tasks, and the visual system delivers a single unified percept despite differing degrees of retinal disparity across fixations. Similar binocular coordination was observed in the present non-reading task relative to that observed in investigations of reading. It appears, therefore, that cognitive or linguistic processing may not modulate aspects of binocular coordination (Experiment 3 was designed to address this issue). Rather, fixation disparity appears to occur as a consequence of low level oculomotor characteristics of the saccadic orienting system, such as the amplitude and degree of asymmetry associated with binocular eye movements during the generation of a saccade.

Chapter Three

Binocular coordination and dyslexia

To date the findings are mixed regarding the extent of visual processing deficits within the dyslexic population and whether these problems represent a cause, correlation or a consequence of the reading difficulties remains highly controversial. However, a body of evidence has accumulated over the past twenty years that has demonstrated that a number of visual processing problems are associated with dyslexia (see Farmer & Klein, 1995 for a review). While the majority of those researching dyslexia accept the notion that phonological deficits are prevalent in developmental dyslexia, some propose that poor phonological performance simply reflects poor performance more generally in terms of sensorimotor behaviour. For example, proposed areas of sensorimotor deficits include auditory (Tallal, 1980), visual (Lovegrove, Bowling, Badcock & Blackwood, 1980), and cerebellar/motor regions (Nicolson & Fawcett, 1995). But an alternative and more controversial theory of dyslexia is the magnocellular-deficit theory (Stein, 2001). This account of dyslexia takes the view that observed phonological and visual deficits are caused by a neurological impairment, whereby the magnocells in the sensory pathways are not functioning as they should. This is not specific to deficits in the visual modality (Stein, 2001).

It has been proposed that magnocells provide the main signals used to control eye movements occurring within the superior colliculus (Munoz & Wurtz, 1992; Sparks, 1986), the posterior parietal cortex (Stein, 1992), and the cerebellum (Rae et al., 1998). Described in these terms, the magnocellular-deficit hypothesis theory of dyslexia is suggested to have biological plausibility. Clearly without accurate, controlled eye movements, a steady visual percept may not be achieved. Stein (2001) suggested that appropriate magnocellular functioning is crucial to maintain stable binocular fixation. More specifically that unstable ocular dominance, which is suggested to be linked to inadequate vergence movements during fixation, plays a causal role in reading difficulties (Stein, Riddell, & Fowler, 1988).

There is a considerable amount of research which has investigated oculomotor control and dyslexia. Some of this research has indicated that dyslexic individual's exhibit substantially disrupted eye movements during reading, relative to that observed for skilled readers. However, this could merely reflect the individuals' difficulties in processing linguistic information; requiring more fixations, longer fixation durations, shorter saccades and more regressive movements. In non-reading tasks, however, the evidence for differences in oculomotor control between dyslexic and skilled readers is much less clear. Studies investigating binocular coordination and dyslexia will be discussed in greater detail later in this Chapter. First, binocular coordination in typically developing children is discussed.

Several studies have identified developmental changes in oculomotor control during reading (Buswell, 1922; McConkie et al., 1991; Rayner, 1986). It has been clearly shown that, as age and reading skill increase, fixation durations decrease saccade lengths increase, the number of fixations decreases, and the frequency of regressions and refixations decrease (Rayner, 1998). It is suggested that these developmental changes in eye movement behaviour largely reflect improvements in reading ability (Rayner, 1998). Interestingly, however, with only one year of reading instruction landing site distributions, which is the ability to target the eyes to an optimum position within a word, are equivalent for children and adults.

When children first learn to read however, there is substantial variability in their eye movement behaviour, which systematically decreases with increased reading ability. McConkie et al. (1991) speculated that the variability in eye movements result from differences in the strategies that children adopt when first learning to read. As they become more skilled, they converge on a common set of strategies.

3.1 Children's binocular coordination in non-reading tasks

Few developmental studies have focused on binocular control during non-reading tasks, perhaps this is due to the same assumption concerning adult binocular coordination during reading mentioned in Chapter 1. However, one such study reported in Yang, Bucci and Kapoula (2002) examined the latency of eye movements in three-dimensional space (version, vergence, and combined version-vergence). They found that the mean latencies for version, vergence, and combined eye movements were all longer for children compared to adults, and that the variability of the latency values was larger in children than in adults. Both pure and combined movement latencies gradually decreased with age, reaching adult levels roughly between the ages of 10 and 12.

Yang et al. (2002) also found that children tended to initially generate the vergence component when making combined version-vergence movements, whereas adults did not show a dominant pattern (the two systems were often initiated simultaneously). However, some similarities did exist between children and adults; for example, saccadic latencies were shorter when viewing was close (20 cm) than when viewing was distant (150 cm). The majority of children in the study also displayed the same pattern of vergence latencies as adults; convergence latencies were longer than divergence latencies.

These results support the suggestion that version and vergence generating mechanisms are distinct (see section *1.2 Binocular coordination in non-reading tasks* for a full description of version and vergence generation). Further, the results indicate that these distinct mechanisms mature progressively with age, perhaps in association with changes in central executive functioning (Yang et al., 2002). Perhaps the most important finding in this study was that the capacity for synchronisation of the two components of combined eye movements (parallel processing of sensory information of direction and depth) develops at a slower rate than maturation of the two components (vergence and version) separately; this synchrony was below adult levels even at age 12.

As demonstrated in Chapter 2, adults have disconjugate saccade metrics for the adducting and abducting eyes (also see Collewijn et al., 1988). Fioravanti, Inchingolo, Pensiero, and Spanios (1995) investigated developmental trends associated with disconjugacy of binocular saccades. Asymmetric movements of the adducting and abducting eyes were found for younger (5-9 years-old) and older (11-13 years-old) children as well as for adults. However, the pattern of asymmetry was reversed in younger children relative to older children and adults. Younger compared to older children displayed smaller amplitudes, smaller peak velocities, longer durations, and larger acceleration times for saccades of the adducting eye in relation to the abducting eye. As a consequence, young children's eyes tended to become converged during saccades. This was in contrast to the reversed pattern that occured in adults (Collewijn et al., 1988) and which Fioravanti et al. found in older children, that is, the abducting eye made the larger, faster saccade than the adducting eye. Subsequently, older children's and adults' eyes tended to become diverged during saccades.

Fioravanti et al. (1995) also assessed children's and adults' saccadic accuracy. Adults consistently undershot their target and made very small post-saccadic drift movements. Children in both age groups initially underestimated amplitudes of large target "jumps" and overestimated amplitudes of small target "jumps" (here "jumps" refer to movements of the target from one location to another). However, landing position error was consistently reduced during post-saccadic drift, similar to, but very often larger than the corrective movements carried out by adults. This indicates that saccade metric mechanisms were working as well in children as in adults. The initial overshoot of the saccade, in response to small target "jumps", was gradually reduced with age.

In Fioravanti et al.'s (1995) study, saccades were made at a viewing distance of 100 cm, yet Yang and Kapoula (2003) suggest a comfortable reading distance is approximately 30-40 cm. With this in mind, Yang and Kapoula (2003) examined the influence of viewing distance on the quality of binocular coordination of saccades (to LEDs) in children and adults. They used two distances: 20 and 150 cm. Children's binocular coordination of saccades was poor both during and after saccades, particularly in children aged 4-6 years old. Poor binocular coordination of saccades in children was distance dependent, such that saccade disconjugancy at the close distance was accentuated, amounting to 10% of the size of the saccade. This did not occur in adults. Yang and Kapoula attributed the distance-dependent disconjugacy to immaturity of cortical or subcortical saccade control rather than to some muscular difference in children and adults. The disconjugancy of saccades was dramatically reduced with age and eventually reached adult levels around the age of 10 to12 years old. The stability of the eyes after the saccade and the quality of binocular alignment during fixation, however, was poor in younger children regardless of the viewing distance.

3.2 Children's binocular coordination during reading

There are relatively few developmental studies of binocular coordination during reading. Bucci and Kapoula (2006) used binocular recordings (by way of electro-oculography) to evaluate the quality of binocular saccade coordination to single words and LEDs in normally reading children aged 7 years old, compared to adults. (Note that the recordings were of low resolution due to the manner in which eye movements were recorded.) The single word reading task involved fixating a cross on the left side of the screen, then sub-vocally pronouncing a word containing either 5, 7, or 9 characters, centrally presented, then fixating a cross on the right side of the screen. The LED presentation involved a standard paradigm; a target-LED jumped horizontally from 0º to 10º or 20º, leftwards or rightwards. Participants' performance was compared across the two tasks for rightwards saccades only.

Bucci and Kapoula (2006) found that the latency and coordination of binocular saccades were not influenced by the type of task; this was consistent with findings from Juhasz et al. (2006). They found that binocular control during isolated word reading was poor in children relative to adults, confirming and extending the findings of Yang and Kapoula (2003). Bucci and Kapoula suggested that Hering's law (1868, as cited in Howard, 1999), stating that the two eyes are well yoked because they receive equal innervation, is not always applicable during reading. Furthermore, they suggested that poor binocular control in children could interfere with learning to read and contribute to the long fixation durations observed in beginning readers.

Previous studies examining the coordination of the two eyes have rarely employed natural reading tasks. Thus, it is not clear that conclusions from these studies generalise to normal reading performance. One study designed to address this apparent gap in the literature was reported in Blythe et al. (2006). In this study the binocular coordination of children and adults during sentence reading was measured. The binocular eye movements of 12 adult and 12 child participants were recorded. The groups showed fixation disparity, both at the start and at the end of a fixation. Children, however, displayed greater disparity magnitudes than adults and a greater proportion of crossed fixations. Blythe et al. argued that the larger proportion of crossed fixations in children than adults was due to a pattern of asymmetric saccadic movements for the adducting and abducting eyes that was opposite to the one observed in adults. These data demonstrate that fixation disparity during processing of complex visual stimuli is similar to that observed in studies examining disparity during the processing of simple visual stimuli. Blythe et al. argued that the visual system is able to tolerate considerable disparity between the two retinal inputs and still achieve a unified percept during reading. This is particularly striking since the cognitive demands associated with reading are greater for beginning than for skilled readers; nonetheless, beginning readers tolerated a greater fixation disparity than skilled readers. Thus, this finding is consistent with others in which no strong relation has been found between text processing difficulty and the magnitude of the disparity observed during reading.

In Blythe et al.'s (2006) study, children exhibited a greater proportion of crossed alignments during fixations than adults, although still proportionally fewer crossed than uncrossed fixations. However, 42.7% of younger children's (7-9 years) unaligned fixations were crossed, compared to 35.9% of older children's (10-11 years) fixations. This demonstrates a developmental difference in the alignment of fixation disparity. These results are consistent with evidence for developmental trends in binocular coordination that are observed in non-reading tasks. As mentioned above, these studies have demonstrated that the amplitudes of the saccadic metric for the adducting and abducting eyes are reversed for younger children compared to adults (Fioravanti et al., 1995). This reversal in asymmetrical amplitude may contribute to the greater proportion of crossed fixations found in younger than in older children. Combining the results of Blythe et al. (2006) and Fioravanti et al. (1995), it appears that developmental changes in binocular coordination cannot be attributed solely to high-level cognitive processes that occur during reading, as the level of complexity of the visual stimuli differed in the two studies considerably. Rather, the differences appear to be due to low-level visual/ocular development. Thus, it appears that trends of maturation do exist in eye movement behaviour alongside cognitive development in terms of improvement in reading skill.

Again, it is worth noting that reading researchers have focussed on binocular coordination during fixations, rather than during saccades. Despite this, however, differences between adults and children appear to be highly consistent regardless of whether coordination is assessed by means of fixations or saccades. Younger children's eyes tend to become transiently converged during saccades and crossed disparity during fixations are observed, whereas older children's and adults' eyes become transiently diverged during saccades and uncrossed disparity during fixations are observe. Furthermore, developmental studies provide converging evidence that binocular coordination systematically changes with age and that both temporal and spatial coordination is poorer in children than in adults. Limited data also suggest that viewing distance modulates binocular coordination in children. Differences in binocular coordination (either conjugate or disjunctive movements) achieve adult levels at about 12 years of age. In real world viewing situations, most eye movements involve combined movements, responding to both depth and direction. The capacity to perform these movements in synchrony matures more slowly than the capacity to perform the individual pure movements. These developmental trends were observed in experiments using visual stimuli of differing levels of complexity and in tasks that involved the engagement of cognitive processes to differing degrees. Thus, it appears that age related differences in binocular coordination are not driven by cognitive development.

All of the studies discussed thus far have reported data from experiments in which binocular eye movement recordings were taken. The findings provide a coherent and consistent account of binocular coordination in children across different tasks. Studies that have examined binocular coordination in individuals with dyslexia, however, have often used quite different methods and therefore the same level of coherence in regard to this population is somewhat lacking; in fact, in many cases, eye movement data have not been recorded. Some confusion has arisen in respect to a suggested causal link between binocular coordination and reading difficulties. A lack of eye movement data directly measuring the binocular coordination system is, in part, responsible for some of this confusion.

3.3 Developmental dyslexia

Diagnosing dyslexia.

Given the appropriate tuition, most children find that the ability to read and write is a relatively straightforward process to learn. However, despite otherwise normal intelligence and educational opportunity, some children display a persistent difficulty in acquiring literacy skills. This may indicate that a child is dyslexic; however, identification is dependent on certain diagnostic criteria. The 1994 DSM-IV Criteria for Reading Disorder (dyslexia) are that: (a) reading achievement, as measured by an individually administered, standardised test of reading, is substantially below that expected given the person’s chronological age, measured intelligence, and age-appropriate education; (b) the disturbance interferes with academic achievement or activities of daily living that require reading skills; (c) if a sensory deficit is present, the reading difficulties are in excess of those usually associated with the specific sensory deficit.

The two criteria most commonly used, by both researchers and educators for diagnosing reading difficulties are: the ‘age-discrepancy’ and ‘IQ-discrepancy.’ Children who have a reading age below their chronological age, regardless of their general intelligence, are considered to be ‘age-discrepant’ readers. Children from this population of deficient readers are often referred to as ‘garden variety’ poor readers (Gough & Tunmer, 1986; Stanovich, 1988). Children who have a reading age below the level which is predicted for their level of general intelligence (IQ) are considered ‘IQ-discrepant’ readers.

Findings suggest that there are valid reasons to consider that dyslexia is a separate issue from poor reading (Badian, 2005). The majority of researchers investigating differences between typically developing children and children with dyslexia therefore consider the IQ-discrepant group to be the core dyslexic population (e.g. Ellis, McDougall & Monk, 1996). Furthermore, the IQ-discrepancy criterion is often used to diagnose children with specific reading difficulty (SRD). However, a proportion of these children will possibly have a reading ability above their chronological age, but below the predicted reading level for their IQ and Siegel (2003) suggested that these children should not be considered dyslexic as they seem not to have a problem with acquiring literacy; rather their performance is below that expected from their cognitive abilities more generally.

With limited special educational needs (SEN) resources available within schools, accurate diagnosis is necessary to enable appropriate individual educational plans (IEP) to be implemented. If IQ-discrepancy is the primary criterion used to diagnose dyslexia in the school environment, it is clear from Figure 3.1 (Stevenson, 2008) that the very worst readers would fail to be identified as dyslexic; rather their reading ability, albeit age-discrepant, is commensurate with their IQ. Therefore, their inability to acquire literacy skills would be considered due to their low general intelligence (IQ score). In contrast, basing a diagnosis on the age-discrepancy criterion, some children with a high IQ who are not reading to their full potential would fail to be identified as having reading difficulties.

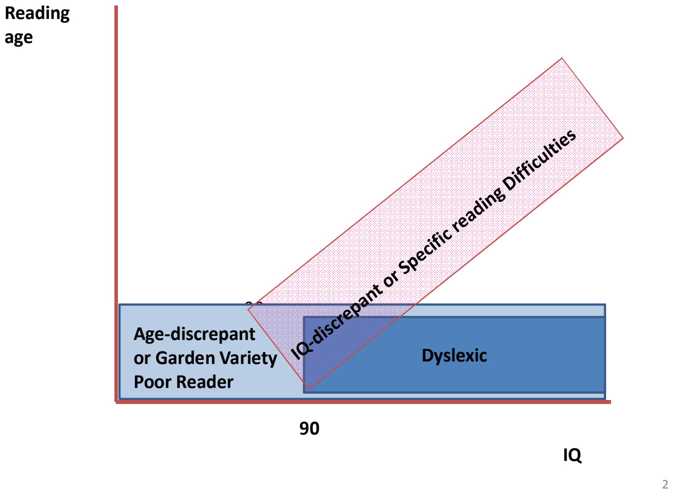

Figure 3.1

The general definitions of reading difficulties.

Clearly, these two methods of identification have weaknesses which make them somewhat inadequate as a reliable method by which to diagnose dyslexia. It is important to diagnose dyslexia at the earliest point, all children with dyslexia will benefit greatly if their disability is identified early enough to put the appropriate remediation in place. Therefore, more objective, early methods of detection have often been sought. The two most promising methods of early identification are genetic identification and measures of oculomotor behaviour. However, as yet, neither of these methods has proved to be a practical diagnostic tool.

The children with dyslexia that participated in the studies presented throughout this thesis had all received a prior diagnosis of dyslexia either through their school SEN resources or by Dyslexia Action, a dyslexia charity organisation. But, as described above, the criteria for diagnosing a child as potentially dyslexic can be unreliable as all the criteria listed in the definition at the start of the section are not always addressed. The studies conducted by Stein et al. are often criticised due to flawed participant selection; their samples of dyslexic children were generally selected from a population that had been referred to an ophthalmologist, as well as having demonstrated reading difficulties. For the current studies, it was considered necessary to adopt and adhere to more stringent recruitment criteria. As there was the possibility that the children involved in the current studies had been diagnosed with dyslexia based on different criteria, regardless of diagnosis, all participants completed a comprehensive battery of off-line measures (described in full in Chapter 4 (section 4.1 *Introduction).* These measures included tests of phonological skill, oral language skill, reading skill (including word recognition, non-word reading and reading comprehension) and orthographic ability.

Origins of dyslexia

Dyslexia is now generally considered to have a genetic origin. As early as 1950, Hallgren reported that more than 80% of children with dyslexia had other members of their family with the same disabilities. Evidence recorded from family and twin studies strongly suggests a genetic predisposition toward reading difficulties. Children with other family members with dyslexia are certainly more at risk of dyslexia compared to the general population (DeFries, Fulker, & Labuda, 1987). Furthermore, a child's reading ability is more severely affected when they have two parents diagnosed with dyslexia compared to a child with only one parent with dyslexia (Nopola-Hemmi et al., 2001).

With the advances in human genome research, geneticists are beginning to identify specific chromosomal loci associated with dyslexia-related phenotypes, which many researchers suggest contribute to the predisposition to dyslexia (Fisher et al., 2002; Londin, Meng, & Gruen, 2003; Taipale et al., 2003). However, identifying the 'dyslexic gene' has proven to be difficult; this is suggested to reflect the fact that reading is a complex task that involves many cognitive processes. Therefore, it is considered more likely that a complex interaction between several genes and the environment underlies developmental dyslexia (Stevenson, 2008).

There remains, however, no single unified theoretical account of dyslexia. As indicated above, this may be partly due to the fact that reading involves multiple cognitive processes and, as such, issues of heterogeneity are reflected within the dyslexic population. As mentioned earlier the most influential theory is the phonological-deficit theory of dyslexia (Liberman, 1973; Stanovich, 1988; Snowling, 2000). According to this view, dyslexia occurs as a consequence of cognitive deficits specific to the representation and processing of speech sounds (phonology). Good phonological awareness is crucial for accurate and fluent reading, and often young children with poor phonological awareness become poor readers (Bradley & Bryant, 1983). Both the children diagnosed with dyslexia and the “garden variety poor readers” (Badian, 1994) demonstrate poor phonological awareness. By improving children’s phonological awareness, improvements are observed in their reading skill regardless of an individual’s IQ (Hatcher & Hulme, 1999). Therefore, for many researchers, it follows that phonological deficit, or more specifically phonological awareness deficit, is the underlying cause of reading difficulties (e.g. Snowling, 1995; 2000; Stanovich, 1988). Difficulties in learning to read are indeed predominantly preceded by difficulties in pre-school rhyming tasks and acquiring speech (Bishop & Adams, 1990; Scarborough, 1990). The phonological awareness deficit is suggested to arise from a congenital dysfunction of the cortical areas responsible for phonological processing and reading (Galaburda, 1985; Paulesu et al., 2001; Temple et al., 2001). However, the precise nature of a phonological deficit and exactly how it disrupts normal reading acquisition is not fully understood. In addition to these issues, phonological awareness is suggested to develop with increased reading experience; therefore suggesting the two issues (reading development and phonological awareness) have a bidirectional relationship for very young children learning to read (Wagner & Torgesen, 1987). Thus it is difficult to disassociate cause from affect.

Subtyping dyslexic deficit profiles

The phonological-deficit theory, briefly discussed above, does not address the heterogeneity observed within the population of children with reading difficulties. As indicated above dyslexia is not considered to be a unified disorder; rather, a variety of deficits may underlie reading difficulties (e.g. Rayner & Pollatsek, 1989) and these specific deficit profiles have been the basis for sub-typing within the dyslexic population. In fact several studies have attempted to differentiate between subtypes of dyslexia associated with distinct deficit profiles (e.g. Baddeley, Ellis, Miles, & Lewis, 1982; Castles & Coltheart, 1993; Frith, 1985). There is a large body of experimental evidence that indicates developmental dyslexia exists in at least two subtypes (e.g. Castles & Coltheart, 1993; Manis, Seidenberg, Doi, McBride-Chang & Petersen, 1996; Murphy & Pollatsek, 1994). These two subtype profiles are seen to replicate the “surface” (orthographic) and “phonological” outline reported for patients that are diagnosed with acquired dyslexia due to stroke or head injury (Patterson, Marshall & Coltheart, 1985).

Accurate reading requires both the acquisition of good orthographic processing as well as good phonological processing (Castles & Coltheart, 1993). Orthographic processing allows the recognition and semantic identification of more familiar words through their visual form. When words are less familiar to the reader, reading is more dependent on their phonological form. This allows the reader to read using the sound represented by the parts of the word, down to individual letters, together with conversion laws and morphology that relates the sounds to meaning. Castles and Coltheart (1993) subtyped the dyslexic population on the basis of their ability to pronounce non-words (e.g. tuffel) and irregular words (e.g. yacht). This approach to subtyping was based on the dual route model of reading which proposes that word identification utilises a sublexical and lexical route during reading, as illustrated in Figure 3.2.

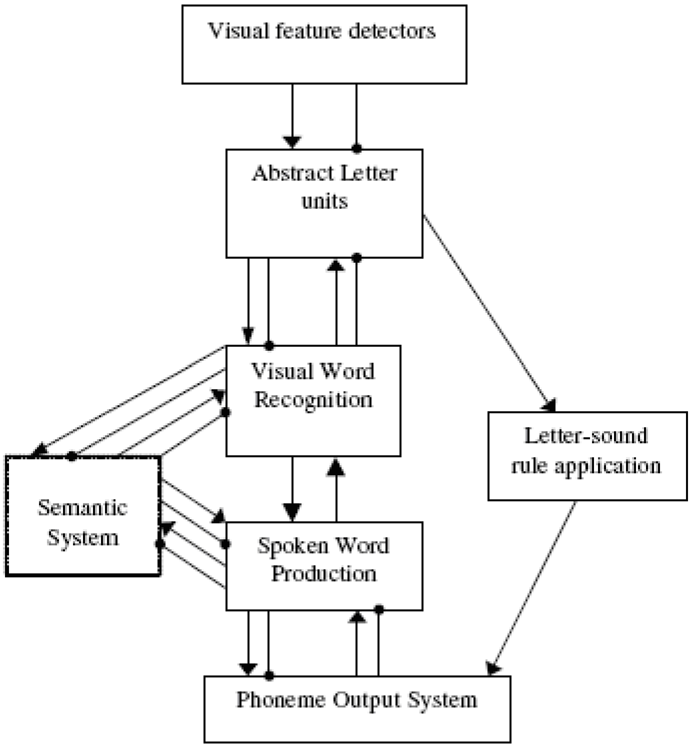

Figure 3.2.

The dual route model of reading (Coltheart et al., 2001)

Two main subtypes were thus identified. The *Phonological* dyslexic group was characterised as finding non-word reading difficult; suggesting a sublexical deficit. The *Surface* dyslexic group was characterised as finding irregular or exception word reading hard, reflecting a possible lexical processing deficit. Castles and Coltheart proposed that the dyslexic population would also contain a third subgroup which would reflect both sublexical and lexical deficits and find both irregular word and non-word reading hard; this group was referred to as the *Dysphoneidetic* dyslexic group.

Other studies have aimed to categorise dyslexic subtypes by the speed and accuracy of the spoken word production they achieve while reading. Van Strien, Bouma and Bakker (1993) subtyped dyslexic readers again into two main groups. The dyslexic readers that displayed a fast reading speed with low levels of reading accuracy, were referred to as the *Linguistic* group and those who displayed a slow reading speed with high levels of accuracy, were referred to as the *Perceptual* group. Van Strien and co-authors also suggested that there might be a third group within the dyslexic population which would display all the proposed characteristics of both main subgroups: slow reading speed and low accuracy levels. This group was referred to as the *mixed* group.

3.4 Deficits in the magnocellular system

The magnocellular account of dyslexia takes the view that the observed phonological and visual deficits in dyslexia are caused by a neurological impairment, where the magnocells in the sensory pathways are not functioning as they should. Note, that the magnocellular account is not specific to deficits in the visual modality (Stein, 2001).

The suggestion that perception is achieved via (at least) two distinct, visual pathways is nothing new (for a review see Milner & Goodale, 1995). The two main retino-cortical parallel pathways are referred to as the parvocellular or P-stream and the magnocellular or M-stream. The magnocellular stream extends via the dorsal pathway, which connects V1 with the posterior parietal lobe. This pathway receives input from both rods and cones across the retina; M-cells have receptive fields that are approximately twice the area of P-cells at any retinal eccentricity, so contrast sensitivity is consistent over the visual field and therefore, M-cells are less affected by retinal eccentricity (Croner & Kaplan, 1995). The magnocellular stream extends from ganglion cells into the two distinct layers of the lateral geniculate nucleus (LGN) and further projects via the visual cortex where the dorsal stream extends to the parietal cortex. M-cells have large cell bodies and are sensitive to low contrast, high temporal frequencies and therefore, are most adept in detecting motion. Cells within the dorsal pathway however, also respond to static objects, which enables one to grasp, and reach for objects with great accuracy. The dorsal pathway is adept at detecting the position and movement of objects in the visual field and analyses visual input in relation to guiding motor behaviour to respond to the environment or objects within it. Therefore, this pathway is often referred to in the literature as the "where" or, more recently, the “how” pathway (Milner & Goodale, 1995; 2008).

The second visual system, the parvocellular or P-stream extends from the retinal ganglion cells to the smaller cell bodies of the four distinct layers of the LGN. This pathway projects via the visual cortex along the ventral pathway to the inferotemporal cortex. The ventral pathway is sensitive to higher spatial frequency and receives input predominantly from cones. The parvocellular stream receives visual input mainly via the fovea; sensitivity, therefore, decreases dramatically with greater retinal eccentricity of the visual stimuli, i.e. parvo-cells are less sensitive to stimuli that are presented in the periphery. This pathway is primarily responsible for analysing the visual input in relation to recognition and identification. The ventral pathway is adept in the detection of fine spatial details and colour vision. There is, however, considerable interaction between these two parallel pathways (Milner & Goodale, 1995; 2008).

Differences in neuronal anatomy.

Methods of identifying neuronal anatomy such as computed tomography (CT) imaging, magnetic resonance imaging (MRI) as well as post-mortem studies have demonstrated differences between typically developing and dyslexic readers. The area of the brain most frequently investigated is the planum temporale, which is a language-related brain area situated in the posterior temporal cortex. The area is usually larger on the left than the right side of the brain. However, some researchers have found it to be larger on the right than the left in dyslexic brains (Hier, Le May, Rosenberger, & Perlo, 1978) or symmetrical between the two sides (Haslam, Dalby, Johns, & Rademaker, 1981). Anatomic evidence found in support of the magnocellular deficit theory of dyslexia, has identified smaller, less organised cell formations in the magnocellular layers of the LGN for dyslexic readers compared to controls (Galaburda, 1993a, 1993b; Galaburda, Sherman, Rosen, Aboitiz & Geschwind, 1985). Recordings of visual evoked potential (VEP) responses have also found patterns of responses for dyslexic compared to control participants which were consistent with an impaired M-cell function within the visual system (Livingstone, Rosen, Drislane, & Galaburda, 1991). Orthographic decoding has also been found to correlate with VEP responses believed to represent dorsal pathway functioning (Kinsey, Hansen, & Chase, 2006).

Differences detected during functional neuroimaging.

Converging evidence has accumulated from a number of neuroimaging studies employed to investigate sensory and language processing in dyslexia. Eden and Zeffiro (1998) argue that theories of dyslexia, which involve dysfunction of the temporoparietal sites of the brain, are the strongest. Temporoparietal areas of the brain originate (predominantly) from the magnocellular layers of the LGN. Studies using functional magnetic resonance imaging (*f*MRI) have found a reduced activation in MT/V5, an area of the brain suggested to be dominated by magnocells (Demp, Boynton & Heeger, 1997). One further study found a correlation between the amplitude of activation in the *f*MRI signal change in MT/V5 and reading ability (Demp, Boynton, & Heeger, 1998). While Eden et al. (1996) also found differences in activation of MT/V5 between groups of dyslexic and typical readers, these differences were only demonstrated for moving stimuli. When the visual stimuli were static the activation was equivalent between these two groups. Studies which have used phonological tasks have also found decreased activation of the temporoparietal area for dyslexic compared to typical readers (Heilman, Voeller, & Alexander, 1996; Horwitz, Rumsey, & Donohue, 1998; Shaywitz et al., 1998). Pugh et al., (2000) suggest that temporoparietal circuits are associated with “rule-based” analysis and learning. More specifically they suggested this neural network was responsible for constructing and representing the relationship between grapheme (orthography) and phoneme (phonology); which provides a highly integrated representation of a word.

Differences detected during visual psychophysical tasks.

Psychophysical tests designed to investigate deficits within the M-stream generally have used flickering or moving stimuli, which are presented at low contrast and low spatial frequency. Studies using these paradigms have found that greater differences in stimulus amplitude and frequency are required by dyslexic readers before changes can be detected than is the case for typical age equivalent readers (Chase & Jenner, 1993; Martin & Lovegrove, 1984, 1987; Mason, Cornelissen, Fowler & Stein, 1993; Sperling, Lu, Manis & Seidenberg, 2003). Correlations between reading ability and coherent motion detection (Cornelissen et al., 1994; 1998) and velocity discrimination (Demb et al., 1997; 1998) have been reported. More specifically, Sperling et al. (2003) identified the individual factors associated with reading and demonstrated a correlation between orthographic processing and M-cell functioning. Correlational investigations, however, do not provide evidence of the nature of any relationship between M-cell functioning and reading. Furthermore, there are a number of studies which have failed to find magnocellular deficits in groups diagnosed with dyslexia (Ramus et al., 2003; Spinelli et al., 1997; Williams, Stuart, & Castles 2003). Nevertheless, taken together, these independent lines of research provide some indication that magnocellular functioning is somewhat disrupted for dyslexic readers. However, what is not immediately clear is how a deficient M-stream affects reading ability.

3.5 How might magnocellular deficits affect reading?

In a review of M-stream deficits and the visual processes associated with reading, Boden and Giaschi (2007) review seven hypothesized aetiologies of reading difficulties associated with a deficient M-stream. Stein's suggestion of unstable binocular fixation was one of the hypotheses reviewed in the paper. Stein suggested that unstable ocular dominance, which he linked to binocular coordination, more specifically the accuracy of vergence movements during fixations, plays a causal role in reading difficulties (Stein et al., 1988).

Clearly, adequate eye movement control plays an integral role in reading fluency (Rayner, 1998). Any disturbance to the typical pattern of eye movements during reading (i.e. highly stylised saccades and fixations) may well result in a disruption to an individual's reading rate. There are various models of eye movement control during reading; the two most influential being the E-Z Reader model (Pollatsek, Reichle, & Rayner, 2006; Reichle, Pollatsek, Fisher, & Rayner, 1998) and SWIFT model (Saccade-generation with inhibition by foveal targets; Engbert, Longtin, & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl, 2005). An important factor, which distinguishes the E-Z Reader from the SWIFT model, is the perspective the models take on the issue of serial or parallel processing during reading. Purely to allow the reader to understand what is involved in modelling oculomotor behaviour during reading, a very brief outline of the E-Z Reader model is included.

The E-Z Reader model is a sequential attention shift (SAS) model and assumes, based on Morrison's (1984) model, that covert shifts of attention and oculomotor control are determined by successful lexical activation; indicating that eye movements are under direct cognitive control. The model suggests that when one reads, word recognition is completed sequentially throughout the sentence. To be clear, the E-Z Reader model proposes that when a word is first fixated the focus of attention and the focus (or fovea) of the eyes are at the same spatial location. During this initial stage of word processing the visual characteristics of the text are encoded and lexical identification begins. At a certain stage of lexical identification the focus of attention shifts to the next word in the sentence (n+1). However, the eyes continue to fixate the same location during this period, when attention and fixation are dissociated in this way, parafoveal processing of word n+1 begins and the subsequent saccade is programmed. If n+1 is a short word, of three letters or less, the limited parafoveal processing is, at times, adequate to identify the word and a saccade is programmed to the subsequent word in the sentence (n+2). The covert allocation of attention and low-level parafoveal processing presumably increases reading rate. To the extent that attention and eye movements are very closely related, both in relation to each other and in relation to psychological processes associated with reading, this brief discussion of a model of eye movement control during reading should provide insight as to how motoric control of the eyes is important in reading. It is this link that is central to the magnocellular deficit theory of dyslexia.

Experimental work examining the magnocellular deficit theory of dyslexia has typically examined ocular dominance in relation to reading ability. Researchers proposing this hypothesis suggest that unstable binocular coordination, arising from a lack of dominant eye and/or poor vergence control, precludes the correct encoding of the letters or the order of letters within the word (Stein & Fowler, 1993; Stein, Riddell & Fowler, 1988, 1989; Stein, Talcott & Walsh, 2000; Stein & Walsh, 1997). Following this theory visual confusion and the mis-ordering of letters arise from an inability to fuse two conflicting retinal inputs during fixation, this leads to an alternating perception of the order of the letters within a word. In addition to this, psychophysical data indicate that the magnocellular system is important in the allocation of attentional resources (Omtzigt & Hendriks, 2004); attention shifts covertly prior to an overt attentional shift during an eye movement (Deubel & Schneider, 1996; McPeek, Maljkovic, & Nakayama, 1999; Shepherd, Findlay, & Hockey, 1986). This shift in covert attention provides the oculomotor system with spatial information required to locate the subsequent word in a sentence within the fovea (reviewed in Rayner, 1998).

3.6 Dyslexic individual's binocular coordination in non-reading tasks

Some researchers have suggested that atypical development of eye dominance is related to the ability to maintain a steady visual percept, and that this influences reading ability (Bigelow & McKenzie, 1985; Cornelissen, Bradley, Fowler, & Stein, 1992; Cornelissen, Munroe, Fowler, & Stein, 1993; Stein & Fowler, 1992; Stein et al., 1986; 1988). Very few studies, however, have directly recorded binocular eye movements during both reading and non-reading tasks. The majority of research on binocular control and dyslexia has used a reference eye test called the Dunlop Test (Dunlop, Dunlop & Fenelon, 1973) or a similar methodological paradigm, the Tranaglyph (see Bigelow & McKenzie, 1985).

In the Dunlop Test (DT), a participant views two slides (Clement Clark fusion slides F69 and F70) simultaneously, one with each eye, through a synoptophore. Both slides depict a house; one slide displays a small tree on one side of the door and the other slide displays a large tree on the opposite side of the door. Other than this difference, the slides are identical and when they are viewed dichoptically the door is in the centre of the visual field, with the large tree on one side and the small tree on the other. The experimenter then adjusts the synoptophore such that the two slides are slowly drawn apart while the participant fixates on the door. At some point, fusion is broken; immediately before this occurs, most individuals report that one of the two trees moves. The tree that does not move is the stable image and the consistency with which the stable image is associated with one of the two eyes determines the stability of ocular dominance.

The nature of the proposed relation between unstable ocular dominance and binocular coordination is not entirely clear. Some researchers argue that children who lack a stable dominant eye are unable to make adequate vergence movements to maintain a fused percept. The Dunlop test is used to assess the stability of ocular dominance, which, in turn, indexes vergence capabilities required for fusion. A serious concern regarding this methodological approach is the extent to which subjective reports on the Dunlop test (DT) adequately reflect natural and spontaneous vergence movements that occur during fixations in reading. Furthermore, it is important to consider studies examining relations among stability of ocular dominance, poor binocular coordination, and dyslexia, within the context of recent binocular research for adults and typically developing children (discussed in Chapter 1 and earlier in this Chapter) that have directly measured binocular eye movements during reading. Recall that typically developing children (as well as adults) exhibit considerable fixation disparity. Thus, binocular alignment is far from perfect during reading in non-dyslexic populations; the two eyes often fixate different letters within a word. This research, therefore, has clear implications for claims that poor binocular coordination has a causal role in reading difficulties. This is particularly true since much of the work described above has not actually monitored binocular eye movements.

Bishop, Jancey, and Steel (1979) reported a longitudinal study in which the DT was administered to assess eye dominance development. They tested 147 children around eight years of age. Off-line measures of reading ability and intelligence (IQ) were administered. Bishop et al. found no significant difference in reading ability between those children with a stable dominant eye and those without, when IQ was controlled. Further analyses showed no eye-dominance differences between a group of 17 poor readers (those reading 15 months below the expected level for their age) and an IQ matched control group with age appropriate reading ability.

Other studies, however, have found results consistent with a relation between eye dominance and reading performance (Stein et al., 1986; 1988; see also Cornelissen et al., 1993). Stein et al. (1986) reported a strong relation between age and performance on the DT. The proportion of children with stable ocular dominance increased steadily from 52% in 5 year-olds to almost 90% in 10 year-olds. Further, they found that participants who achieved stable ocular dominance were reading, on average, 6.3 months ahead of those who had not. Stein et al. argued that these differences in eye dominance reflected unstable binocular fixation, which he suggested related to successful reading development. Recall that Stein et al. argued this was a consequence of abnormal magnocellular function. More specifically, Stein et al. suggested that appropriate magnocellular functioning was crucial in maintaining a stable binocular fixation on small targets and was also necessary to prevent unintended eye movements that lead to visual confusion, blurring, broken and mis-ordering of letters. They suggested that visual confusion arises from an inability to fuse disparate patterns of retinal stimulation (Cornelissen et al., 1993), or alternatively, from fluctuating eye dominance leading to alternating perceptions of a word (Stein, 2001). To reiterate, cells involved in maintaining stable binocular visual fixation are located in the superior colliculus (Munoz & Wurtz, 1992), which is dominated by magnocells.

Stein, Riddell, and Fowler (1988) recorded binocular eye movements as an objective measure of fixation stability during two synoptophore vergence tests (one in which visual slides subtended 2.5 degrees – standard DT conditions, and the other in which the slides subtended 7 degrees). Over a period of three months, children between the ages of 8 and 11 who had a reading level 2 standard deviations below that expected for their age and IQ were recruited. Participants were asked to fuse the picture and maintain this fused state for as long as possible as the synoptophore tubes were abducted or adducted (at a rate of approximately .5° per second). Participants pressed a key as soon as they experienced diplopia (double vision). Stein et al. recorded eye movement data during trials of both the 2.5 and 7 degree synoptophore tests. The control group made convergent and divergent eye movements as appropriate under test conditions. By contrast, dyslexic readers with unstable ocular dominance made more inappropriate conjugate eye movements than the group of normal readers. This difference was particularly pronounced when participants tracked small compared to large targets (though no formal statistical analyses were reported in the paper).

Visual instability in dyslexia, caused by deficient oculomotor control, was investigated by Fischer and Hartnegg (2000). They reanalysed data from a previous study to assess stability of fixations, as measured by the number of intrusive saccades (unnecessary rapid shifts in eye position) during periods when participants fixated on a stationary target. Dyslexic and non-dyslexic children, between 7 and 17 years of age, had simultaneous horizontal eye movements of both eyes recorded using an infrared-light reflection method. With the exception of the group aged 7-8, all of the dyslexic children generated more intrusive saccades than non-dyslexic children. Furthermore, the difference between the groups increased with age; dyslexic participants showed a systematic lag in the development of fixation stability. Note, however, that no aspects of binocular coordination were analysed even though binocular eye movements were recorded.

Dyslexia and fixation disparity were also the focus of an investigation conducted by Jaschinski, König, Schmidt, and Methling (2004). The participants were dyslexic and typically developing children aged 7–16. The sample of 50 children was comprised of 30 dyslexic participants, who had both reading and writing disabilities, and 20 typically developing children. A psychophysical measure of fixation disparity was determined by the use of dichoptically presented nonius lines. In the nonius line-test of disparity, the observer views two dichoptically presented vertical lines, one above the other. Participants adjust the lines in the horizontal plane until they appear collinear (vertically aligned); any stimulus offset that remains indexes fixation disparity. An alternative method that is sometimes employed involves the brief presentation of pairs of nonius lines. Participants make a forced choice (collinear or not); again, the offset at which participants report collinearity indexes disparity.

Jaschinski et al. employed central fusion stimuli, consisting of 5 squares, that were presented dichoptically by means of shutter goggles with 0.5° disparity. After 400 ms, two dichoptic nonius lines (each visible to only one eye) were presented for 80 ms, one above and one below the central stimulus. The amount of horizontal offset between the lines was varied in a step procedure designed to initiate corrective vergence eye movements. Participants indicated whether the lines appeared collinear. The experimental procedure included 30 trials in which the squares required a convergent movement to attain fusion and 30 in which a divergent movement was required. Nonius line collinearity judgements indexed the magnitude of vergence movement. Jaschinski et al. used this method to estimate vergence velocity and found more children with large amounts of variability in the dyslexic than the control group. This, in turn, led to a mean fixation disparity for the dyslexic group that was 0.3 minutes of arc larger than for the typically developing group. Jaschinski et al. concluded that dyslexic readers had significantly worse binocular coordination than typically developing children, though they also suggested that further research is needed to investigate the temporal and spatial characteristics of vergence movements during fixations with respect to dyslexia.

Bigelow and McKenzie (1985) used a Tranaglyph, rather than a synoptophore, to assess the association between unstable ocular dominance and reading ability. Note, however, that similar principles underlie the two methods. In the Tranaglyph test, two slides, one green and one red, are viewed through glasses with red and green lenses. The two slides form a picture, or in this case, letters and blobs subtending 2.5° of visual angle, when they are overlaid and viewed binocularly. The green section of the image stimulates the right eye (wearing the red lens) and the red section stimulates the left eye (wearing the green lens). The two slides are gradually moved apart and vergence eye movements are required to maintain a fused percept. As with the synotophore test, one of the coloured sections seems to move prior to a break in fusion. The coloured section that remains constant indicates the dominant eye. Bigelow and McKenzie tested two groups of children, consisting of good and poor readers. An IQ discrepancy criterion was used to define poor readers (i.e. reading at least 17 months behind the expected level for their IQ); thus, poor readers were, on average, 2.1 years older than good readers. Stability was assumed when the same eye was dominant on 80% or more of trials and unstable dominance was assumed when the same eye was dominant on fewer than 80% of trials. In line with findings from Stein et al. (1988), Bigelow and McKenzie observed increased unstable eye dominance in poor compared to typically developing readers. Bigelow and McKenzie did not argue that this relation was causal; instead, they argued that the process by which ocular stability is operative requires further explication before a causal relation may be assumed.

A recent study by Kapoula et al. (2007), investigated binocular coordination in groups of dyslexic and non-dyslexic children. The children, aged 9 to 13, were assessed on several different aspects of their vergence capacity by way of orthoptic tests. The near point of convergence was determined by presenting a small pen light in the midplane of the participant’s binocular visual field. This was slowly moved nearer to the participant’s eyes until one eye lost fixation. They found that dyslexic children were less able to converge their eyes onto points very near to their face than were non-dyslexic children. Non-dyslexic children converged their eyes on the pen light when it was held as close as 6 cm or less. Dyslexic children, however, lost fixation when the pen light was around 7-10 cm in front of their eyes. A second test assessed vergence capacity using prism bars. Participants were shown a small letter, presented at a far distance (400 cm) or a near one (30 cm). The prism was placed in front of one eye and the convergent/ divergent power of the prism was increased until the participant reported blurring or diplopia. The maximum prism power at which clear single vision was recovered represented the maximum relative convergence or divergence capacity. Kapoula et al. found no significant vergence capacity difference between the two groups, for near or far targets. They did, however, demonstrate a divergence limitation for the dyslexic children, for both near and far targets. The dyslexic children had a 6 prism diopter reduction in their divergence capacity at both distances compared to the non-dyslexic children.

It is important to consider these results in the context of studies that have examined vergence during fixations in reading. As discussed in earlier sections, vergence movements during fixations tend to be corrective for the residual disparity from the preceding saccade (Blythe et al., 2006). Specifically, children tend to make divergent movements during fixations, whereas adults make convergent movements. If children with dyslexia are poor at making divergent movements, as found by Kapoula et al. then they might be less effective than typically developing children at reducing disparity during fixations in reading.

Many researchers have questioned the causal link between unstable eye dominance and dyslexia. For example, Bishop (1989) reviewed Stein and colleagues' work and suggested that experience with reading text affects performance on the DT. It should be noted that unstable ocular dominance has been demonstrated in many participants with excellent reading and spelling abilities. This poses a problem for those who argue that lack of fixed reference on the DT is causally related to reading difficulties (Lennerstrand, Ygge, & Rydberg, 1994; Newman et al., 1985).

A longitudinal study was conducted by Lennerstrand, Ygge and Jacobson (1993) to assess whether poor binocular coordination accurately predicts later reading ability. They compared good and poor readers before poor readers were diagnosed as dyslexic (Lennerstrand et al. 1993) and reanalyzed the data from 40 of the original participants once they received a diagnosis (Lennerstrand, Ygge, & Rydberg, 1994). Ophthalmological evaluations were conducted when the children were between 8 and 9 years of age. The sensory tests included an ocular dominance test with a synoptophore. Here, (in line with Stein & Fowler's, 1982, methodology), the images were gradually drawn apart until a single image was no longer perceived. The children indicated when they were no longer able to fuse the disparate images and diplopia occurred.

In addition to participants' subjective reports, binocular eye movements were recorded from children aged 8-9 and 11-12. Eye movement recordings allowed for the assessment of vergence movements that occurred during the presentation of the synoptophore test. With regard to binocular coordination, Lennerstrand et al. reported no significant group differences (dyslexic compared to typically developing children) for stable or unstable ocular dominance. Furthermore, no significant group difference was found in vergence fusion capacity for images extending 2.5° of visual angle in either age group. For images subtending 7.5° of visual angle, no group difference was found for children in the 8-9 age range; however, 11-12 year old dyslexic children had a higher capacity for divergence than typically developing children of the same age. Note that this finding is opposite the pattern reported by Kapoula et al. (2007). Kapoula et al. found that dyslexic participants of similar age were limited in their capacity for divergent eye movements. Lennerstrand et al. (1994) proposed that the discrepancy between their findings and those of Stein et al. (1986) might reflect differences in participant selection procedures. Lennerstrand et al.'s sample differed only with respect to reading capacity not with respect to socio-economic status, visual problems, or intellectual ability.

With these studies in mind, it is at least possible, and some may argue probable, that unstable ocular dominance may prove to be a correlate of dyslexia rather than a causal factor in reading difficulties. Clearly, however, a considerable amount of further research providing accurate binocular eye movement data regarding small vergence movements during fixations is needed before the suggestion that visual abnormalities cause, or are co-existent with dyslexia, can be instantiated or rejected.

From the studies reviewed here, it is clear that results in this area are highly contradictory. Some studies have found a link between poor binocular coordination and reading difficulties in dyslexia (Bigelow & McKenzie, 1985; Kapoula et al., 2007; Stein et al., 1986; 1988; Jaschinski et al., 2004), whereas others have not

(Bishop et al., 1979; Lennerstrand et al., 1993; 1994). It is, therefore, very difficult to draw strong conclusions in favour of, or against, the claim. What one can do, however, is consider why the results in this area have been so inconsistent. An important point in relation to this question is that only three of these studies actually recorded eye movements; all of the other experiments used tasks in which aspects of binocular coordination were inferred without actually measuring the positions of the eyes. Three studies used the Dunlop Test, one used nonius lines, and the other used a prism test. The validity of the DT for assessing binocular coordination is questionable. The nonius line task provides accurate information about binocular alignment (Jainta, Hoormann, & Jaschinski, 2007), but the task may be different enough from normal reading that findings do not generalise to binocular coordination during reading. A similar argument may be levelled at the method of prism assessment. Overall, the data are suggestive of some correlation between dyslexia and vergence control in some participant populations. However, a causal link between reading difficulties and poor binocular coordination has not been compellingly demonstrated.

3.7 Dyslexic individual's binocular coordination during reading

As mentioned in Chapter 1, the two binocular visual inputs must be successfully fused for a single visual percept to be formed (Liversedge, Rayner, White, Findlay & McSorley, 2006). Thus, Cornelissen, Bradley, Fowler, and Stein (1992) asked children to read single words with both eyes open and then with one eye occluded to investigate the effect of unstable binocular control on reading. They reasoned that monocular viewing would remove any visual confusion stemming from poor integration of the two retinal inputs. Children were asked to read two lists of single words (presented in the form of a paragraph) that were matched for length and difficulty. Cornelissen et al. predicted that children who failed the DT would make fewer reading errors (i.e., accurate recognition of words) when they read with one eye occluded than when they read binocularly. Children with unstable binocular control made fewer non-word reading errors for monocular than binocular viewing of the text. Cornelissen et al. (1992) concluded that failure to successfully integrate the two retinal inputs caused visual confusion and led to the non-word reading errors made by dyslexic readers. They suggested two possible ways in which binocular coordination may not compensate adequately for visual disparity between the two inputs in participants who fail the DT. First, the fusion system may not establish correspondences between the two disparate retinal inputs; hence, fusion may not be achieved. Alternatively, confusion may occur regarding the direction of vergence movements in order to correct for fixation disparity.

In a follow up study, Cornelissen, Munro, Fowler and Stein (1993) addressed these possibilities by monitoring participants' binocular eye movements as they read lists of single words presented as paragraphs. They found that adults had significantly smaller disparity magnitudes (or "vergence errors", to use their terminology) than children aged 9-11. Typically developing children had, on average, fixation disparity of 0.12° (SD .12°); non dyslexic adults had, on average, fixation disparity of 0.08° (SD .06°). However, no difference in the disparity magnitude of fixations was found between groups of children who passed or failed the DT. Cornelissen et al. concluded, therefore, that poor vergence control during reading fixations was not the primary cause of the non-word reading errors that they had demonstrated in children who failed the DT.

Cornelissen et al.'s (1992) suggested that a brief period of monocular occlusion may prove beneficial to children with reading deficits. This was confirmed in a study by Stein, Richardson and Fowler (2000). Children who failed the DT later acquired a stable dominant eye (as assessed by the DT) after wearing glasses to occlude one eye during reading for a period of 9 months. Those children who gained a stable dominant eye as a consequence of the monocular occlusion intervention (64%) showed significant improvement in reading ability compared to children who did not receive the intervention. Stein et al. argued that improvements in reading ability were a consequence of gaining a stable dominant eye, which lead to greater binocular control during fixation. However, the results also showed that 54% of the children who did not receive the occlusion intervention also obtained a stable dominant eye within the time frame of the study.

Again, the data from these studies are far from compelling with respect to a causal relation between binocular coordination and dyslexia. Some researchers suggest that binocular instability (or the lack of a stable dominant eye) brings about visual confusion, whereas others argue that this is not the case. The theory is supported with evidence from intervention studies. However, the number of dyslexic children with unstable ocular dominance is unclear as is the nature of the relation between visual deficits and dyslexia. In studies that have controlled for IQ differences between dyslexic and typically developing children, reading ability has not been associated with fixed or unfixed ocular dominance. Furthermore, a considerable proportion of the population with excellent reading and spelling abilities have unfixed ocular dominance.

In conclusion, the relation between binocular eye movements and dyslexia is not yet clear. This is true for a number of reasons. The most important, perhaps, is the lack of studies specifically examining binocular coordination in dyslexic readers during both non-reading and natural reading tasks.

Chapter Four

Binocular coordination during a non-reading task: a comparison between typically developing children and children with dyslexia

4.1 Introduction

The aim of Experiment 2 was to examine the characteristics of typically developing and dyslexic children's binocular coordination during a non-reading task. The literature presents mixed findings as to whether eye movements play a causal role in dyslexia, or instead whether dyslexia disrupts typical eye movement behaviour. Throughout this Thesis it has been suggested that much of the controversy was due to three important issues, a lack of research directly measuring the movements of the two eyes during reading and non-reading visual tasks, the possibility that the findings from studies using different methods of binocular coordination assessment may not generalise to reading and the method by which some researchers have selected participants.

It was clear that in order to support the claim that poor binocular coordination was a cause of dyslexia it was necessary not only to demonstrate poor binocular coordination in children with dyslexia, but also that the binocular coordination of typically developing children was, in some way, better or improved in comparison. Furthermore, it was important to demonstrate differences during a non-reading task. A difference between typically developing (TD) and dyslexic (D) children on a reading task alone would leave the researcher unable to distinguish whether poor binocular coordination is a cause, correlation or consequence of their reading difficulties. Were such poor binocular coordination found to occur for dyslexic children during non-reading tasks, in the absence of any linguistic processing demands, then at least it can be concluded that reading difficulty is not the cause of any such differences in binocular coordination. It was with this hypothesis in mind that the current experiment was designed.

As discussed in section 3.5 (*Deficits in the magnocellular system*) a substantial body of evidence has lead to the proposal that deficits within the magnocellular pathway of the visual system cause reading difficulties. To reiterate, proposers (e.g. Stein, 2001) of the magnocellular-deficit theory of dyslexia suggest that some of these children experience deficits in the visual perception of text and this is due to their uncoordinated oculomotor control. There have been several suggestions in the literature as to the characteristics of their inappropriate eye movements. These include: greater fixation disparity due to inadequate binocular coordination; poor vergence control during fixation; and an increased number of intrusive saccades (microsaccades, or an inability to maintain a stable fixation) during fixations (Eden, Stein, Wood, & Wood, 1994; Evans & Drasdo, 1990; Fischer & Hartnegg, 2000; Kapoula et al., 2006; Stein & Fowler, 1993; Stein et al., 1987; 1988).

The aim of Experiment 2 was to examine whether differences existed, in either the magnitude and direction of fixation disparity or the vergence movements which occurred during fixations, between typically developing children and children with dyslexia. The first prediction for the study was based on the results of Blythe et al. (2006), who found that fixation disparity was common for typically developing children while reading, even at the end of a fixation. It was anticipated therefore, that disparity would be observed between the fixation points of the two eyes for all child participants. In the binocular data of Blythe et al. systematic reduction of the disparity, observed at fixation onset, for the child participants was not demonstrated. Their data differed to those reported in Liversedge, White et al. (2006), where systematic reductions of onset disparity were found at fixation offset. This was also found to occur in the adult data presented in Chapter 2; where adult's tended to make corrective vergence movements during fixations on strings of dot stimuli. Blythe et al. concluded that these differences were likely to arise from their saccade selection procedure. Blythe et al. found saccades were selected in a consistently more "conservative" way than the saccades of Liversedge et al. To be clear, this would mean that the start and end point of a fixation would be placed later and earlier, in respect to the end of the prior saccade and the start of the forward saccade. Therefore, Blythe et al. concluded that this procedure would result in a systematic decrease in the measured magnitude of vergence that occurred during a fixation. With this in mind the second prediction was based on the results of Liversedge, White et al. (2006), which was supported in the pattern of results observed in Experiment 1. It was therefore anticipated that vergence eye movements would occur during fixation. Furthermore, that vergence would be in the direction that reduced the disparity present at fixation onset.

The literature is somewhat less clear however, in relation to predictions concerning possible differences between the two groups of children (typically developing children and children with dyslexia). Recall that the examination of vergence eye movements through both subjective reports (Dunlop tests) and more objective eye movement recordings have yielded mixed results. One possible prediction, based on the results of Stein et al. (1981; 1982; 1983; 1988; 1989), Kapoula et al. (2007), Bucci, Bremond-Gignac & Kapoula (2008) and Jaschinski et al. (2004), is that the magnitude of fixation disparity would be increased for children with dyslexia in comparison to typically developing children. This would be caused by reduced vergence movements made during fixation for children with dyslexia compared to typically developing children. However, a second possibility, based on the work of Lennerstrand et al. (1993; 1994), would be that no significant differences are likely to be observed between the two groups of children with and without dyslexia, in either the magnitude of fixation disparity or the vergence movements that occur during fixation. Lennerstrand et al. found that children with dyslexia made equivalent vergence responses to dichoptically presented disparate images as did typically developing children during non-linguistic tests of binocular coordination.

The studies reported by Stein and colleagues (Stein & Fowler, 1981; 1982; 1983; Stein, Riddell, & Fowler, 1988; Stein, 1989) have frequently used methods which may be considered to be subjective, to measure the binocular coordination of children with dyslexia. It is debatable whether these tasks effectively test the highly stylised oculomotor control required during reading. Nonetheless, several studies have used this method, some reporting eye movement data, whilst others relying quite heavily on the subjective self-report of young children (Bigalow & McKenzie, 1985; Stein & Fowler, 1981; 1982; 1983; Stein, 1989). Stein demonstrated that typically developing children made vergence movements up until the point at which fusion broke, children with dyslexia however, failed to make appropriate vergence movements and instead, they made parallel drift movements of the two eyes (Stein, Riddell, & Fowler, 1988).

In addition to the studies by Stein and colleagues, there are other studies in which children with dyslexia have been found to have a reduced capacity to verge the eyes during fixation. This has been demonstrated in on both non-reading and single-word reading tasks (Bucci et al., 2008; Kapoula et al., 2007). However, rather than a generic inability to verge the eyes, children with dyslexia displayed a reduced capacity to diverge the eyes when compared to typically developing children.

More recently Bucci, Bremond-Gignac and Kapoula (2008) made comparisons between typically developing and children with dyslexia's binocular coordination while reading single words and during a LED presentation task. The reading task required the following: an inward saccade from a fixation cross presented on the left of the screen onto a single word, that the word be read silently followed by an outward saccade to a further fixation cross presented on the right of the screen. The saccade data obtained during this task were compared to the saccade data recorded during LED presentations; the LEDs were placed randomly at 0° and 10° or 0° and 20° to the right or to the left of the screen. Bucci, et al. (2008) found that binocular coordination was consistent over the two tasks for all the children. However, significant between-group differences were demonstrated in the magnitude of disparity (measured as the mean disconjugacy in binocular saccade amplitude) that occurred during the saccade. The mean disconjugacy for saccades to words was found to be 1.17° and .41° for dyslexic and typically developing children respectively. For saccades to LED displays the amount of saccade disconjugacy was .95° and .34° for children with and without dyslexia respectively. The disconjugacy between the two eyes' saccadic movements was found to represent a convergent change (where the amplitude of the left eye's saccade was greater than the amplitude of the right eye's saccade). Furthermore, differences in the fixation vergence movements were found between the two groups of children (with and without dyslexia). Typically developing children demonstrated a pattern of eye movements that represented a reduction of fixation disparity, commensurate with the numerical tendency in the data of Blythe et al. (2006), the adult data of Liversedge, White et al. (2006) and the adult data presented in Chapter 2. However, Bucci et al. found no such change in the magnitude and direction of disparity at fixation onset, or similar vergence movements during fixation for the children with dyslexia.

The children that participated in Experiment 2 were between the ages of 7 and 11 years. Half of the group had been diagnosed dyslexic at some time prior to the testing sessions and half were age and IQ matched control participants with no known reading deficits. In order for the current research to be meaningful, it was necessary to adopt and adhere to stringent recruitment criteria in relation to the selection of the dyslexic participants. Therefore all participants in the dyslexia group had been diagnosed by either Dyslexia Action or their school special educational needs (SEN) coordinator. However, all participants also completed a comprehensive battery of off-line measures of reading ability. This included measures of phonological skills, oral language skills, reading skills (including word recognition, non-word reading and reading comprehension) and orthographic ability.

Primarily the investigation aimed to examine any differences between children with dyslexia and typically developing children in relation to either the magnitude and/or the direction of fixation disparity during a non-reading task. In addition to this, the experiment was designed to examine the influence of a number of visual characteristics associated with the stimuli, on typical binocular coordination in typically developing children and children with dyslexia.

The current experiment therefore, consisted of three tasks that were identical to those of experiment 1; one of these tasks was designed to require eye movements that were analogous to the saccade and fixation sequences frequently demonstrated during reading. Child participants were required to scan, from left to right a series of dot stimuli. The task was designed to place similar demands on the oculomotor coordination system as reading in the absence of any linguistic processing. Under these conditions if oculomotor coordination was disrupted for dyslexic participants in comparison to their age matched controls, differences could not be due to differences in reading ability.

Two further non-reading tasks, each requiring precise saccadic orienting, were conducted. As noted above the secondary aim of the investigation was to examine the effect of the visual characteristics of the stimuli on children's binocular coordination. Here, once again, the visual stimuli used were the same as those used in Experiment 1. Recall that the tasks were designed to enable the investigation of the effect of target size, target location (distance and direction) and the target's visual availability. Comparisons, between groups of children, were further conducted to explore whether, and if so, the extent to which visual characteristic of the stimuli differentially modulate binocular coordination in the two groups of children.

4.2 Methods

Participants. The 17 child participants were recruited from local schools or through their attendance at Dyslexia Action, a national charity that provides support for people with dyslexia and literacy difficulties. Their age ranged from 7-11 years mean age for the children with a diagnosis of dyslexia was 10.3 with a SD 1.5. Mean age of the typically developing child participants was 9.1, with a SD 1.1. All child participants had English as their first language with normal, uncorrected vision. All participants were naïve as to the purpose of the experiment.

Apparatus. Two Dual Purkinje Image eye trackers were used to record the participant's binocular eye movements. Eye positions were monitored every millisecond. A Pentium 4 computer interfaced with the eye trackers and all the visual stimuli were presented on a Philips 21B582BH 24" monitor. The stimuli (2D dots) were presented at a viewing distance of 1000 mm. Each dot covered 0.29° of a visual angle and were presented in white on a black background. The room was dark except for a small dim indirect light source. To minimise participants head movements during the experiment, they were required to bite on a sterilised bite bar covered in dental wax, to lean into two forehead rests and a Velcro strap was secured behind their head, allowing for accurate oculomotor date to be obtained.

Reading tests. It was very important to demonstrate differences in reading ability between the two groups of children participating in the current research. As described in Chapter 3 (Section 3.3 *Diagnosing dyslexia*) the criteria used in diagnosing dyslexia often vary considerably, and at times phonological processing is the primary measure considered when making a formal diagnosis. Some children with phonological deficits may not necessarily demonstrate other deficits frequently found in the dyslexic population. Therefore, in addition to a recognised diagnosis of dyslexia, all child participants were tested on a series of tasks designed to assess literacy skills. These measures included tests of phonological skill, oral language skill, reading skill (including word recognition, non-word reading and reading comprehension) and orthographic ability.

Two subtests of the 1999 Wechsler abbreviated scale of intelligence (WASI) were administered; the vocabulary subtest, a 42-item task, which measured the individual’s expressive vocabulary, verbal knowledge and general information knowledge. This task is suggested to tap cognitive abilities such as, memory, learning ability, concept and language development (Sattler, 1988). The matrix reasoning subtest was also administered. This was a 35-item task where the participant was required to complete a gridded pattern by stating the correct item from a string of possible items. The task measured nonverbal fluid reasoning and general intellectual ability. By combining the results of these two subtests an IQ score for each child was obtained.

An orthorgraphic forced choice task was also administered to both groups of child participants. This measure consisted of two-alternative forced-choice orthographic decision tasks. The tasks required participants to choose rapidly between a correctly spelled word and a pseudo-homophone (e.g. soap/sope) by circling the word they considered to be correctly spelt. The word lists were separated into regular words, where every letter represented the most common sound, and irregular words, where they did not. For instance *kin* is a regular word, but *kind* is irregular. These word lists were based on the stimuli used in the study reported in Coltheart & Leahy (1992).

All child participants were also tested for reading skill; here the reading subtest of the Wechsler Individual Achievement Test Second UK Edition (WIAT-II, 2005) was utilised. This subtest involved word reading which assessed the child’s phonological awareness (phonemic identity, phonemic categorisation and phonemic blending) and a variety of decoding skills (e.g. letter identification). It also included pseudoword decoding which assessed the child’s ability to apply phonetic decoding skills to novel non-words, and also reading comprehension that assessed the child’s ability to understand what they had read.

Child participants were further tested for exception word reading. The task consisted of a word list that contained letter clusters that were pronounced differently in this word than they would typically be pronounced (e.g. the *ou* pronunciation in the word *touch).* The child was required to read aloud the list of exception words with unusual orthographic structures (the list was based on a similar list used by Castles et al., 1999). The standardised scores for the word reading subtest of the WIAT-II provided a reading age for each participant and differences between the child’s reading age and their chronological age were then calculated. The standardised scores for the comprehension subtest of the WIAT-II provided a comprehension age for each participant and the difference between the child's comprehension age and their chronological age were also computed.

Eye tracking stimuli. The stimuli used in the current experiment were reported in Chapter 2 (see Figures 2.1, 2.2, & 2.3). The current investigation employed three separate eye tracking tasks. Task 1 consisted of horizontal rows of dot targets, presented simultaneously and remained visible throughout the trial. The stimuli consisted of horizontal rows of five equally spaced single dot targets, twelve strings of two dots, eight stings of four dots and six strings of six dots. Task 2 consisted of two single dot targets these dots were again presented simultaneously and separated by 5.5˚ of visual angle. The two dots were presented on the horizontal axis along the vertical midline and remained visible within the parafovea throughout the trial. Task 3 consisted of single dot targets that were presented in isolation at four possible locations along the horizontal axis. Presentation was randomly assigned to a position which corresponded to 5.5˚ or 2.1˚ either to the left or right of a central fixation cross.

Procedure. The same experimental procedure as described in Chapter 2 was employed during the current experiment. During Task 1 a horizontal row of dot targets were presented; participants were instructed to fixate a cross, presented on the left side of the screen. The fixation cross was then replaced by a row of dot targets, either single dots or strings of dots, and participants were required to scan the targets from left to right. Participants were instructed to fixate the target strings of dots as a whole rather than make repeated fixations on each individual dot of the string. Finally, participants were required to hold fixation on the last target until it disappeared. After the row of targets disappeared, a fixation cross reappeared on the left side of the screen indicating the start of a new trial. The task consisted of six trials for each four target size conditions 24 trails in total.

During Task 2 two single dots were simultaneously presented and participants were instructed to fixate the centrally present cross until it was replaced by two single dots. Participants were instructed to make saccades between the two dots, temporally dictated by the pace of a metronome (set at 60 beats per minute) until the targets disappeared. After this a central fixation cross appeared that indicated the start of the next trial.

During Task 3 single dots in isolation were presented. These could be in one of four possible positions, the child was required to fixate a centrally presented cross, and when that disappeared a target dot appeared in one of the four locations. The child was required to make an eye movement and fixate the dot until it disappeared and was replaced by the central cross once again. The entire task consisted of six trials in the four positions, a total of 24 trials. All instructions were given both verbally and in writing prior to calibration. Participants were allowed to ask questions at that point if they did not understand any of the instructions.

Calibration. Left and right eye calibrations were performed monocularly (e.g. when calibrating the left eye the right was occluded and vice versa). During calibration the participant was instructed to stare at one of three fixation points presented horizontally to the left, centre and right of the screen. Monocular eye positions were recorded for each of these fixation points and then visually checked for accuracy. This was then repeated for the other eye and again checked for accuracy. When calibration was complete the experimental stimuli were presented. Following every three presentations of experimental stimuli the calibration accuracy was visually verified and the eye tracker recalibrated if necessary. All participants were given a break halfway through the experiment and were also able to take a break if and when they required one throughout the experiment. The experiment lasted 40-50 minutes in total.

*Analysis. S*egmenting fixations was performed manually (see *Figure 2.4*); this was to ensure that any eye movements associated with a saccade and the dynamic overshoots associated with such movements were eliminated from the fixation data. A custom-designed software package was utilised to analyse all the data.

4.3 Reading test results

Recall that orthographic ability was tested by two-alternative forced-choice orthographic decision tasks; one assessed irregular word reading and the other regular word reading. No significant differences for the regular word list (TD children $\mu = 19.43$, SD = 0.79, Children with dyslexia $\mu = 18.50$, SD = 2.14; t (15) = 1.08, $p = 0.30$) or for the irregular word list (TD children $\mu = 17.57$, SD = 2.07, Children with dyslexia $\mu = 16.13$, SD = 1.96; t (15) 1.39, p =0.19) were found. During this task performance was consistently good, as the very worst children were still able to obtain 80% correct responses on this task. While a small numerical trend in the predicted direction was found in these data, there were no reliable differences between the two groups. This null effect while initially surprising can be explained by two factors associated with the task. First, the test words in this task were limited to words which typical nine year old children would have acquired and be fully familiar with. Second, the task did not require full lexical identification of the test words. At no time were the children required to read aloud or spell aloud the test words. Therefore, the task requires a comparatively shallow level of processing where recognition of word form and shape may provide the child with enough information to choose a correct spelling over an incorrect one. I will now describe tasks in which deeper levels of processing was required and in which significant differences were found. Reading skill was assessed with the reading subtest of the WAIT-11. The results for both groups of child participants are presented in Table 4.1

Table 4.1

Results reading subtests of the Wait-11 for typically developing and children with dyslexia

	Pseudoword reading	Word reading	Comprehension	Exception word reading
TD Children	μ =102.71 SD = 14.24	μ = 102.71 SD = 14.71	μ = 116.29, SD = 10.04	μ = 37. 86 SD = 5.70
Children with dyslexia	μ = 89.13 SD = 8.89	μ = 87.75 SD = 11.54	μ = 104.63 SD = 13.74	μ = 31.62 SD = 5.68
T-Tests	t (15) = 2.25, $p < .05$	t (15) = 2.21, $p < .05$	t (15) = 1.85, p > .05	t (15) = 2.18, $p < .05$

The standardised scores for the word reading subtest of the WAIT-11 provide a reading age for each participant. The difference between a child's reading age and their chronological age was calculated (where a (–) indicated that their reading age was below the child's chronological age). There was a significant difference between the mean difference between chronological age and reading age for TD children (μ = 1.09, SD = 2.05) and children with dyslexia (μ = -1.52, SD = 1.75, *t* (15) = 2.67, $p < .05$). The standardised scores for the comprehension subtest of the WAIT-11 provide a comprehension age for each participant. The difference between a child's comprehension age and their chronological age was also computed. There was no significant difference between these scores for TD children (μ = 2.96, SD = 1.91) and children with dyslexia (μ = .73, SD = 2.22; *t* (15) = 2.08, $p > .05$).

Two subtests of the WASI (Wechsler abbreviated scale of intelligence, 1999) were administered to provide an IQ score for all children. Importantly, there were no significant differences between typically developing children (μ = 114.43, SD = 14.64) and children with dyslexia (μ = 112.25, SD = 11.90; *t* (15) = .32, $p > .05$) on measures of IQ. The results of the off-line tests ensured that any differences, between the two groups of children, were associated with linguistic processing and not on measures of IQ and chronological age.

4.4 Eye movement results

One of the primary questions under investigation was whether the magnitude and direction of fixation disparity was comparable between a group of children with dyslexia and a group of typically developing children. As with the adult data (Experiment 1) fixation disparity was calculated at both fixation onset and offset to provide a measure of binocular coordination and an index of vergence movements that occurred during fixation for both groups of children (see Table 4.2).

At fixation onset mean fixation disparity was .39° for typically developing children and .33° for children with dyslexia. Fixation offset was almost identical in both participant groups (.40° for typically developing children and .33° for children with dyslexia). Repeated measures ANOVA showed no significant main affect of sample point in fixation (start vs end of fixation) *F* (1, 15) 0.82, $p = .38$ and no between-subjects effect of group (TD vs. Children with dyslexia) *F* (1, 15) 1.31, $p = .27$. Furthermore, no significant interaction was demonstrated between the sample point of fixation and the group of child participants, *F* (1, 15) 3.84, *p* = 0.07. This was consistent with the developmental data of Blythe et al. (2006) where fixation disparity was not found to significantly reduce during a fixation (see Figure 4.1 for distribution of fixation disparity at start and end of fixation).

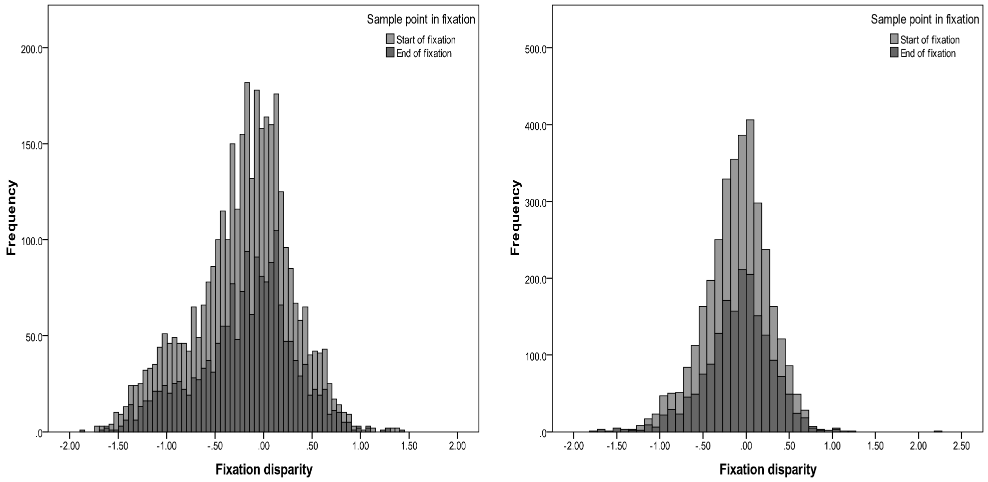

Figure 4.1

Distribution of start and end of fixation disparity, obtained during Task 1. A negative number represents an uncrossed fixation. Left panel represents disparity data for typically developing children and the right panel represents data for children with dyslexia.

Consistent with the study reported in Chapter 2, and in line with Liversedge, White et al. (2006), fixations were categorized as aligned or unaligned. To reiterate, to be considered as an aligned fixation, the fixation points of the two eyes were required to be within one dot space of each other (.29°). Therefore an unaligned fixation represented an absolute disparity of more than one dot. Unaligned fixations were further categorized into those that were uncrossed and those that were crossed. A crossed fixation was defined as one where the point of fixation of the left eye is to the right of the point of fixation of the right eye. An uncrossed fixation was defined as the converse of this.

Table 4.2

Mean fixation disparity (SD) for typically developing children (TDC) and dyslexic children (DC) at fixation onset and offset for all participants

Participants	Mean start of fixation disparity & (SD)	Mean end of fixation disparity & (SD)
1 TDC	0.33 (.23)	0.32 (.23)
2 TDC	0.57 (.41)	0.53 (.38)
3 TDC	0.38 (.27)	0.44 (.36)
4 TDC	0.43 (.31)	0.48 (.43)
5 TDC	0.35 (.31)	0.37 (.39)
6 TDC	0.46 (.34)	0.49 (.39)
7 TDC	0.28 (.19)	0.33 (.25)
8 TDC	0.29 (.25)	0.31 (.31)
Mean	**0.39 (.31)**	**0.40 (.36)**
1 DC	0.25 (.19)	0.24 (.18)
2 DC	0.48 (.34)	0.44 (.35)
3 DC	0.22 (.19)	0.21 (.17)
4 DC	0.63 (.39)	0.67 (.44)
5 DC	0.38 (.29)	0.32 (.22)
6 DC	0.36 (.34)	0.37 (.34)
7 DC	0.33 (.21)	0.34 (.24)
8 DC	0.26 (.21)	0.31 (.23)
9 DC	0.33 (.26)	0.32 (.27)
Mean	**0.33 (.28)**	**0.33 (.28)**

Table 4.3 shows the overall alignment patterns of the two eyes at both the start and end of fixations. Also presented in Table 4.3 are the proportions of fixations that are aligned crossed or uncrossed at the end of fixation, as a function of their alignment at fixation onset. First, the probability of making an aligned fixation compared to an unaligned fixation both at the start and the end of a fixation was computed. For both groups of children the eyes were numerically more often aligned than unaligned, however a one sample *t*-test comparing the proportion of aligned fixations to chance showed that during a fixation the fixation positions of the two eyes were not significantly more often aligned (within one dot space) than chance (.05). This was found both at the start (*t* (16) = .48, *p*= .64) and at the end (*t* (16) = .30, *p*= .77) of fixation. For 48% of fixations which were made across the horizontal arrays of dot strings the eyes remained disparate the equivalent of one dot size or more at the end of fixation. This is quite consistent with adult data described in Chapter 2. The patterns of data found during Experiment 1 and during the current investigation are also consistent with the findings of both Liversedge et al. (2006a)

and Blythe et al. (2006), who demonstrated that the eyes were not always aligned by the end of a fixation during reading.

It was further demonstrated that the proportion of aligned fixations at the start compared to the end of fixation were not significantly different (*F* (1, 15) 1.54, p = 0.23); thus indicating that children do not verge their eyes during fixation so as to align them at the end of fixation. This was found to be consistent for both groups of children where the between-subjects analysis found no significant differences for the proportion of aligned fixations between groups (*F* (1, 15) 0.78, $p = 0.39$). Furthermore, there was no significant interaction between the proportion of aligned fixations at the start and end of fixation and the two groups of participants (*F* (1, 15) 0.36, $p = 0.56$). Therefore, it seems that vergence movements during fixation, which have been found to reduce the disparity between the fixation points of the two eyes, were equivalent for children with and without dyslexia during a non-reading task.

Unaligned fixations were further categorised as either crossed or uncrossed. Since these two categories are dependent, comparisons were made between groups on the probability of making an uncrossed fixation. Repeated measures ANOVAs were conducted to compare the proportion of uncrossed fixations for children with and without dyslexia at the start and the end of fixations. There was a significant effect of sample point in fixation (*F* (1, 15) 20.50, $p < 0.01$) where the proportion of uncrossed fixations were significantly reduced between the start (μ = 57%) and the end (μ = 52%) of fixation. Thus the proportion of crossed fixations increased from the start of fixation (μ = 43%) to the end of fixation (μ = 48%). Between-subjects analyses showed that changes in ocular alignment, relative to unaligned fixations were equivalent for both groups of children (with and without), (*F* (1, 15) 0.85, p = 0.37). Further no interaction between group and sample point in time was demonstrated (*F* (1, 15) 2.38, $p = 0.14$) where the pattern of data for both groups of participants demonstrated a reduction in the proportion of uncrossed fixations at the end compared to the start of fixation.

Presented in Table 4.4 are the mean fixation durations and binocular saccade lengths for every fixation made during all the three tasks during the experiment. There was no significant difference found between children with dyslexia and typically developing children in the time they spent fixating a dot target (*t* (15) 0.10, $p = 0.92$).

During these dot scanning tasks, where no linguistic processing is required, it is not particularly surprising there are no differences in fixation duration; children with dyslexia experience difficulty processing linguistic information and it is this difficulty which increases fixation durations during reading compared to the average fixation duration for typically developing children. The saccade amplitude data for the two eyes were compared using one way repeated measures ANOVAs. No significant difference was found between the mean saccade amplitude for the left and right eyes (*F* (1, 15) = 0.37, *p* = .55).

Table 4.3

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

	All start Data (%)	End Aligned (%)	End Crossed (%)	End Uncrossed (%)
T D Children				
All end data		48%	18%	33%
Start Aligned	49%	86%	9%	5%
Start crossed	16%	15%	85%	0%
Start uncrossed	35%	16%	0%	84%
Children with dyslexia				
All end data		56%	21%	23%
Start Aligned	55%	83%	11%	6%
Start crossed	18%	15%	84%	1%
Start uncrossed	27%	27%	1%	72%

Table 4.4

Mean fixation duration, saccade amplitudes and mean disparity during saccades.

	Fixation duration (SD)	Mean saccadic amplitude for the left eye (SD)	Mean saccadic amplitude for the right eye (SD)	Mean saccadic disparity (SD)
Typically developing children	422 ms (339)	1.39˚ (1.60˚)	1.42˚ (1.61˚)	.14˚ (.18˚)
Children with dyslexia	438 ms (393)	1.49˚ (1.76˚)	1.49˚ (1.71˚)	.14˚ (.27˚)

Furthermore, there was no significant difference in the binocular saccade amplitudes between groups (*F* (1, 15) = 0.02, *p* = .90). In addition to this there were no interaction between the binocular saccade amplitudes and group (*F* (1, 15) = 1.26, *p* = .28). During a saccade the two eyes were disparate, on average, by .14° of visual angle. This result was equivalent for both the groups of children.

Is binocular coordination affected by the visual characteristics of the stimuli?

In the next set of analyses the influence of the visual characteristics of the stimuli are considered. In the first instance the affect of target size was analysed to determine whether fixation disparity was increased for targets with a greater horizontal spatial extent than for those with reduced horizontal extent. In Chapter 2 while the reasoning for the investigation of target size was sound and based on the hypothesis that smaller and more spatially localised stimuli would require reduced fixation disparity during saccadic orientating, the data did not support this hypothesis. The small (single dot) targets did not result in more tightly coordinated saccades of the eyes and therefore a reduced horizontal disparity at fixation onset was not demonstrated while fixating smaller (single dot), compared to larger (six dot) targets. However, this prediction had not been tested for typically developing children and children with dyslexia. Therefore, it was not clear whether similar patterns of binocular eye movements to targets of different sizes would be found for children as was the case for adult participants.

Absolute disparity magnitudes as a function of target size were examined. The data acquired during Task 1, horizontal arrays of dot stimuli were analysed. In line with Chapter 2, there was no significant effect of target size on disparity at the start of fixations (*F* (3, 42) = 0.14, *p* = .94); and this held for both groups of child participants (with and without dyslexia) where no significant effect of group was demonstrated (*F* (3,42) = 1.35, *p* = .27; one dot TD μ = .47, SD = .29; D μ = .25 SD = .12; two dot TD μ = .43, SD = .20, D μ = .29 SD = .11; four dot TD μ = .40, SD = .26, D μ = .32 SD = .25; six dot TD μ = .36, SD = .29, DC μ = .44 SD = .16) this was also found for the measures of fixation disparity recorded at fixation offset, (*F* (3, 42) = .16, *p* =.92), and again held for both groups of children where again no significant effect of group was demonstrated (*F* (3, 42) = 1.39, *p* = .26; one dot TD μ =.54, SD = .37, D μ = .24, SD = .15; two dot TD μ = .44, SD = .21, D μ = .27, SD = .09; four dot TD μ = .44, SD = .32, D μ = .32, SD = .23; six dot TD μ = .39, SD = .29, D μ = .42, SD = .23).

Again the numerical trends that exist within the data for the typically developing children are in the same direction as the adult data reported in Chapter 2. The smaller the target size, the greater the magnitude of disparity found, though again, these effects were not significant. However, the numerical trends in the dyslexic children's data for the target size analyses showed the magnitude of fixation disparity did increase as target size increased, but these differences were not significant. Although the data pertaining to the group of children with dyslexia were in the opposite direction to the adult and typically developing children's data, no reliable influence of target size was demonstrated on fixation disparity, regardless of whether it was measured at the start or end of fixations. Thus, it appears that fixation disparity was unaffected by the horizontal spatial extent of target stimuli. In addition to these analyses, ANOVAs were conducted to examine whether there was any modulatory influence of target size on the proportions of alignment. These analyses also failed to reveal significant effects (all *F*s < 1.11). These results indicate that binocular coordination (measured as both the magnitude and direction of fixation disparity) remained consistent over all the target sizes investigated.

During Task 2, random presentation of a single dot, child participants were instructed to move their eyes from a central fixation cross to a single dot and to fixate the dot for 3000 ms, then the dot was replaced by a central fixation cross that they were required to return to ready for the next trial. The dots were presented along the horizontal axis at different degrees of eccentricity from the central fixation cross (5.5° or 2.1°) to the left or to the right of the fixation cross. Therefore, as reported in Chapter 2 there were four possible presentation positions for the single dot target to appear and the presentation location of the dot was randomised. All analyses concerning the effect of distance and direction on the magnitude of fixation disparity were conducted on fixation onset data as it was demonstrated in Experiment 1 that the preceding saccade amplitude had a significant effect on the magnitude of disparity on the subsequent fixation at onset. Furthermore, it was predicted that any possible modulation of fixation disparity by the direction of the preceding saccade would be more evident at fixation onset.

Consistent with the adult data described in Chapter 2, the preceding saccade amplitude was found to influence the magnitude of fixation disparity, where the greater the amplitude of the preceding saccade produced a greater the magnitude of fixation disparity (F (1, 15) = 11.29, $p < .01$). This was found to be equivalent for both groups of children (with and without dyslexia). The analysis in the current investigation showed that the direction of the preceding saccade had a reliable affect on the magnitude of fixation disparity (*F* (1, 15) = 4.92, *p* = .04). The mean absolute disparity magnitudes were equivalent for typically developing children and children with dyslexia. Interestingly the effect of direction has not been examined in previous binocular coordination experiments. The possibility that saccadic direction may affect fixation disparity is interesting in terms of the frequency of regressive eye movements found for children during reading. Although these results suggest a modulatory effect of saccade direction on fixation disparity it would be unrealistic to generalize these results measured during a non-reading task to linguistic material. There was also an interaction between the effect of distance and direction on the magnitude of disparity at fixation onset *F* (1, 15) = 6.21, *p* = .03. As shown in Figure 4.2 fixations to near targets on the left of the screen were less disparate than all other fixation locations. This was consistent for both groups of children (with and without dyslexia); however, there is no prior reason to anticipate an asymmetric effect such as this. Furthermore, no other effects of this kind were described in any other measures, and it seems highly likely, therefore, that this effect is spurious.

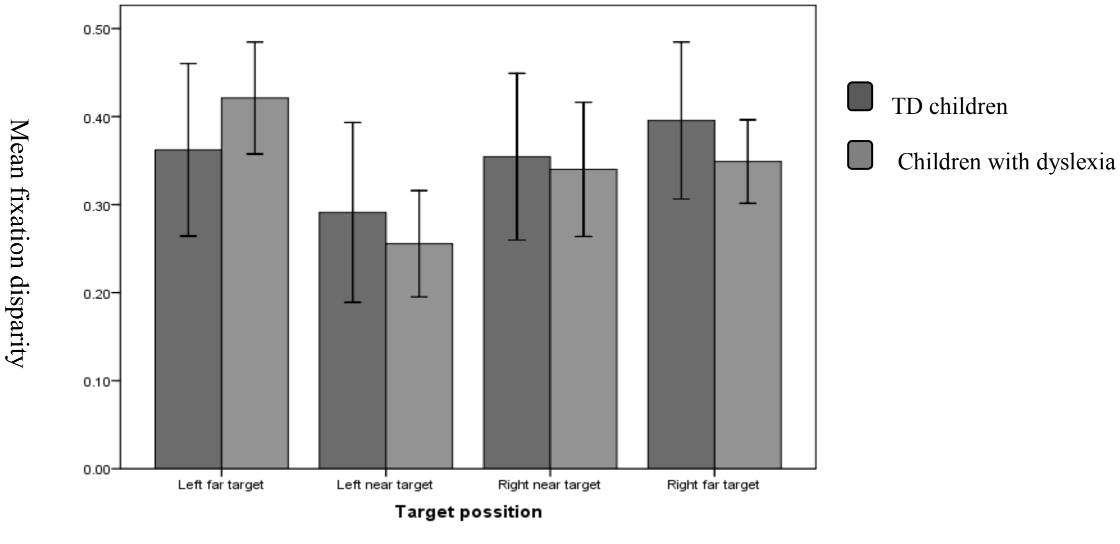

Figure 4.2

Mean and SD data for start of fixation disparity following a saccade to a target presented to either the left or the right and either near or far from the centre of the screen

The following analyses addressed the influence of the preceding saccade on the direction of ocular alignment during the subsequent fixation. The proportions of fixation onset ocular alignment were compared. Neither the proportions of aligned vs. unaligned fixations, or the nature of the unaligned fixations (uncrossed vs. crossed) were modulated by the direction of the preceding saccade (*F*'s < 1). However, there was a significant effect of distance on the proportion of aligned fixations at fixation onset; where the proportion of aligned fixations were reduced when the fixation followed a larger (5.5˚), rather than smaller (2.1˚), saccade amplitude, F (1, 15) = 5.23, p = .04. However, the proportions of those fixations categorized as unaligned were not affected by the increased distance required to fixate the target (*F's* < 1). Proportionally unaligned fixations were more often uncrossed than crossed. Note however, that similar to the data described by Blythe et al., children in the current study demonstrated an increased proportion of crossed fixations compare to the adult data described in Chapter 2.

It was possible due to directly compare the data obtained during Task 3 (categorised as visually elicited saccades) with the data obtained during Task 2 (categorized as repeated saccades between two continuously visible targets). Recall that during Task 2 participants were required to make a saccade and fixate a single target dot; the dots were positioned on the screen as to require a mean saccadic movement of 5.5° of visual angle. During Task 3 targets were presented to the left and right of a central fixation cross and in some of these conditions the mean saccadic amplitude required to fixate the target was also 5.5° of visual angle. Therefore, it was possible to make a direct comparison between children's binocular coordination during an eye movement triggered by the onset of the target or an eye movement which was pre-programmed to continually present targets. Recall that, both conditions require a saccade of equivalent amplitude (5.5˚) to fixate a single dot extending .29˚. Again the mean values were calculated from all valid fixations.

The analyses presented here compare the disparity magnitudes and the proportions of alignment categorisations for the data recorded at fixation onset. Following the same logic as Experiment 1, it was predicted that binocular eye movements to targets that were continually present may be facilitated somewhat, in comparison to the target onset elicited eye movements. However, consistent with the data presented in Chapter 2, binocular coordination was comparable regardless if the target remained visible during the trial or was randomly presented during the trial (*F* (1, 15) = .52, *p* = .48). Furthermore, this was consistent for both groups of children (*F* <1). Alignment proportions at fixation onset were found to be consistent between groups of typically developing children and children with dyslexia, regardless of whether the target was continually present within the parafovea or a saccade was elicited by the onset of a target. Repeated measures ANOVAs were conducted which first compared the proportions of aligned fixations. The pattern of data indicated that the continual presence of a target did not affect the proportions of aligned fixations at the start of fixation (*F* (1, 15) = .26, *p* = .62). If it was the case that the time available to plan and execute a saccade was related to the degree to which the two eyes were aligned during a fixation, then one would predict that during Task 2 fixation disparity would be reduced in comparison to during Task 3 were the sudden onset of a target elicited a saccade. The pattern of results found in both the current study and Experiment1 (the adult data) indicate that this was not the case as disparity remained consistent regardless of whether there was a saccade was pre planned or elicited by the onset of the target, *F* < .01.

Further analyses were conducted on the unaligned fixations, which again had been categorised as uncrossed or crossed. The proportion of uncrossed fixations was analysed, (again eliminating the requirement to analyse crossed data due to the dependent nature of these results). The continual presence of a target had no effect on the proportions of unaligned fixations (*F* (1, 15) = .19, *p* = .67) and this was consistent for both groups of children (with and without dyslexia) *F* < 1.

4.5 Discussion

In summary 12 of the 17 participants tested had magnitudes of disparity between the points of fixation for the two eyes which amounted to more than the size of one dot (.29°). Typically developing children's fixation disparity magnitudes were not significantly reduced in comparison to children with dyslexia. Both groups of children were more likely to make uncrossed fixations when their eyes were unaligned during fixation. When the eyes made vergence movements during fixation, both groups of child participants were more likely to make convergence than divergence movements. In terms of the magnitude and direction of fixation disparity there were no between group differences. The visual characteristics of the stimuli were not found to modulate children's binocular coordination, with the exception of the preceding saccade amplitude. Here the greater the preceding saccade amplitude the greater the fixation disparity magnitude. This result was consistent for both groups of children and consistent with the adult data reported in Chapter 1.

Overall, the pattern of results found in the current data is consistent with the pattern found in the adult data, described in Experiment 1. However, consistent with the literature (Blythe et al., 2006) children's fixation disparity magnitudes were increased compared to adult's fixation disparity magnitudes. For the adult data it was relatively rare for the eyes to fixate a target where the left eye is further to the right than the right eye (i.e. a crossed fixation). However, for children this was not the case. Although both groups of children were more frequently in an uncrossed pattern of fixation when the eyes were unaligned, there were increased proportions of crossed fixations compared to the adult data.

The current data demonstrates that the developing visual system is adept at dealing with varying degrees of fixation disparity on a fixation-by-fixation basis. The fusion system is still achieving a unified percept from disparate retinal stimulations. Indeed none of the children that participated in the experiment reported blurring or diplopia.

Small vergence movements were shown to occur during fixations for both groups of children. These movements were predominantly in a non-parallel direction, in order to converge the points of fixation for the two eyes. The magnitude of convergence and divergence was equivalent between the two groups of children. This finding is in direct conflict with the suggestion that dyslexic individuals demonstrate a reduced capacity to verge the eyes during fixation (Kapoula et al., 2007). Note that this had been suggested as a cause of some children's reading difficulties. While there is a possibility that a deficient oculomotor system and more specifically, a reduced capacity to verge the eyes during fixations, is one causal component in the etiology of reading difficulties and if this was the case you would expect to observe greater fixation disparity during fixations. This cannot be supported by the data obtained during the current experiment.

Consistent with the findings presented in Experiment 1, children's binocular coordination was unaffected by the size of the fixation target. It was predicted that children would demonstrate reduced fixation disparity magnitudes while fixating targets with reduced horizontal spatial extent. Similar to the adult data, this relationship was not found in the current data.

The results showed that children's binocular coordination was equivalent when fixating targets that appeared as onsets and for targets that were continuously available. This indicated that pre-programmed saccades and reflexive saccades are equivalent in terms of binocular coordination; this was also the case for adult participants described in Experiment 1. Furthermore, the effects were the same for children with dyslexia and typically developing children.

The current data strongly suggest that children's binocular coordination seems to be a low-level phenomenon that is driven primarily by the disconjuency arising during a saccade. This supports the conclusions previously drawn and reported in Chapter 1. The amplitude of the preceding saccade was found to modulate the magnitude of the subsequent fixation disparity. Increased saccadic amplitude equated to increased magnitudes of fixation disparity for both groups of child participants. One of the findings during the current investigation was somewhat counter intuitive, in that for children, fixations that located targets presented on the left of the screen were found to have smaller magnitudes of disparity than fixations to targets presented on the right Indeed of the screen. There is no immediate and obvious explanation for this finding. This result may represent a spurious result of the current experiment. This requires further investigation. During Experiment 3 disparity following a regressive eye movement and disparity following a forward saccade will provide the opportunity to follow this issue up.

Chapter Five

Binocular coordination during reading; adult, child and dyslexic populations

5.1 Introduction

The aim of Experiment 3 was to examine the characteristics of binocular coordination for adult, child and dyslexic populations during reading. As discussed in Chapter 1 it had been considered that, for reading to progress undisturbed, two precisely coupled retinal inputs were necessary for visual encoding and lexical identification. In Sections 1.3 (*Adults' binocular coordination during reading*) and 3.2 (*Children's binocular coordination during reading*) studies were reviewed that have demonstrated, in a range of experimental designs, that this assumption of precise binocular coordination during reading, is not always correct and that fixation disparity is frequently observed while adults and typically developing children read.

To summerise the findings, fixation disparity frequently occurs during reading; the mean disparity is regularly more than one character space, but rarely more than two. When the two eyes are not aligned at the point of fixation the direction of the disparity is more often uncrossed (where the right eye is further to the right than the left eye) than crossed (where the left eye is further to the right than the right eye, though see Nuthmann & Kliegl, 2009). Vergence movements in a corrective direction often occur and these reduce the disparity between the two eyes during fixations (although Blythe et al., 2006 failed to replicate this finding). However, despite these vergence movements, at the end of fixation some degree of disparity is still evident. These findings hold for both adults and typically developing children, although differences in the magnitude of disparity are found for these groups. A series of strong predictions follow, therefore, from the binocular coordination research for adult and typically developing child participants. Each one of these predictions will now be discussed in turn.

Based on the evidence briefly discussed above and reviewed in more detail in Chapters 1 and 3, the first prediction was that disparity would remain between the points of fixation for the two eyes until the end of fixation. This was predicted for adult participants as well as both groups of child participants (there was no reason to predict that children with dyslexia would demonstrate any less disparity during fixation than had been observed for typically developing children). The second prediction was generated on the basis of binocular coordination studies that have characterised the alignment of the eyes during fixation (e.g. Liversedge, White et al., 2006). Here the prediction follows that adults would demonstrate greater proportions of uncrossed than crossed unaligned fixations; where the prediction for children, based on the findings of Blythe et al. (2006), was that an increased amount of crossed unaligned fixations would be demonstrated compared to adults. However, proportionally more uncrossed than crossed fixations would also be found for children when the two eyes were unaligned.

Research comparing the binocular coordination of typically developing children and adults has demonstrated differences in the magnitude and the direction of fixation disparity during both reading and non-reading tasks (Blythe et al., 2006; Yang & Kapoula, 2003). The cognitive demands associated with processing linguistic stimuli are far greater for younger children (in particular those that have recently learnt to read), compared to older children and adult skilled readers who have years of reading experience. Hence any differences in binocular coordination between beginning and skilled readers could be due to a) the development of binocular coordination control, or b) linguistic processing difficulty. The pattern of results from Experiments 1 and 2 indicate that children's binocular coordination is somewhat less coordinated than adults in the absence of linguistic and cognitive processing. Therefore, comparisons of beginning and skilled readers show that while there are developmental differences in binocular coordination, these may not be attributable to the increased processing difficulty associated with reading for children. Therefore, the fourth prediction was that the magnitude of fixation disparity would be greater for children than for adults during reading.

Throughout this thesis, in which binocular coordination is explored, the experiments were designed to address two important theoretical issues: primarily, whether a link between binocular coordination and reading difficulties could be substantiated; but also, to investigate the factors (visual and cognitive/linguistic) which possibly influence binocular coordination. The results of Experiment 2 demonstrated that fixation disparity was no greater for children with dyslexia than for typically developing children, in a non-reading task that required no cognitive or linguistic processing. If linguistic processing difficulties were to influence binocular coordination, then during reading those children with reading difficulties may display a different pattern of disparity compared to adults and typically developing children that may find linguistic processing less demanding.

Recall that in studies aimed at investigating the effects of linguistic processing difficulties with adult participants, only one showed any significant effects on binocular coordination (Hendriks, 1996). However, it is well documented that increased processing demands during reading influence oculomotor control; typically, fixation durations are increased and saccadic amplitudes are reduced (Rayner, 1998). It has now been established that the magnitude of fixation disparity is significantly influenced by the amplitude of the preceding saccade (Experiments 1 and 2, this thesis); more specifically, the greater the amplitude of the preceding saccade the greater the magnitude of fixation disparity. This finding holds for both children as well as adults. Therefore the disparity effects evident in the data reported in Hendriks (1996) can equally be attributed to the influence of preceding saccade amplitude. While Heller and Radach (1999) claimed to have shown an effect of processing difficulty on binocular coordination, a more recent, and very thorough investigation, has failed to replicate their findings. Juhasz et al. (2006) found no effect of text difficulty on binocular coordination in skilled adult readers. Overall, text manipulations with skilled adult readers have found mixed results; however, on balance there is currently little robust evidence to suggest that for adults at least, cognitive processing difficulty influences binocular coordination, indicating that more precise binocular coordination is not necessary when reading text compared to scanning non-linguistic stimuli.

The results of several studies have shown that children tend to have greater magnitudes of disparity between the two points of fixation than adults during reading (Blythe et al., 2006) and during non-reading tasks (Experiment 2, in this Thesis). However, word frequency effects were not found for child participants in the study reported in Blythe et al. Therefore, they were unable to explore the effect of word frequency (i.e. linguistic processing difficulty) in their binocular coordination data for child participants.

The fifth prediction therefore, concerns the influence of processing difficulty on binocular coordination. A target word was included in each of the experimental sentences which were manipulated for frequency. The aim was to induce differences in processing difficulty and investigate a possible influence on binocular coordination. For adults binocular coordination has not been found to be significantly affected by processing difficulty (e.g. Juhasz et al., 2006). However, similar investigation into the affects of processing difficulty on binocular coordination has not been conducted with typically developing children or children with dyslexia. It is clear, therefore, that this is an area that requires further investigation. Therefore, the fifth prediction states that increased processing difficulty will differentially affect the binocular coordination of children with and without dyslexia compared to adults. It is suggested that beginner readers may be able to tolerate greater magnitudes of fixation disparity when reading more frequent words compared to when they read less frequent words.

Recall that Stein (2001) and others have suggested that visual deficits, such as unstable binocular coordination during fixation and poor vergence control can lead to letter and word processing difficulties (Eden, Stein, Wood, & Wood, 1994; Cornelissen, Bradley, Fowler, & Stein, 1992; Cornelissen, Munro, Fowler, & Stein, 1993; Evans & Drasdo, 1990; Kapoula et al., 2007; Stein & Fowler, 1993; Stein, Riddell, & Fowler, 1986; 1988). Specifically, it was claimed that individuals with dyslexia fail to make appropriate vergence movements during fixations in reading and, thus, experience an unstable visual percept from the two retinal inputs – letters moving around on the page. There are often anecdotal reports that dyslexic readers experience blurring of letters, letters moving around in a word, and letters obscuring one another. Intuitively the notion that fixation disparity disrupts the visual percept of the fixated word while children with dyslexia read fits well with these anecdotal reports.

There are, however, studies which have not found differences between groups of typically developing children and children with dyslexia in their capacity to verge the eyes. Experiment 2 of this thesis found no differences. Also Lennerstrand and colleagues conducted a longitudinal study, reported in a number of papers (e.g. Lennerstrand, Ygge, & Jacobson, 1993; Lennerstrand, Ygge, & Rydberg, 1994). A synoptophore test was used to examine vergence capacity and binocular eye movements were recorded during single sentence reading. With respect to the eye movement data, the amplitudes of the two eyes' saccades were compared to examine the asymmetry of the saccadic movements. Children with dyslexia were found to be equal to typically developing children with respect to vergence control on the synoptophore test. Interestingly, however, differences in saccade coordination were found on the reading task with greater binocular asymmetry (measured during saccades) in the children with dyslexia compared to the typically developing children.

The data reported in Lennerstrand et al. strongly suggest that an effect will occur during reading. Therefore, there is a clear possibility that children with dyslexia have a language specific deficit and differences in binocular coordination may be found between children with dyslexia and typically developing children. However, the results of Lennerstrand et al were based solely on saccadic asymmetry measures, rather than absolute magnitude of fixation disparity. It is the relatively still period, spent fixating the word, when cognitive and linguistic processing occurs. Therefore, it is important to investigate this time period of oculomotor control during reading. Furthermore, it is during a fixation that the influence of language processing difficulty would be most apparent. Note however, even if children with dyslexia are found to have greater disparity during fixation, whether this pattern of effects is likely to be caused by the condition of dyslexia itself, or a consequence of the condition may remain unclear.

Overall, the research conducted thus far, in relation to binocular coordination and dyslexia, led to the following predictions in regard to the magnitude of fixation disparity. Based on the results of Stein et al. (1981; 1982; 1983; 1988; 1989), Kapoula et al. (2007), Bucci, et al. (2008) and Jaschinski et al. (2004), the one prediction would state that fixation disparity would be increased for children with dyslexia compared to typically developing children. These groups of researchers have suggested that increased fixation disparity for children with dyslexia was caused by their deficient vergence movements during fixation. However, recall that in Experiment 2, children's binocular coordination was directly measured (compared to the indirect method of assessment the Dunlop Test provides) and the pattern of results then indicated that binocular coordination was not significantly different for the two groups of children during a non-reading task. Therefore, one might predict that the pattern of fixation disparity results for the two groups of children during the current reading task would be similar to that found during Experiment 2. The final prediction is based on the work of Lennerstrand et al. (1993; 1994). Recall that Lennerstrand and colleagues found no evidence to support the suggestion that children with dyslexia demonstrated a generic deficit in generating the small vergence movements in response to disparate stimuli; rather differences in the magnitude of asymmetry between the two eyes during saccades were found during the reading task alone. Therefore, while no between group differences were found during the non-reading task, increased fixation disparity for dyslexic compared to typically developing children was predicted during the reading task.

5.2 Method

Participants. The eleven adult participants were all students from the University of Southampton (Mean age = 21.09, SD = 3.05; age range = 18 – 26 yrs). The 16 child participants were recruited from local schools or through their attendance at Dyslexia Action, a national charity. Their age ranged from 8-12 years; mean age for the children with dyslexia was 11.05 with a SD 1.3. Mean age of the typically developing child participants was 10.04, with a SD 1.3. A subgroup of the participants with dyslexia was also tested during the non-reading study reported in Chapter 4. All participants had English as their first language with normal, uncorrected vision. Adult participants were either paid in cash or earned course credits for volunteering to take part. All participants were naïve as to the purpose of the experiment.

Apparatus. Two Dual Purkinje Image eye trackers were used to record binocular eye movements. Eye positions were monitored every millisecond. A Pentium 4 computer interfaced with the eye trackers and all the visual stimuli were presented on a Philips 21B582BH 24″ monitor. The sentences were presented in white, Courier New font size 14, on a black background. The room was dark except for a small dim indirect light source. The sentences were presented at a viewing distance of 100 cm. To minimise participants' head movements during the experiment, they were required to bite on a sterilised bite bar, which was covered with dental wax, to lean into two forehead rests, and to have a Velcro strap secured behind their head. This allowed for accurate oculomotor data to be obtained from both the right and left eyes.

Stimuli. Seventy two experimental sentences were constructed, 36 of which contained a high frequency target word and 36 containing a low frequency target word. Stimuli consisted of sentences with simple syntactic structures to ensure children's comprehension. All target words were controlled for word length (six characters long) and age-of-acquisition. The mean frequency for the high frequency words was 198 counts per million (range: 3 to 1926 per million) and the mean frequency for low frequency words was 19 counts per million (range: 0 to 105 per million). All target word frequencies were taken from the Children's printed word database (Department of Psychology, University of Essex), the target words in the stimuli were chosen as they would all be acquired by the age of 8 years old (AOA information obtained from The MRC psycholinguistic database, pp. 497-505; Coltheart, 1981). During the analyses of the data pertaining to adult observations, all frequency counts for adults were calculated based on The MRC psycholinguistic database, pp. 497-505; Coltheart, 1981) frequencies for the same target words as counts for adult readers are generally different (Joseph, Blythe, & Liversedge, 2009). The mean adult frequency for the high frequency words was 125 counts per million (range: 13 to 847 per million) and the mean frequency for low frequency words was 15 counts per million (range: 1 to 65 per million).

All sentences were between 46 and 67 characters long (including spaces) when displayed normally (i.e. no inter-letter spaces and one inter-word space). Examples of the stimuli with the word frequency manipulation are given in Table 5.1 In addition to the experimental sentences 12 practice sentences were constructed; six included a high frequency target word and six a low frequency target word which were similar to the experimental stimuli. These practice sentences were given to the dyslexic participants to ensure that they were able to accurately read sentences. All the dyslexic participants were able to accurately read the practice sentences. Furthermore, after 15% of the sentences, a comprehension question was presented, these were distributed randomly throughout the experiment, and participants used a consol to respond yes/no.

Table 5.1

Examples of the experimental sentences

Condition	Sentence
A high frequency target word	The workman carried the new *window* to the house they were building.
A low frequency target word	The workman carried the new *hammer* to the house they were building.

Reliability measure. Two separate questionnaires each containing half of the 72 experimental sentences was given to children recruited from year 3 (age 7-8 years old) attending a local infant's school. Ten children read the sentences aloud (to ensure that typically developing children around the age of 7 to 8 years old were able to accurately read the sentences). Participants were asked to rate the sentences on a 7-point scale where 1 was "very easy to read", and 7 was "very hard to read". All children were able to read the sentences and the mean ratings are shown in Table 5.2. Participants were further required to answer a simple "yes"/"no" question concerning the sentence; if they did not know the answer they were instructed to circle "not sure". All the experimental sentences had a mean rating below 2, and the results indicated that all sentences were suitable for the child participants to read and understand.

Table 5.2

Children's mean ratings on a 1-7 scale for sentence ease of reading and error rates for comprehension questions (standard deviation in parentheses).

Condition containing	Children 7-8 yrs (N = 10)	Percentage of correct answers	Percentage of incorrect answers	Percentage of not-sure answers
A high frequency target word	1.98 (1.3)	80%	10%	10%
A low frequency target word	1.78 (1.3)	75%	4.2%	20.8%

Procedure. All participants were instructed to read the sentences normally, to take care to comprehend the sentences and then answer the question when they were asked one as accurately as possible. Left and right eye calibrations were performed monocularly (e.g. when calibrating the left eye the right was occluded and vice versa). During calibration the participant was instructed to stare at one of three fixation points presented horizontally in the middle of the screen to the left, centre and right of the vertical midline. Monocular eye positions were recorded for each of these fixation points and then checked for accuracy. This was then repeated for the other eye. When calibration was completed the experimental stimuli were presented.

Following every three trials the calibration accuracy was checked and the participant recalibrated for each eye whenever this proved necessary.

Analysis. Fixations and saccades were manually selected. A custom-designed software package was utilised to analyse all data. The analyses were based on all valid fixations and saccades recorded during sentence reading. Fixations with durations of less than 80 ms, along with the subsequent saccade, were excluded from the analyses (624 fixations). A further 16 fixations were excluded due to them having durations that exceeded 1200 ms. A further 237 fixations and saccades were excluded from the disparity analyses due to an absolute end of fixation disparity greater than 2 SD from the mean for each participant. Also a further 340 fixations were excluded due to an absolute disparity of greater than 2 SD from the mean for each participant at fixation onset. Strict exclusion criteria ensure conservatism in respect of effects. All analyses were therefore taken from a data set consisting of 9112 fixations and saccades.

5.3 Results

Reading test results.

All child participants were again tested on a comprehensive battery of off-line tests. These were as described in Chapter 4 (Section 4.1 *Introduction*) and included measures of orthographic ability, reading skill, tested by the WAIT-11 divided into tests of reading comprehension, word reading and phonological ability, and exception word reading. All child participants were also tested using the WASI (Wechsler Abbreviated Scale of Intelligence, 1999), a measure of IQ.

Orthographic ability was tested by two, two-alternative forced-choice orthographic decision tasks; one used irregular words and the other regular words. There was a significant difference in the means for the irregular word list (TD children $\mu = 19.13$, SD = 1.35, Children with dyslexia $\mu = 15.63$, SD = 1.99; $t\ (14) = 4.10$, $p < 0.01$), however, no significant difference in the means for regular word list reading (TD children $\mu = 19.63$, SD = .74, Children with dyslexia $\mu = 17.75$, SD = 4.10; $t\ (14) = 1.27$, $p = 0.22$). Reading skill was assessed with the reading subtest of the WAIT-11. The results are presented in Table 5.3.

The standardised scores for the word reading subtest of the WAIT-11 provide a reading age for each participant. There was a significant difference between the reading age for typically developing children ($\mu = 12.09$, SD 2.04) and children with dyslexia ($\mu = 8.02$, SD 1.07; $t\,(14) = 4.59$, $p < .01$). Two subtests of the WASI (Wechsler abbreviated scale of intelligence, 1999) were administered to provide an IQ score for all children. There was no significant difference between typically developing children and children with dyslexia on scores of IQ as measured by the WASI (TD children $\mu = 108.89$, SD = 8.75) and (children with dyslexia $\mu = 106.00$, SD = 17.12; $t\,(14) = .38$, $p = .71$). Furthermore, there was no significant difference in the chronological age of typically developing children ($\mu = 10.04$, SD = 1.3) and children with dyslexia ($\mu = 11.04$, SD = 1.30; $t\,(14) = .94$, $p = .37$).

Table 5.3

Means and standard deviations for the reading subtests of the Wait-11and exception word reading for typically developing children and children with dyslexia.

	Pseudoword reading	Word reading	Comprehension	Exception word reading
TD Children	μ =106.00 SD = 8.75	μ = 105.50 SD = 9.40	μ = 117.50, SD = 9.35	μ = 41.25 SD = 3.33
Children with dyslexia	μ = 83.25 SD = 10.44	μ = 81.87 SD = 14.07	μ = 102.57 SD = 13.48	μ = 31.25 SD = 6.34
T-Tests	$t\,(14) = 4.72$, $p < .01$	$t\,(14) = 3.95$, $p < .01$	$t\,(14) = 2.52$, p < .05	$t\,(14) = 3.95$, $p < .01$

Global eye movement measures.

The mean fixation durations, saccade lengths and regression frequencies were calculated (presented in Table 5.4). As can be seen in Table 5.4, children made, on average, longer fixations, shorter saccades and more regressions than adults during reading. Furthermore children with dyslexia made, on average, longer fixations, shorter saccades and more regressions than the typically developing children. A series of one way ANOVAs were conducted on the results of mean fixation duration, saccade length and regression frequency. There was a significant difference between the groups (duration $F_1\,(2, 24) = 10.85$, $p < .01$; saccade length $F_1\,(2, 24) = 4.63$, $p <$

.05; and regressions F_1 (2, 24) = 4.25, $p < .05$). With Bonferroni corrections mean fixation duration was significantly increased for typically developing children and children with dyslexia compared to that found for adults (p's < .01). Children with dyslexia had significantly reduced mean saccade amplitude compare to that observed for adults ($p < .001$) and increased frequency of regressive eye movements to that observed for adults ($p < .001$). However, all other independent samples t-tests with Bonferroni correction were non significant (p's > .05). The differences between typically developing children, children with dyslexia, and adults, in measures of oculomotor behaviour during reading, although not significant, largely reflect increased processing difficulty for children compared to skilled adult readers, which is amplified for children with dyslexia compared to typically developing children. There was a significant main effect of the mean number of fixations made over the entire sentence (F (2, 24) = 15.50, $p < .01$). Adults made significantly fewer fixations than typically developing children $p < .01$ and children with dyslexia $p < .01$. While there was again a numerical increase in the mean number of fixations for children with dyslexia compared to typically developing children this was not significant ($p > .05$). Furthermore for mean total sentence reading time there was a main effect (F (2, 24) = 16.71, $p < .01$). Again it was found that adults had a significantly reduced total reading time compared to that found for typically developing children ($p < .01$) and children with dyslexia ($p < .01$). While again there was a numerical trend in the data to suggest children with dyslexia were taking longer to read the sentences than typically developing children this was not significant ($p > .05$). The developmental trends in these data are similar to those reported by Rayner (1986); and these data demonstrate that all three participant groups were reading normally.

The accuracy scores for the comprehension questions further demonstrate that all participants, regardless of reading ability, were able to read and understand the sentences without any difficulty. The mean score for adults was 98% correct, for typically developing children 94% correct and for children with dyslexia 88% correct. A One-Way ANOVA was conducted and showed that these were not significantly different between the three groups F (2, 24) = 2.41, $p = .11$.

Here it may be helpful to combine the findings of the off-line and on-line data thus far. The off-line measures of several literacy tasks clearly demonstrated significant differences between the performances of the children with dyslexia compared to that found for the typically developing children, where as the global eye movement measures did not show differences between the two groups of children. Clearly this inconsistency needs to be addressed. Note that typically developing children were somewhat younger than the children with dyslexia this may have contributed to the non significant differences for typical measures of eye movement behaviour during reading. However, more importantly, the experimental sentences were specifically designed to be easily read by both groups of children (with and without dyslexia). Therefore, by creating simple sentences accurate measurement of typical oculomotor coordination as it occurred during reading was ensured. To reiterate, while it was important on the one hand to verify that the child participants were correctly diagnosed as dyslexic, it was equally important to ensure that sentences were being read for meaning and not simply being superficially scanned without comprehension. As these data indicate while the children with dyslexia have significantly worse performance during the off-line tasks, they were able to read and understand the stimuli that were presented.

Table 5.4.

Mean number of fixations and duration, saccade length, regression frequency and mean total reading times for adults, typically developing children and children with dyslexia. Standard deviations are shown in parentheses.

	Fixation duration (ms)	Saccade length (characters)	Regression frequency (%)	Mean number of fixations	Mean total reading time (ms)
Adults	195 (81.8)	7.3 (5.1)	18.6 (8.8)	9 (2.8)	1741 (572)
Typically developing children	231 (104.1)	6.4 (4.9)	26.2 (5.8)	13 (4.3)	3105 (1091)
Children with dyslexia	244 (123.4)	5.5 (5)	28.4 (7.1)	16 (6.1)	4075 (1695)

End of fixation disparity analysis

Following the same categorisation criteria as described in Chapter 2 (section 2.3) and in line with Liversedge et al. (2006), fixations were defined as aligned or unaligned. To be considered an aligned fixation the points of fixation of the two eyes were required to be within one character space of each other (0.24°). Unaligned fixations were those occasions when the disparity between the two points of fixation for the eyes was greater than one character space. The unaligned fixations were further categorized into uncrossed (where the right eye was further to the right than the left eye) and crossed fixations (where the left eye fixated further to the right than the right eye fixated).

Table 5.5 shows the mean disparity magnitudes at the end of a fixation. This measure is taken after any vergence movements during a fixation had occurred. Therefore, this was considered the most conservative sample point during fixation at which to measure the magnitude of fixation disparity. The data are based on all valid fixations that occurred at any point during reading of the sentence (see exclusion criteria in Section 5.2 method subsection *Analysis* P112); furthermore, these are fixations which occurred after both regressive saccades and forward saccades.

Table 5.5

Mean absolute magnitude of fixation disparity, shown as character spaces; standard deviations are shown in parenthesis.

	Adults	Typically developing children	Children with dyslexia
Start of fixation disparity (characters)	1.1 (1.14)	1.02 (.82)	2.6 (2.85)
End of fixation disparity (characters)	1.1 (1.15)	.97 (.82)	2.6 (2.85)

The data show that at the end of fixation the mean fixation disparity for adults was 1.1 character spaces. For typically developing children, the end of fixation disparity magnitude was .97 character spaces. For children with dyslexia, the end of fixation disparity between the positions of the two eyes had a mean magnitude of 2.6 character spaces. One-sample *t*-tests were conducted to compare the mean absolute disparity to one character space (0.24° visual angle); this was to determine if the eyes always fixated within one character space within a word for all three participant groups. The *t*-tests showed that for both adult (*ts <2.03*) and typically developing children (*ts* < *0.*45) the mean disparity between the positions of the two eyes was not significantly greater than one character. For the children with dyslexia however, the mean absolute disparity between the two eyes was significantly greater than one character space (t_1 (7) = 2.31, *p* = .05; t_2 (35) = 7.32, *p* < .01).

A one-way ANOVA comparing the mean absolute disparity in adults, typically developing children and children with dyslexia (data presented in Table 5.6) showed that there was a significant effect of group on absolute end of fixation disparity (F_1 (2, 24) = 4.10, *p* = .03; F_2 (2, 105) = 47.70, *p* < .01). The Dunnett *t*-test was used and treated the dyslexic group as a control, and compared the typically developing child group and the adult group against this value. A one tailed hypothesis was considered based on the prediction that children with dyslexia would demonstrate significantly greater disparity magnitudes than observed for adults, and typically developing children.

Table 5.6

Absolute disparity magnitudes at fixation onset, and offset differences between the two eyes for each of the participants tested in the three groups during reading single sentences. Standard deviations are provided in parentheses.

	Adult participants		Typically developing children		Children with dyslexia	
Participant	Absolute disparity magnitudes at fixation onset	Fixation disparity at offset	Absolute disparity magnitudes at fixation onset	Fixation disparity at offset	Absolute disparity magnitudes at fixation onset	Fixation disparity at offset
1	0.21 (.17)	0.20 (.16)	0.14 (.11)	0.14 (.10)	0.64 (.38)	0.65 (.38)
2	0.43 (.21)	0.42 (.20)	0.16 (.15)	0.15 (.13)	0.81 (.39)	0.80 (.40)
3	0.27 (.15)	0.24 (.13)	0.27 (.18)	0.27 (.18)	0.42 (.31)	0.41 (.29)
4	0.16 (.11)	0.16 (.12)	0.53 (.32)	0.52 (.36)	1.30 (1.16)	1.30 (1.16)
5	0.29 (14)	0.27 (.13)	0.26 (.16)	0.23 (.14)	0.48 (.17)	0.43 (.14)
6	0.75(.54)	0.74 (.52)	0.21 (.15)	0.18 (.14)	0.23 (.14)	0.24 (.15)
7	0.21 (.13)	0.21 (.15)	0.35 (.16)	0.33 (.15)	0.32 (.19)	0.31 (.19)
8	0.12 (.09)	0.12 (.08)	0.15 (.11)	0.15 (.11)	0.19 (.12)	0.19 (.12)
9	0.11 (.07)	0.09 (.06)				
10	0.17 (.14)	0.17 (.22)				
11	0.12 (.11)	0.13 (.15)				
Mean	0.26 (.27)	0.26 (.28)	0.25 (.20)	0.23 (.20)	0.63 (.68)	0.62 (.68)

These contrasts revealed that the group diagnosed dyslexic demonstrated significantly increased disparity between the positions of the two eyes at the end of fixation compared to adults (for participants $p = .02$; and items $p < .01$) and typically devloping children (for participants $p = .02$; and items $p < .01$). These results indicate that disparity magnitudes at the end of fixation found to occur in children with dyslexia during reading are significantly greater than those found for adults and typically developing children of a similar age. The mean proportions of alignment at the end of fixation are shown in Table 5.7.Similar to Liversedge, White et al. (2006a) and Blythe et al. (2006) we categorised fixations as aligned or unaligned. To reiterate, aligned fixation were those where the fixation points of the two eyes were within one character space of each other (.24°). Therefore an unaligned fixation represented an absolute disparity of more than one character (greater than .24°). Unaligned fixations were further categorised into those that were uncrossed and those that were crossed. The mean proportions of aligned, uncrossed and crossed fixations at the start and end of fixations are presented in Table 5.7.

For adults and typically developing children numerically more fixations were found to be aligned, fixations were uncrossed less often and crossed least often. One sample *t*-tests, for the adult data, comparing the proportion of aligned fixations to chance (50%) showed the eyes were not significantly more often aligned than chance at the end of a fixation for participants ($ts < 4.96$) this was also the case for typically developing children ($ts < 4.79$). Although these t values may appear high, it is important to note that, here and later in the chapter, that no effects were reliable both by participants and items. These results indicate that while fixation disparity is frequent during reading, there was a numerical trend towards more aligned fixations to occur than unaligned at the end of a fixation for adults and typically developing children. The majority of all valid fixations made by children with dyslexia were unaligned. Again a one-sample t-test compared the proportion of aligned fixations to chance (.5), and here it was found that the proportion of aligned fixations was reaching significance ($t_1\ (7) = 2.26, p = .06$; $t_2\ (35) = 8.93, p < .01$). This indicated that, in contrast to adult and typically developing children, when children with dyslexia read, the fixation points of the two eyes were numerically more frequently disparate than chance.

Table 5.7

Mean alignment proportions at the start and end of fixation (all percentages have been rounded to whole numbers)

	All start data (%)	End aligned (%)	End Uncrossed (%)	End crossed (%)
Adults				
All end data		62	27	11
Start Aligned	60	94	3	3
Start Uncrossed	30	15	84	0
Start Crossed	10	16	0	84
TD Children				
All end data		60	29	11
Start Aligned	57	90	5	4
Start Uncrossed	33	22	78	0
Start Crossed	10	16	0	84
Children with dyslexia				
All end data		29	55	16
Start Aligned	29	86	8	6
Start Uncrossed	56	13	87	0
Start Crossed	15	12	0	88

A one-way ANOVA compared the proportions of aligned fixations between groups (adults, TD children and children with dyslexia) and showed there was a significant difference between groups (F_1 (2, 24) = 4.20, $p < .05$; F_2 (2, 105) = 69.27, $p < .01$). Further, three independent samples *t*-tests comparing the proportion of aligned fixations between the three groups, found that children with dyslexia made significantly fewer aligned fixations than adults (t_1 (17) = 2.67, $p = .02$; t_2 (70) = 9.95, $p < .01$) and fewer compared to typically developing children (t_1 (14) = 2.44, $p = .03$; t_2 (70) = 9.94, $p < .01$). However, there was no significant difference in the proportions of aligned fixations made by adults and typically developing children (t_1 (17) = .35, $p = .73$; t_2 (70) = .45, $p = .65$). To summarise the results for the end of fixation analyses, children with dyslexia were found to have greater magnitudes of fixation disparity and fewer aligned fixations compared to adults and typically developing children.

For adults 38% of all valid fixations were disparate by the magnitude of one character space or more at the end of fixation. A mean of 40% of all valid fixations were unaligned for typically developing children and 71% for children with dyslexia. The unaligned fixations were further categorised as either crossed or uncrossed. Again, since these two categories are dependent, comparisons of the probability of making an uncrossed fixation against chance (50%) also held for the proportions of crossed fixations. One sample *t*-tests were conducted to compare the proportion of uncrossed fixations, for all groups, to chance. These showed that for the end of fixation data, when the two eyes were not aligned, the proportion of uncrossed fixations were significantly higher than chance (50%), for typically developing children (t_1 (7) = 2.07, $p = .07$; t_2 (35) = 8.43, $p < .01$) and for children with dyslexia (t_1 (7) = 3.85, $p < .01$; t_2 (35) = 9.37, $p < .01$). For adults, a comparison of the proportion of uncrossed fixations to chance was not significant (*ts* < 8.08). Therefore for all participant groups, numerically at least, when the eyes were in an unaligned position at the end of fixation, the pattern of alignment was more often uncrossed than chance (50%).

A One way ANOVA was conducted and showed that proportions of uncrossed (and therefore crossed owing to the dependent nature of the results) were equivalent for all three participants groups (F_1 (2, 24) = .94, $p = .41$; F_2 (2, 105) = 1.26, $p = .29$). These results indicate that when the eyes were not aligned to within one character space in a word, the pattern of alignment was found to be more often uncrossed than crossed. Therefore, while children with dyslexia were found to have a reduced proportion of aligned fixations when their eyes were unaligned their alignment was in the same pattern (i.e. uncrossed) as adults and typically developing children.

To summarise, at the end of fixation children with dyslexia had greater disparity magnitudes than adults and typically developing children and they also had a higher proportion of unaligned fixations than adults and typically developing children. When the eyes were in an unaligned position at the end of fixation all participant groups were found to have significantly more uncrossed than crossed fixations. Proportions of uncrossed fixations were further found to be equivalent for the three participant groups.

Start of fixation disparity analyses

The disparity magnitudes and the proportion of alignment for the disparity were also examined at the start of fixations. These analyses were undertaken to examine first, whether disparity characteristics are the same at the start of fixation compared to the end of fixation; and second to assess differences between the start and end of fixation to examine the nature of vergence movements that occurred during the fixations. Absolute disparity for the start of the fixation was taken at the initial offset of the preceding saccade. Again the alignment of disparity was categorised as aligned or unaligned and unaligned fixations were further categorised as uncrossed and crossed.

Table 5.5 shows the mean absolute disparity magnitudes at the start of fixation for all participant groups. As before these data were calculated for all valid fixations made during the experiment. The start of fixation, mean disparity magnitudes in character spaces were; adults 1.1, 1.02 for typically developing children and 2.6 for children with dyslexia. One-sample *t*-tests for adults and typically developing children comparing start of fixation absolute disparity with one character space (.24°) showed that the disparity between the two eyes at the start of fixation was no greater than one character space (adults *ts* < 2.38; typically developing children *ts* < 0.97). However, as with the end of fixation data, start of fixation disparity for children with dyslexia was significantly greater than one character space (t_1 (7) = 2.28, $p = .05$; t_2 (35) = 7.56, $p < .01$). A one-way ANOVA comparing the mean absolute disparity at the start of fixation for adults, TD children and children with dyslexia showed that there was a significant effect of group on absolute disparity magnitude (F_1 (2, 24) = 4.16, $p = .03$; F_2 (2, 105) = 47.96, $p < .01$). The Dunnett *t*-tests were again used and treated the group consisting of children with dyslexia as a control with which typically developing children and adult's disparity magnitudes were compared. As before a one tailed hypothesis was considered as it was predicted that disparity magnitudes for children with dyslexia would be significantly greater than found for adults, and typically developing children. This was indeed the case in comparison to the adult data (for participants $p = .01$; and items $p < .01$) and compared to the typically developing child data (for participants $p = .02$; and items $p < .01$). Thus the start of fixation data was consistent with the end of fixation data, where children with dyslexia had significantly greater fixation disparity than both adults and typically developing children.

The mean proportions of aligned, uncrossed and crossed fixations at the start of fixations are presented in Table 5.7. As was the case for end of fixation alignment proportions to be considered as an aligned fixation, the fixation points of the two eyes were required to be within one character space of each other (.24°). Therefore, an unaligned fixation represented an absolute disparity of more than one character (greater than .24°). Unaligned fixations were further categorised into those that were uncrossed and crossed fixations. Again a one way ANOVA was used to directly compare the proportion of aligned fixations observed in all three participant groups (adults, TD children and children with dyslexia). As was the case for the end of fixation results, the analyses showed that the proportions of aligned fixations for the three groups were significantly different (F_1 (2, 24) = 4.16, $p < .05$; F_2 (2, 105) = 47.96, $p < .01$). Further, three independent samples *t*-tests comparing the proportion of aligned fixations between the three groups, showed that children with dyslexia made significantly fewer aligned fixations than adults (t_1 (17) = 2.49, $p = .02$; t_2 (70) = 10.24, $p < .01$) and fewer compared to typically developing children (t_1 (14) = 2.14, $p < .05$; t_2 (70) = 9.56, $p < .01$). However, there was no significant difference in the proportions of aligned fixations made by adults and typically developing children (t_1 (17) = .45, $p = .66$; t_2 (70) = .94, $p = .35$). Therefore, at the start of fixation children with dyslexia demonstrated a similar pattern of binocular coordination as had been found at the end of fixation. Disparity magnitudes were found to be greater for children with dyslexia compared to that found for adults and typically developing children and they also had a higher proportion of unaligned fixations than adults and typically developing children. Therefore, for children with dyslexia fixation disparity was not only larger but it was also more frequent.

Finally, in respect to disparity alignment, the proportions of those fixations categorised as unaligned at the start of fixation were compared. Initially three One-sample *t*-tests were conducted to compare the proportions of uncrossed fixations to chance (50%) for adults (t_1 (10) = 1.38, $p = .20$; t_2 (35) = 10.29, $p < .01$), TD children (t_1 (7) = 2.90, $p = .02$; t_2 (35) = 11.37, $p < .01$), and children with dyslexia (t_1 (7) = 4.26, $p < .01$; t_2 (35) = 9.91, $p < .01$). It was found that for all child participants when the two eyes were unaligned at the start of fixation the eyes were significantly more often uncrossed than chance. For adults, while there was a numerical trend to suggest the two eyes were more often uncrossed than chance, this was not found to be significant. Again a one way ANOVA was conducted, similar to the end of fixation data, it was found that at the start of fixation the proportions of uncrossed (and therefore crossed owing to the dependent nature of the results) were equivalent for all three participants groups (F_1 (2, 24) = .68, p = .59; F_2 (2, 105) = 1.07, p = .35).

To summarise, the pattern of data regarding fixation disparity magnitudes at the start of fixation were very similar to those taken at the end of fixation. There was greater disparity for children with dyslexia than for either adults or typically developing children both at the start and end of a fixation. On average the magnitude of disparity for all participant groups was greater than one character space, and for children with dyslexia this was greater than 2 character spaces. Furthermore, children with dyslexia made fewer aligned fixations than adults and typically developing children at the start and end of fixation. However, the proportion of uncrossed fixations was similar for all participant groups, where it was shown that if the eyes were unaligned at the start and end of fixation they were more often uncrossed than chance. However, note that, as described above, some effects were not significant in the participant analyses.

Comparison of start and end of fixation disparity

Comparisons were conducted between the disparity magnitudes that occurred at the start and the end of fixation for all three participant groups. These analyses were conducted to examine whether any movements of the two eyes occurred during fixation, and whether these movements during fixation differed between groups (adults, TD children and children with dyslexia). Table 5.5 shows the mean disparity magnitudes for all participant groups, presented as character spaces. Figure 5.1 shows the frequency distribution of fixation disparity (at the start and end of fixation) for the three participant groups.

A 3 (participant group: adults, TD children and children with dyslexia) x 2 (sample point in fixation: start vs. End) repeated measures ANOVA showed a marginal main effect of group (F_1 (2, 14) = 3.11, p = .07; F_2 (2, 70) = 50.78, p < .01); this indicates that children with dyslexia had greater magnitudes of disparity both at the start and end of fixation compared to those found for adult and typically developing child participants. There was also a significant main effect of sample point in fixation (F_1 (2, 14) = 7.00, p = .03; F_2 (1, 35) = 41.08 p < .01); this result indicates that the mean for the start of fixation disparity magnitude was significantly reduced by the end of fixation. There was no significant interaction between group and sample point in fixation (F_1 (2, 14) = .33 p = .72; F_2 (2, 70) = 1.08, p = .35). The result indicates that the oculomotor control system was equally efficient at reducing fixation disparity for three participant groups. Note that these are equiverlant despite there being differences in disparity.

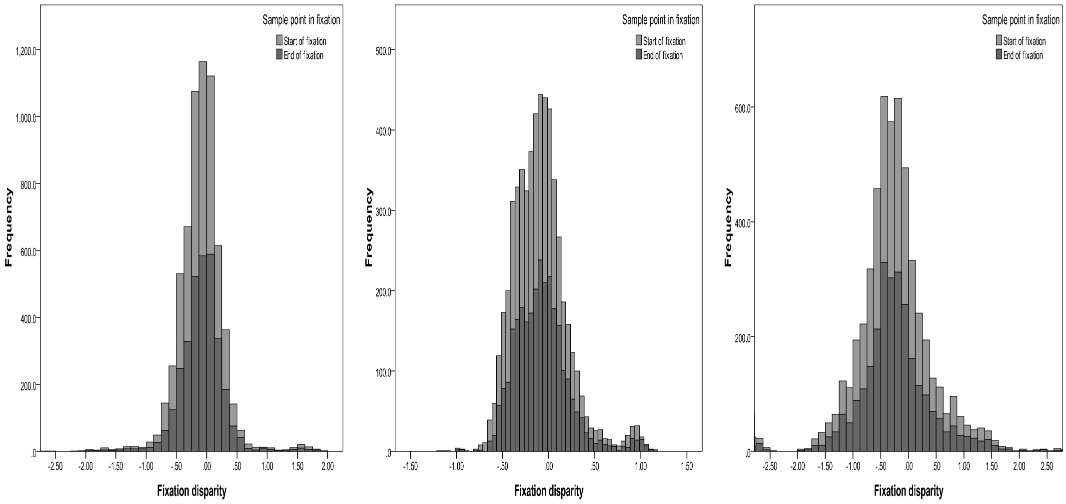

Figure 5.1

Distribution of start and end of fixation disparity, obtained during reading. A negative number represents an uncrossed fixation. Left panel represents disparity data for adult participants, centre panel data for typically developing children and right panel data for children with dyslexia.

Table 5.7 shows the overall alignment patterns both at the start and end of fixation for all groups. Table 5.7 also shows the end of fixation alignment (aligned, uncrossed and crossed) as a function of start of fixation alignment. Repeated measures ANOVAs were again conducted to investigate differences in the proportion of aligned fixations at the start and end of fixation for the three participant groups. Although the effect only approached significance, the numerical trend in the data suggested that children with dyslexia made fewer aligned fixations than adults and TD children, both at the start and end of fixation (F_1 (2, 14) = 2.93 p = .08; F_2 (2, 70) = 71.73, $p < .01$). There was a reliable main effect of sample point in fixation (F_1 (1, 7) = 12.36 p = .01; F_2 (1, 35) = 22.80, $p < .01$), where the proportion of aligned fixations at the end of fixation was greater than the proportion of aligned fixations at the start of fixation. There was no significant interaction between group and sample point in fixation (F_1 (2, 14) = 1.25 p = .32; F_2 (2, 70) = 4.44, p = .02), indicating that for all participant groups the proportion of aligned fixations increased from start of fixation to the end of fixation.

Finally repeated measures ANOVAs were conducted on the proportions of unaligned fixations at the start and end of fixation (uncrossed proportions were used but hold for crossed due to the dependent nature of the data). There was no effect of group where all three groups showed statistically similar proportions of uncrossed fixations (F_1 (2, 14) = .70 p = .51; F_2 (2, 70) = 1.10, p = .39), however, the effect of sample point in fixation was reaching significance (F_1 (1, 7) = 5.31 p = .06; F_2 (1, 35) = 32.18, p < .01), where the mean proportion of uncrossed compared to crossed fixations decreased during a fixation. This was the case for all participant groups, since there was no significant interaction between group and sample point in fixation for the proportion of uncrossed fixations (F_1 (2, 14) = 1.85 p = .19; F_2 (2, 70) 2.43, p = .10).

In summary, group differences were shown in both the magnitude of fixation disparity and the alignment of the eyes at both the start and end of a fixation. Here it was shown that children with dyslexia exhibited significantly greater magnitudes of disparity than adults and TD children at both the start and end of fixation. However, all three participant groups significantly reduced the magnitude of disparity between the start and end of fixation. Furthermore, although fewer aligned fixations occurred for the children with dyslexia than occurred for adults and TD children, all participant groups showed increased proportions of aligned (compared to unaligned) fixations at the end compared to the start of fixation. Finally, if the eyes were unaligned, they were more likely to be uncrossed than crossed at both start and end of fixation, however, there was a reduction in the proportion of uncrossed compared to crossed fixations between the start and end of fixation.

Movement during fixation

Previous research has described vergence eye movements that occur during fixation; here the aim was first, to precisely characterise the nature of these movements and second to determine whether there were significant differences between the three groups of participants (adults, TD children and children with dyslexia). Four main categories were identified; first stable, where both eyes moved less than (or equal to) 10% of a character space (.02°). Only 16% of adults, 8% of TD children and 9% of children with dyslexia's fixations were stable using this criterion. There was a reliable difference between groups in the proportion of stable fixations to occur (F_1 (2, 24) = 8.62, p < .01; F_2 (2, 105) = 46.23, p < .01). Post hoc comparisons showed that adults made significantly more stable fixations than TD children and children with dyslexia (*p* s< .01) but there was no significant difference between the proportion of stable fixations for TD children and children with dyslexia (*p* s> .05).

The second category was drift movements, where the eyes move in the same direction for an equal amount and the difference in the movement for the two eyes was less than .02°. The three groups of participants were shown to make similar proportions of drift movements, adults 11%, TD children 11% and children with dyslexia 12% (F_1 (2, 24) = 1.34, *p* >.05; F_2 (2, 105) = .31, *p* > .05).

Of all the valid fixations 78% showed a difference in movement between the two eyes that represented more than 10% of a character space. These fixations are defined as those where vergence movements occurred. These were further defined in relation to the final two categories. The third category was convergence, where the fixation positions for the two eyes verge nearer to one another; where one or both eyes move more than 10% of a character space during fixation. For adults convergence occurred in 48% of all fixations, for TD children 54% of all fixations, and for children with dyslexia 49%.

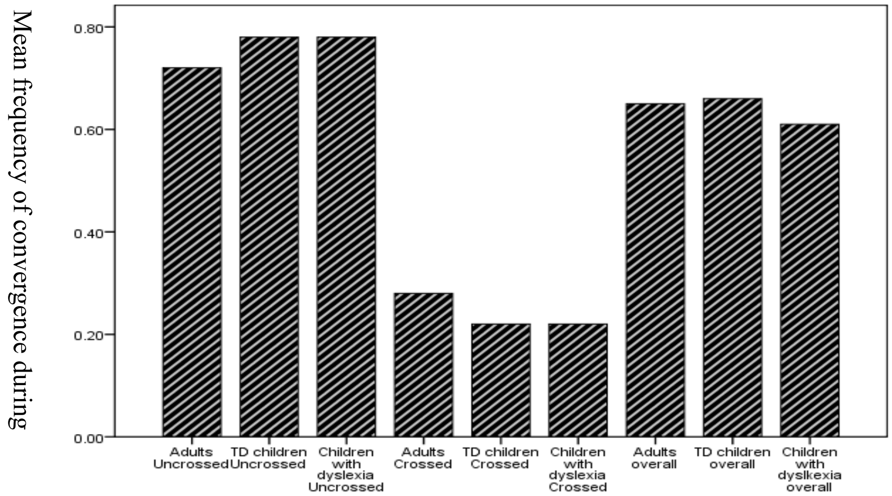

Figure 5.2

The proportion of convergence movements during a fixation as a function of fixation alignment (crossed and uncrossed) in adults, TD children and children with dyslexia.

Figure 5.2 shows the proportion of convergent movements observed during fixation as a function of start of fixation alignment (crossed and uncrossed) and the overall convergent proportions. The final category is divergence, where the point at which the eyes' lines of sight cross moves away from the viewer. Again divergence was defined as being caused by one or both eyes moving more than 10% of a character space during fixation. For adults divergence occurred in 25% of all fixations, for TD children 27% of all fixations, and for children with dyslexia 31%. A one way ANOVA showed that children's eyes diverged numerically more often made numerically more divergence during fixation than adults, though this was not significant (F_1 (2, 24) = 1.89, p >.05; F_2 (2, 105) = 13.18, p < .05). Post Hoc bonferroni tests indicated that TD children made no more divergent movements during fixation than adults (p > .06); though children with dyslexia made more divergent fixations than adults (p < .01) and TD children (p = .02). Taken together, these data indicate that for both adults and children, when the eyes move in a non-parallel way during fixation this is more often converging the points of fixation than diverging them. However, children with dyslexia make more divergent movements than adults and TD children.

To summarise, during fixation the eyes were more likely to make small movements than to remain stable. Furthermore, these movements were more often vergence than drift movements. While adults were shown to make more stable fixations there was no significant difference in the proportion of stable fixations for TD children and children with dyslexia. For all participants it was more likely that vergence movements were convergent, however, children with dyslexia made significantly more divergent movements than did adults and typically developing children. During the current series of experiments, designed to explore binocular coordination, the focus had primarily been on the either the magnitude or direction of fixation disparity. However, Stein and colleagues suggested that inappropriate or inadequate vergence control led to increased fixation disparities which in turn made the possibility of fusing the disparate retinal inputs more difficult and this was a cause of dyslexia. The pattern of data described above, describing vergence movements during fixation, indicated that the difference shown in the magnitude of fixation disparity, between dyslexic and non-dyslexic participants (adults and children), was not due to inappropriate or inadequate vergence control.

The effect of word frequency

In all of the sentences a target word was included. This target word was either a high frequency or a low frequency word but matched on other characteristics including age of acquisition and word length. The target word was included to investigate whether linguistic processing difficulty modulated the magnitude of fixation disparity at the end of fixation. This would also allow for the examination of differences in modulatory effects of frequency between groups (adults, TD children and children with dyslexia).

First fixations on the target word of less than 80 ms and more than 1200 ms were excluded from the analyses; this accounted for 4% of the data for adult participants, 8% of data for TD child participants and 8% of all the data for children with dyslexia. During the analyses of fixation disparity, disparities that were larger than the mean + 2SD both at the start and end of fixation were excluded. This accounted for 15% of all end disparity data (5% made by adults, 3% made by TD children and 6% made by children with dyslexia).

It was anticipated that the frequency manipulation would induce processing difficulties for all participant groups. Therefore, first fixation, gaze duration, regression path duration, total reading time and the total number of fixations were all calculated for the target word for all three groups; these are presented in Table 5.8.

Table 5.8

Mean (and SD in parenthesis) first fixation duration, first pass duration, total reading time regression path and number of fixations for target word analyses for all participant groups

	Adults		Typically developing children		Children with dyslexia	
Target word	High frequency	Low frequency	High frequency	Low frequency	High frequency	Low frequency
First fixation duration (ms)	195 (51)	189 (34)	218 (33)	239 (34)	209 (33)	286 (79)
Gaze duration (ms)	212 (48)	207 (31)	286 (82)	349 (108)	371 (66)	443 (128)
Number of fixations	1.38 (.41)	1.33 (.30)	1.89 (.38)	2.89 (.30)	2.39 (.53)	2.62 (.36)
Total reading time (ms)	253 (70)	246 (48)	414 (71)	524 (123)	515 (143)	655 (137)

Consistent with a large number of studies which have found that low frequency words induce longer reading times than high frequency words (see

Rayner, 1998), the frequency of the target word was found to significantly affect measures for first fixation duration (TD children, t (7) = 2.39, $p < .05$; children with dyslexia t (7) = 2.55, $p < .05$), the number of first pass fixations was also affected by the frequency of the target word (TD children t (7) = 2.78, $p < .05$; children with dyslexia t (7) = 2.54, $p < .05$) and also the total reading time was affected by the frequency manipulation (TD children t (7) = 3.42, $p < .01$; children with dyslexia t (7) = 4.75, $p < .01$). However, the frequency of the target word was not found to significantly affect gaze durations for typically developing children (t (7) = 1.40, p = .20) nor for children with dyslexia (t (7) = 1.64, p = .15).

Not surprisingly no effect of frequency was found in the adult data as the target words used in the experiment were extremely easy to read so as to ensure that children of all reading abilities were able to comprehend them, all t s < .90.

Consistent with the suggestion that fixation disparity is not influenced by the frequency of a word (Juhasz et al., 2006) there was no reliable evidence for a modulatory effect of frequency on the magnitude of fixation disparity at the end of fixation for typically developing children (t_1 (7) = 1.44, p = .19; t_2 (30) .= 84, p = .41) and for children with dyslexia (t_1 (6) .36, p = .73; t_2 (27) = .27, p = .79).

5.4 Discussion

I will first summarise the start and end of fixation data. 1) All participants had disparity between the points of fixation for the two eyes. However, children with dyslexia had significantly greater magnitudes of disparity compared to TD children and adults. 2) When the eyes were unaligned during fixation, all participants were more likely to fixate in an uncrossed rather than a crossed pattern of alignment. However, children with dyslexia had an increased proportion of crossed fixations compared to TD children and adults. 3) For all participants, vergence movements occurred in the majority of valid fixations. The majority of vergence movements were convergent where the two eyes points of fixation are drawn together, and as such the magnitude of fixation disparity was reduced. However, children with dyslexia were found to have significantly greater proportions of divergent vergent movements compared to TD children and adults.

The aim of Experiment 3 was to examine the characteristics of binocular coordination for adult, child and dyslexic populations during reading. The data showed that, similar to the results reported by Liversedge, White et al. (2006), fixation disparity frequently occurred and was found to be regularly more than one character space, but rarely more than two for adults and typically developing children. However, children with dyslexia showed an increased magnitude of disparity between the points of fixation for the two eyes, compared to adults and TD children and the disparity was significantly greater than one character space. Therefore, it was less likely for children with dyslexia to align their eyes within one character space during fixation than it was for adults and typically developing children, this was shown at the start and end of fixation. When the two eyes were not aligned (disparity between the points of fixation for the two eyes greater than one character space, measuring .24°) at the plane of the screen, the direction of the disparity was found to be more often uncrossed (where the right eye was further to the right than the left eye) than crossed (where the left eye was further to the right than the right eye) for all participant groups. Though for children with dyslexia there was an increased proportion of crossed fixations compared to the number of crossed fixations for adults and typically developing children. Vergence movements in the corrective direction were shown to reduce the magnitude of disparity between the two eyes during fixations. The eyes were more likely to verge during a fixation than remain stable. These movements were more often convergent than divergent. However, children with dyslexia showed a significant increase in the proportion of divergent movements compared to adults and typically developing children.

Lets us now consider these findings in relation to the predictions that were made in the introduction of this Chapter. The first prediction was that disparity would remain between the points of fixation for the two eyes until the end of fixation, for both adult participants and child participants. The end of fixation measure of disparity was taken after any vergence had occurred during the fixation; therefore this point during fixation was considered the most conservative point in respect to disparity magnitudes. Although disparity was found between the two points of fixation throughout a fixation, at the end of fixation, mean disparity magnitude for adults (1.1) and typically developing children (.97) was not significantly greater than one character space. However, for children with dyslexia (2.6) this was not the case, mean disparity magnitudes of more than one character space were found for this group of children. Furthermore, the disparity for the children with dyslexia was significantly greater than that found for typically developing children and adults. It has been shown in prior studies that the two eyes are frequently unaligned during fixation, with the two eyes fixating on different letters within a word. For these fixations, where the eyes are unaligned, the direction of alignment has been further categorised as uncrossed (the right eye further to the right than the left eye by more than one character space) and crossed (the left eye more to the right than the right eye by more than one character space).

The alignment characteristics of fixation disparity during reading are well-established in adults (Liversedge, White et al., 2006, and children (Blythe et al., 2006). There have been, however, notable differences recorded in the proportions of unaligned fixations (crossed and uncrossed). As previously stated in Chapter 2 the majority of the published data have found a higher proportion of uncrossed than crossed fixations for adult participants and again this includes the current data set. Studies that have recorded binocular saccadic coordination of child participants during reading and non-reading tasks, have found that younger children's eyes became crossed during saccades; while, older children demonstrate similar patterns of saccadic asymmetry to those found for adult readers, where the eyes become uncrossed during saccades. The second prediction was that when the eyes were unaligned, a greater proportion of uncrossed than crossed fixations would be demonstrated by the adult participants. As predicted for the adult skilled readers the majority of unaligned fixations were found to be in an uncrossed direction.

In line with the findings of Blythe et al. (2006) and Fioravanti et al. (1995) the third prediction was that children would demonstrate an increased amount of crossed unaligned fixations compared to adults. Consistent with this prediction, proportionally more uncrossed than crossed fixations were found for typically developing children when the two eyes were unaligned. In fact, similar proportions of uncrossed and crossed unaligned fixations were found for typically developing children as were found for adult participants. However, for children with dyslexia there was a numerical increase in the number of crossed compared to uncrossed unaligned fixations. The saccadic data reported in Fioravanti et al. (1995), showed that young children's saccadic disconjugacy was in the reverse direction compared to that found for adults. Fioravanti et al. demonstrated that binocular saccades showed an abducting – adducting asymmetry which was in the converse direction for younger children compared to older children and adults. This finding was supported and extended by the findings of Blythe et al. (2006) where it was demonstrated that the difference in ocular alignment persisted during fixation and an increased proportion of crossed fixations were found for younger compared to older children and adults. The difference in the data described here and the pattern found to occur in developmental binocular studies such as Blythe et al. (2006) suggests the children that participated in the current study had reached an age where their binocular coordination was equivalent to that of adults (mean age = 10.5 years old). These findings support the suggestion that, for typically developing children at least, binocular coordination represents a developmental trend. More specifically that the proportion of crossed compared to uncrossed unaligned fixations may typically reduce alongside chronological age.

Interestingly children with dyslexia did made a numerically increased proportion of crossed unaligned fixations compared to typically developing children and adults. This finding is somewhat surprising as the two groups of children were controlled for chronological age (as binocular coordination is considered to develop as a function of age, reflecting a fundamental low-level factor, rather than a factor associated with reading age/ability). Therefore, what is clear is that a similar pattern of alignment, during unaligned fixations, is apparent for children with dyslexia as had previously been found in young typically developing children (Blythe et al., 2006; Fioravanti et al., 1995). This may reflect a developmental delay in respect to typical binocular coordination development for children with dyslexia.

The fourth prediction was that the magnitude of fixation disparity would be greater for children than for adults during reading. The pattern of data presented here differs from the data described in Chapter 3, and from the findings of Blythe et al. (2006). During previous studies during both reading and non-reading tasks typically developing children were shown to have increased binocular fixation disparity compared to that found for adults. One possible cause of these inconsistencies with previous data is that in the study reported in Blythe et al. the age of the child participants ranged between 7 and 11 years old with a mean age of 9 years and 11 months. The age range for typically developing child participants in Experiment 2 was also 7 to 11 years old with a mean age of 9 years and 1 month. The child participants in the current reading study ranged in age between 8 years and 8 months to 12 years and 1 month with a mean of 10 years and 6 months. This small difference in the age of the participant may account for the different pattern of disparity found in the current study compared to that found during Experiment 1 and the study reported in Blythe et al. Only 2 of the child participants in the current study were aged between 8 and 10, where the remaining 6 participants were aged between 10 and 12 years of age. Conversely in Experiment 2 there were 5 participants that were 7, 8, and 9 years old and only 3 participants that were 10 years old.

Fioravanti et al. (1995) found that spatial disconjugacy of binocular saccades was greater for younger children (age range 5-9 years) compared to older children (age range 11-13). This was in addition to the reversed direction of abducting and adducting asymmetry discussed earlier. The magnitude of disconjugacy found between the saccades of the two eyes accounted for as much as 1.97° for younger children, .63° for older children and .48° for adults. While the majority of typically developing child participants in Experiment 2 would represent Fioravanti et al.'s younger age group, this was not the case during Experiment 3, where the majority of typically developing child participants would represent Fioravanti et al.'s older age group.

Increased fixation disparity was found during reading for children with dyslexia compared to typically developing children and adults. This raises the possibility that reading difficulties associated with dyslexia are linked somehow to poor binocular coordination. While replicating the findings of previous binocular studies (e.g. Blythe et al., 2006), as well as the findings of Experiments 1 and 2, significant differences between groups were found, in respect to the magnitude of disparity during fixation. Binocular coordination for adults and typically developing children was found to be equivalent, but critically, a significantly increased magnitude of fixation disparity was found for dyslexic children compared to both of these groups. The results indicate that the poor binocular coordination observed in dyslexic children when reading is perhaps a consequence of their reading difficulties. This will be discussed in more depth in Chapter 6 and 7.

The fifth prediction concerns processing difficulty. A target word was included in the experimental sentence which was manipulated for frequency. The aim was to induce differences in processing difficulty and subsequently to investigate a possible influence on binocular coordination. Both Hendriks' (1996) and Heller & Radach's (1999) research suggested that disparity (during fixation) was influenced by processing difficulty. However, Hendriks, (1996) argued that the effects were at least partially attributable to the influence of the preceding saccade amplitude on fixation disparity. While these studies have found an effect of processing difficulty on binocular coordination, Juhasz et al. as well as Bucci and Kapoula (2006) found no effect of any of three manipulations of processing difficulty upon binocular coordination in skilled adult readers. During the current experiment no significant effect of processing difficulty was found to modulate binocular coordination for adults and both groups of children. This supports the suggestion that binocular coordination is affected by low level factors that influence oculomotor control generally.

Chapter Six

Supplementary analyses of binocular fixation disparity during reading
and a dot scanning task; in adult, child and dyslexic populations.

6.1 Introduction

In Chapter 6 an additional three sets of statistical analyses are presented that were conducted to compare effects across experiments and therefore provide a formalisation of the results between groups and across tasks. Throughout the Thesis thus far, separate analyses of variance were carried out on the data, by-items and by-subjects. The reliability of a factor was only accepted as significant when the effect was significant across both items and subjects. During the current analyses linear mixed effect (LME) models were conducted; this form of statistical analysis provides an opportunity to overcome issues associated with unbalanced designs that may have arisen from empty cells in the eye movement data. There were three main explanations for missing data points: a) the stringent criteria by which the dyslexic participants were recruited meant that testing large numbers of children was impossible, and therefore the number of participants in each of the three experimental groups were, at times, unbalanced; b) the difficulties associated with obtaining binocular eye movement data from children meant that just 3 in 5 child participants recruited were able to take part in the experiments, (this is most often tracker limitations in relation to the size and shape of a child's eye, rather than issues associated with their binocular coordination); c) infrequent situations where a child was either unable to complete a trial during the experimentation period or the eye tracking machines were unable to detect the position of one or other of the eyes, very briefly, during a trial. The difficulties associated with recording binocular data made it impossible to collect data from a large number of children (in particular those children diagnosed with dyslexia). Therefore, it was important, to conduct LME analyses to provide a sufficiently robust analysis of the data. The LME analyses allowed for each participant's data, irrespective of whether there were missing data points or not, to contribute to the analyses. This was one of the benefits of conducting LME analyses

As has been discussed above, the analyses reported below used LME modelling, conducted using the lme4 package in R (2007). Mixed effect models are a relatively new development in statistical analyses (see Baayen, Davidson, & Bates, 2008). These models with crossed random effects of participants and items offer an approach which can be compared to (multiple) linear regression. The models included a) participants and items as random effects, and b) theoretically motivated fixed effects (Pinheiro & Bates, 2000). In the present analyses participant group (adults, typically developing children and children with dyslexia), incoming saccade length, and the position of fixation on the screen relative to the centre, were considered as fixed factors. The results for start of fixation disparity were used as the dependent variable in all the LME analyses as end of fixation disparity was broadly similar in relation to the pattern of effects between the three groups. The model parameters can be interpreted in a similar way to regression weights; for example if there is a value of .106 for typically developing children this means that the intercept (.239˚) is .106˚ of visual angle larger in the model for typically developing children than for the baseline, which in the current analysis corresponds to the adults. All factors and interactions are included in the start model after which model fitting consists of checking whether a factor or an interaction contributes significantly to the fit of the model. If not, the factor or interaction is removed from the model. Below the most parsimonious model is reported that delivers the best fit.

In Set 1 of these analyses the results reported in Experiments 1 and 2, the non-reading scanning task, were extended to include the three participant groups (adults, typically developing children and children with dyslexia). It was predicted that disparity would be significantly greater than 0˚ of visual angle for all participant groups; furthermore, that children would have greater fixation disparity than adults. The models allowed for the simultaneous consideration of all the factors that would potentially contribute to an understanding of the structure of the data. More specifically, in addition to investigating the influence of the fixed effects manipulated within the design, (i.e. the effect of participant group, saccade amplitude, fixation position on the screen), random effects associated with the item (e.g. target size) and with the participant (e.g. participant's chronological age) were included in the model. Furthermore, while the effect of target size was not shown to be significant in either the analyses reported in Chapter 2 (the adult data) or Chapter 4 (the child data) the LME analyses offer a more robust exploration of the data.

Recall that Experiment 1 examined adult binocular coordination and Experiment 2 assessed the binocular coordination of typically developing children and children with dyslexia using the same non-reading task. There are three important methodological points to note here, the first one being in the current set of analyses the binocular coordination data were exclusively obtained during Task 1 (scanning of horizontal rows of dot targets). Second, that only start of fixation disparity was analysed. Finally, the data represented absolute magnitude of fixation disparity and therefore, no predictions were tested relating to the direction (crossed and uncrossed) of fixation disparity. The design parameters specified above will now be discussed. The decision to analyse data exclusively collected during Task 1 of Experiment 1 and 2, was based on the logic that the experimental stimuli, which consisted of horizontal rows of different sized dot strings, were designed to demand analogous oculomotor control to that typically observed during reading, in as much as a series of saccades and fixations from left to right were required. Thus the data obtained during Task 1 allowed for investigation of reading-like oculomotor coordination in the absence of linguistic and cognitive processing, which potentially differentially affects the three participant groups.

Recall that in Task 1, (Experiments 1 and 2) participants were specifically instructed to treat each dot string as a target. This is, arguably, a situation that is similar to that in reading. The decision to analyse the start of fixation data was based on the following considerations; as reported in Chapter 3 (section 3.1 *Children's binocular coordination in non-reading tasks* and section 3.2 *Children's binocular coordination during reading*) differences in saccadic asymmetry were found for children compared to adults and further for typically developing children compared to children with dyslexia. Therefore, the start of fixation was considered to be the optimum point at which to test any predictions concerning the magnitude of fixation disparity for the 3 participant groups, prior to any corrective vergence movements that typically take place during fixation. Finally, the decision to conduct the analyses on the absolute magnitude of fixation disparity data was based on the null effect of participant group shown in Experiments 1, 2, and 3 for the direction (crossed and uncrossed) of unaligned fixations. Therefore, no predictions were tested relative to the direction of fixation disparity for each participant group during the current analyses.

In Set 2 of the analyses, factors that influence binocular coordination during reading were considered. The aim was to construct a model which accounted for the variance in the data and considered fixed as well as random effects. Again the main aim was to support the ANOVA analyses by showing a significant effect of group. But also, to test predictions relating to the influence of the preceding saccade amplitude and the influence of the position of fixation on screen relative to the centre for example; these were not considered during ANOVA analyses of variance during Experiment 3. In previous binocular coordination studies these factors were shown to influence the magnitude of fixation disparity that occurred during both reading (e.g. Liversedge, White et al., 2006; Nuthmann & Kliegl, 2009) and non-reading tasks (Collewijn et al., 1988; Experiments 1 & 2, this Thesis). The same methods were used here to collect and analyse the reading data as in the non-reading studies (reported in Chapters 2 and 4). Experimental sentences were constructed that were designed to be easy for children with and without dyslexia to read. All participants were instructed to read the sentences normally, to take care to comprehend the sentences and then answer each question that they were asked as accurately as possible. Recall that the pattern of results for the typical reading measures, detailed in Chapter 5 (section 5.3 *Global measures of dyslexic eye movement data)* demonstrated that all participants, regardless of reading ability, were able to read and understand the sentences.

Finally in the third set of analyses, task comparisons were conducted on a subset of the participants who completed both the dot scanning task and the reading experiment; in fact this subset accounted for 6 of the 9 dyslexic children that were tested during the experiments. To be clear, during Set 3, the absolute magnitude of fixation disparity data pertaining to children with dyslexia was compared across the two tasks. Therefore, it was possible to directly compare binocular coordination performance during a simple scanning task, which did not require cognitive or linguistic processing, and reading for (a subset of) children with dyslexia. These analyses represent the most robust examination of the data described thus far in the Thesis.

6.2 Set one: Mixed effect models of binocular coordination during scanning of non-reading stimuli.

In Table 6.1, the magnitude of fixation disparity for adult participants was represented in the model as an intercept of approximately .239°. This is considered a baseline for fixation disparity during the dot scanning experiment (Task 1, scanning horizontal rows of dot targets). To this value each predictor is added to obtain the predicted disparity value for the magnitude of fixation disparity.

Table 6.1

Start of fixation disparity for all valid fixations during the dot scanning Experiments 1 and 2 combined (Task 1 horizontal rows of dot targets). Coefficients and standard errors are shown and the t-value with significance level for the model for all predictors.

Predictor	Coefficient	Std. Error	t value
Intercept (Adults)	.239	.054	4.418***
TD children	.106	.074	1.444
Children with dyslexia	.037	.073	0.501
Position on screen	-.005	.004	-1.185
TD children X position screen	.033	.005	6.298***
Children with dyslexia X position Screen	.014	.005	2.670**

*p < .05
**p < .01
***p < .001

While adult fixation disparity was significantly greater than 0° of visual angle, the coefficient for typically developing children of .106° was not significant; also the coefficient for children with dyslexia of .037° did not reach statistical significance. This shows that there was no significant increase in the magnitude of fixation disparity when the value for typically developing children and the value for children with dyslexia was added to the intercept (adult fixation disparity). In other words when scanning simple dot stimuli measures of fixation disparity found for both groups of children were comparable to those found for adults. This finding did not support the prediction that children have significantly more fixation disparity than adults.

Preceding saccade amplitude did not contribute significantly to the model of fixation disparity during a non-reading scanning task. Several studies, including the studies reported in Chapter 2 and 4, have found an effect of the amplitude of the preceding saccade on the magnitude of fixation disparity. Quite why these effects were not found in the current analyses was somewhat of a puzzle. Recall, that a significant effect of the direction of the preceding saccade (left or right) was found for children but was not found in the adult data. As the analyses were conducted on absolute saccade amplitude these effects are not found when the direction of the preceding saccade is not taken into consideration. This is obviously an area for future research.

No significant main effect of position on the screen relative to the centre was found, that is the mean fixation disparity was no different if participants fixated the extreme ends of the stimuli compared to the middle of the stimuli. However, there was a significant interaction found for child participants and the position of fixation on screen. This interaction demonstrated that there was an extremely small increase in the magnitude of fixation disparity when children fixated either at the start or the end of a row of stimuli compared to fixating the centre of the screen. In other words, fixation disparity increased by approximately .02° relative to the position of fixation on the screen. The main point that arose from these analyses however, was that similar magnitudes of disparity are evident for adults and children when they scanned simple strings of dot stimuli.

LME analyses were then conducted on fixation disparity magnitudes found exclusively for child participants during the dot scanning task (see Table 6.2). The intercept of .343° corresponds to the observed magnitude of disparity for typically developing children, and this value was found to be significantly greater than 0°. The coefficient for children with dyslexia was -.074° which did not reach statistical significance. (Furthermore, the age of the participant did not significantly contribute to the model.) This result shows that fixation disparity magnitudes were not significantly different between children with dyslexia and typically developing children. Therefore, the patterns in the results thus far indicate that children with dyslexia do not have generic less precise binocular coordination, as their performance during the dot scanning task (a task that did not require linguistic or cognitive processing) was very comparable to both adults and typically developing children of a similar age. A main effect was found for fixation position on the screen, however, the significant interaction for children with dyslexia indicates that the increase in fixation disparity magnitude for typically developing children, when fixating the start or end of a row of stimuli compared to the centre, was not as pronounced for children with dyslexia.

Table 6.2

Start of fixation disparity for all valid fixations during the dot scanning experiment (Experiment 2, Task 1). Here the data relate exclusively to child participants. Coefficients and standard errors are shown and the t-value with significance level for the model for all predictors.

Predictor	Coefficient	Std. Error	t value
Intercept (TD children)	.343	.062	5.569***
Children with dyslexia	-.074	.080	-.914
Position on screen	.029	.004	7.338***
Children with dyslexia X position screen	-.018	.006	-3.085**

*p < .05
**p < .01
***p < .001

6.3 Set two: Mixed effect models of binocular coordination during reading.

Again linear mixed effect models were conducted to analyses fixation disparity with the aim of evaluating the impact of participant group as a fixed factor (see Table 6.3). The intercept of .251° of fixation disparity for adults was found to be significantly greater than 0°, thus demonstrating that while fixating a word during reading the eyes are not always aligned within on character space of each other. There was no significant difference in disparity for typically developing children compared to that observed for adult participants. Again, similar to that found during the dot scanning task adults and typically developing children exhibit similar magnitudes of fixation disparity and the visual system is able to deal with disparate retinal inputs to produce a single fused percept. Fixation disparity was, however, found to be significantly increased for children with dyslexia when they read compared to that found for adult participants during reading. Again there was no main effect of fixation position on screen, however, there was a significant interaction with participant group; the positive coefficient indicates that the magnitude of fixation disparity increased by approximately .012° for child participants when they fixated at either the start or end of a sentence compared to when they fixated in the centre of the screen. Again this effect was similar to that found during the dot scanning task.

Table 6.3

Start of fixation disparity for all valid fixations during reading; data relating to Experiment 3. Coefficients and standard errors are shown and the t-value with significance level for the model for all predictors.

Predictor	Coefficient	Std. Error	t value
Intercept (Adults)	0.251	.060	4.208***
TD children	-0.030	.091	-0.325
Children with dyslexia	.224	.091	2.459*
Position on screen	-.003	.003	-1.080
Incoming saccade length	.010	.003	3.075**
TD children X position screen	.012	.004	2.880**
Children with dyslexia X position screen	.010	.004	2.517*

*p < .05
**p < .01
***p < .001

A main effect of incoming saccade length on the magnitude of fixation disparity was demonstrated; this had an impact of .010° on the intercept. This pattern of results showed that the greater the amplitude of the incoming saccade the greater the disparity on the subsequent fixation. Note that while this effect was significant it was also quite small; this was not surprising as the range of saccadic amplitudes during reading tends not to be extensive. However, the main point to take from Table 6.3 is that children with dyslexia are found to have significantly increased fixation disparity when they read compared to adult readers.

Again the linear mixed effect model was conducted exclusively with the data from child participants during reading (Table 6.4). This analysis demonstrated that when typically developing children read text, a significant magnitude of fixation disparity (presented as the intercept and representing the baseline value for fixation disparity in the current model) was found at the start of fixation.

Table 6.4

Start of fixation disparity for all valid fixations during reading, data relating to child participants exclusively during Experiment 3. Coefficients and standard errors are shown and the t-value with significance level for the model for all predictors.

Predictor	Coefficient	Std. Error	t value
Intercept (TD children)	.230	.073	3.174**
Children with dyslexia	.247	.101	2.444*
Position on screen	.008	.003	2.388*
Incoming saccade length	.005	.004	1.298

*p < .05
**p < .01
***p < .001

Disparity during reading for typically developing children was found to be .230° of visual angle and was significantly greater than 0° of visual angle. The coefficient of .247° demonstrated that children with dyslexia had increased magnitudes of fixation disparity compared to typically developing children when they read. A main effect of position on the screen relative to the centre of the screen indicated that the fixation disparity for both groups of children increased by .008° as they fixated either the start or the end of a sentence compared to fixating the centre of the screen. (Furthermore, as before the age of the participant did not significantly contribute to this model.) The results of the LME models confirmed the conclusions based on the ANOVA (F_1 and F_2 analyses) analyses described above in section 5.4 (*Start of fixation disparity analyses*).

6.4 Set three: A within participants mixed effect models of binocular coordination during the scanning task and reading.

The analysis presented in Table 6.5, showed that when children with dyslexia were required to read sentences the magnitude of fixation disparity was greater than that found when they were fixating simple dot stimuli. During the simple dot scanning task children with dyslexia had .246° of fixation disparity and during the reading task they were found to have .548° of fixation disparity. (Importantly, given the argument presented in Chapter 5, the age of the participants did not significantly contribute to this model.)

Table 6.5

Start of fixation disparity magnitudes during reading and dot scanning. Coefficients and standard errors are shown and the t-value with significance level for the model for all predictors. The data represent those from a subgroup (n = 6) of children with dyslexia.

	coefficient	Standard error	t value
Intercept (dot-scanning task)	.246	.149	1.654
Reading task	.302	.132	2.285*
Position on screen	.013	.003	3.776***

*p < .05
**p < .01
***p < .001

Clearly, the within participants analyse of fixation disparity during a scanning task and during reading, show that children with dyslexia have a stimulus specific deficit in regard to binocular coordination. As a consequence of reading text the magnitude of fixation disparity found for children with dyslexia was significantly increased compared to that which occurred during the simple scanning task. These data are discussed in detail during Chapter 7.

Chapter Seven

General Discussion

It is primarily through the coordination of the two eyes that the visual system is able to fuse two retinal inputs. The literature concerning adult binocular eye movements is substantial and the basic characteristics of the two eyes' coordination during reading is well documented (e.g. Blythe et al., 2006; Heller & Radach, 1999; Hendriks, 1996; Juhasz, Liversedge, White, & Rayner, 2006; Kliegl, Nuthmann, & Engbert, 2006; Liversedge, White, Findlay, & Rayner, 2006; Nuthmann &, Kliegl 2009). These studies have shown that disparity between the points of fixation is common place during reading and the magnitude of disparity often extends more than one character space, but rarely more than two. The two eyes are more frequently found to fixate a word in an uncrossed alignment (where the left eye fixates more than one character space further to the left than the right eye), rather than a crossed alignment (the converse pattern of alignment). However, recent evidence indicate that experimental conditions (e.g. viewing distance, display conditions) may constrain the alignment of the two eyes (Blythe, Kirkby, Drieghe, Benson & Liversedge, 2009). It was somewhat surprising, therefore, given the extent of this research and its implications for reading studies, that the visual factors associated with the stimuli that may influence binocular coordination were largely ignored in the literature.

On the other hand there are relatively few studies which have directly investigated the precise nature of binocular coordination for children; and again, a systematic investigation of the factors that potentially modulate children's binocular coordination was also absent from the literature (c.f. Blythe et al., 2006; Bucci & Kapoula, 2003). Finally, it was apparent from the extensive review of the literature regarding binocular coordination and dyslexia that the majority of investigations in this area had used subjective methodologies, often depending on the self report from, at times, very young children and the role of visual deficits in dyslexia was quite controversial. Therefore, the work presented in this thesis represents a systematic and thorough investigation of the binocular coordination in three participant groups; adults, typically developing children and children with dyslexia. This work was necessary before any solid conclusions could be drawn as to the factors that affect binocular coordination, and whether poor binocular coordination is associated with dyslexia.

7.1 Potential limitations

There are however, potential limitations to the work presented in this Thesis which require some discussion prior to the formation of the final conclusions concerning the current findings and the implications for children with dyslexia. The main limitation in the work is the number of observers tested during the studies. During the dot scanning experiment (Expt 1 and 2) 11 adult and 18 child participants were tested; during the reading experiment (Expt 3) 9 adult and 16 child participants were tested (half of the children were diagnosed with dyslexia in both experimental groups).

There were several reasons why the number of participants was relatively small for both the experiments. To conduct a thorough investigation into the suggestion that binocular coordination is causally linked to dyslexia, it was important to follow stringent criteria by which to recruit and categorize a group of participants as dyslexic and another group as typically developing; thus this in itself meant that testing large numbers of children was impossible. In addition to restrictions due to recruitment criteria which influenced the number of possible participants, it is extremely difficult to collect accurate binocular data using the Dual Purkinje Image tracking system. It is not always possible to collect data from all recruited participants and this is particularly true for child participants. On average just 3 in every 5 child participants recruited were successfully tracked binocularly. The difficulties obtaining accurate binocular eye movement data are most often associated with acquiring two strong Purkinje Images from each eye; the probability of obtaining these images (the first and fourth Purkinje image) is closely linked to the relative size and shape of the child's eye and pupil size and not issues associated with their binocular coordination.

Potential problems that may arise from testing too few participants are (1) there will be insufficient power for a given effect size; (2) the sample is not broad enough to represent the full spectrum of children with dyslexia; (3) the age range of the child participants may limit the extent to which effects vary across age groups.

So let us now deal with each of these potential problems one at a time. (1) Sufficient power to detect a given effect size. If it was the case that the experiments reported in this Thesis suffered from a lack of power, then it could be argued that this caused the null effect in the non-reading task. However, this explanation seems wholly unlikely.

During the linear mixed effect (LME) models analyses no effect of participant group was found on the magnitude of fixation disparity when participants scanned strings of dot stimuli. Conversely, when participants read text the analyses showed a significant difference in the magnitude of fixation disparity for children with dyslexia compared to adults and typically developing children. Therefore, one could argue that if an effect had been present in the dot string task, then, in the same way as the reading experiment was shown to have sufficient statistical power to support an effect of participant group on the magnitude of fixation disparity differences during the dot scanning task would also have been found. That is to say, there was identical power in the dot scanning task and the reading task, and given that reliable effects occurred during reading, then there was the potential for similar such effects to occur during the dot scanning task. Furthermore, it could also be argued that conducting LME models, which provide increased statistical power compared to ANOVAs and t-tests, also deals with the potential problem associated with the limited number of participants tested.

All this said the fact remains that at least some of the arguments generated in the Thesis rest upon finding a null effect in relation to changes in disparity occurring during the dot scanning task for dyslexic children. This raises a more general issue that may be regarded by some as one for concern, concerning whether it is appropriate to form conclusions based on null effects. In respect to such a challenge, it is important to note that in fact the conclusions formulated in this Thesis do not in fact rest solely on a null effect, but instead are based on a different pattern of effects for the same participant population when they carried out two different tasks. This was demonstrated unequivocally, that different effects occurred with respect to disparity in dyslexic children during reading and during dot scanning. In summary, whilst it is important to be cautious in interpreting null effects, in the present experiments, given the interactive pattern, the conclusions that have been formed seem extremely warranted.

Let us now turn to the next potential problem arising from the limited number of participants tested. (2) The sample is not broad enough to represent the full spectrum of children with dyslexia. While it is always desirable to test as many participants as is possibly, the limitations associated with obtaining binocular data (as described above) meant that a small number of diagnosed dyslexic readers were tested during this series of experiments. However, the evidence supporting the hypothesis that poor binocular coordination causes dyslexia illustrates that the proportion of children, whose reading was found to be more than 2SDs behind that predicted from their IQ scores is high (Stein & Fowler, 1993). In Stein, Riddell and Fowler (1988) an eye movement recording study 64% of all dyslexic children tested did not make accurate vergence eye movements in response to disparity. Therefore, given that poor binocular coordination is suggested to affect 2/3 of the dyslexic population, in a sample group of 9 children one would expect to find 6 children that would demonstrate similar oculomotor coordination during both the dot scanning task and reading, and this was simply not the case.

The third and final problem that may arise from testing too few participants is (3) the age range of the child participants may limit the extent to which effects vary across age groups. While there is evidence to suggest that, for typically developing children at least, binocular coordination improves alongside chronological age (e.g. Blythe et al., 2006) no age related improvements have been found for children with dyslexia. In fact Stein, Riddell and Fowler (1988) specifically propose that "….many dyslexic children fail to develop this [vergence] control successfully, until much later, if at all." Therefore, if children with dyslexia are affected by a generic binocular coordination problem and this does not change markedly with age, then one would expect differences to be found during the dot task and the reading task regardless of the particular chronological age of the sample that was selected. This was not the case, furthermore, during the LME analyses age was included in the model as a possible effect but the model was not significantly improved and therefore it was removed. It must also be noted that the age range of the current group of dyslexic readers [7-11 years of age] is comparable with that used in the Stein et al. (1988) study [8-11 years of age].

Let us now turn to a second possible limitation of the studies conducted in this Thesis - whether the stimuli used in the two tasks were suitably matched. To be clear, a prerequisite for validity in comparing binocular eye movement control during a simple scanning task to that required during reading was that the two sets of stimuli required similar oculomotor control as reading but in the absence of cognitive/linguistic processing. It was shown that the eye movements recorded during the dot string task were comparable to those recorded during the reading task. The data presented in Chapter 2, Table 2.3 show that typical eye movements, in terms of, mean fixation duration, saccade amplitude, mean number of fixations per horizontal row as a function of number of dots in a string and the maximum saccade amplitude, reveal that participants made a series of saccades from left to right that were arguably analogous to the behaviour typically observed during reading.

While it is the case that the dot strings demanded similar oculomotor coordination as reading the stimuli are in some ways dissimilar. Linguistic stimuli are more visually complex than dot strings. High and low spatial frequencies comprise words, where as dot strings comprise solely of lower spatial frequencies. Letters are comprised of several visual features which cover a range of orientations compared to dot stimuli. The nature of a visual stimulus can affect the magnitude of fixation disparity that can successfully be fused (Burt & Julesz, 1980; Fender & Julesz, 1967; as cited in Howard, 2002). Therefore, it could be argued that the visual characteristics of the two sets of stimuli may differentially have influenced the magnitude of fixation disparity observed during fixations due to fusion limitations. If this was the case, then the effects would be seen in all three participant groups rather then selectively influencing the dyslexic group alone.

Let us now turn to the third and final possible limitation of the current studies – matching between control participants and children with dyslexia. During both experimental strands of the Thesis child participants were matched in regard to two separate criteria, namely chronological age and IQ scores. Arguably the most important factor to consider while matching control and experimental participants in the current studies was their IQ scores. Consistent evidence indicated that controlling for scores of IQ cancelled out any difference in the proportion of children with and without dyslexia that had a fixed reference eye (which is associated with poor binocular coordination, and hypothesised to negatively influence reading ability; Bishop, 1989; Newman et al., 1985). Furthermore, the direction of the proposed relationship between poor binocular coordination and reading difficulties maintains that poor binocular coordination affects reading ability rather than reading ability improving binocular coordination. Therefore, while some may suggest that the groups of children would be better controlled for reading age than chronological age, the evidence strongly supports the conclusion that vergence control and binocular coordination more generally, develops as a function of chronological age (Bucci & Kapoula, 2006) rather than reading age. Therefore, it was considered important to match the two groups for chronological age rather than reading age.

7.2 Discussion

First, data has been reported which examined the effect of the visual characteristics of the stimuli on binocular coordination. Here participants were either required to scan, from left to right, along horizontal lines of word-like dot strings or to make a single saccade and fixate a target dot. As described in Chapter 1 (1.3 *Binocular coordination during reading*) there have been several studies that have investigated the aspects of linguistic processing that may influence binocular coordination (e.g., Blythe et al., 2006; Bucci & Kapoula, 2006; Heller & Radach, 1999; Hendriks, 1996; Juhasz et al., 2006; Liversedge, Rayner et al., 2006; Yang & Kapoula, 2003). Only one of these studies showed a significant effect of processing difficulty on binocular coordination (Hendriks, 1996). However, as argued throughout this Thesis, the effect could, at least partially, be attributed to a reduction in saccade amplitude that occurs during reading when processing becomes difficult. With this in mind the non-reading stimuli designed for the first series of tasks allowed for the examination of typical eye movement behaviour which occurs during scanning irrespective of cognitive/linguistic influences. The dot string task was specifically designed to require eye moments that were analogous to the oculomotor control that occurs during reading. However, since the task stimuli were non-reading in nature, any processing associated with comprehending text was eliminated. By eliminating linguistic and cognitive processing from the tasks, reading-like eye movements could be recorded to ascertain the degree to which four basic characteristics of the stimuli modulated the magnitude of fixation disparity. Furthermore, by eliminating linguistic processing a participant's reading ability could not underlie any differences that may be found in binocular coordination between the children with and without dyslexia.

From Experiment 1 and 2 a number of key points arose concerning the modulation of binocular coordination by the visual characteristics of the stimuli. For both adults and children the pattern of binocular fixations was not at all chameleon-like, with one eye fixating the beginning and the other fixating the end of a sentence; even during the non-reading tasks where encoding of fine grained detailed visual information was not required to perform the tasks.

1. The fixation disparity magnitudes were greater for children than for adults. However, during the LME analyses, reported in Chapter 6, the increased magnitude of fixation disparity found for children compared to adults was not significant.
2. While children and adults made more uncrossed fixations when the two eyes were not aligned (aligned fixations were characterised as both eyes fixating within one dot space of each other), children had an increased proportion of crossed alignment compared to adults.
3. The magnitude and alignment of fixation disparity while scanning dot targets was not affected by the horizontal spatial extent of the target.
4. At fixation onset, fixation disparity was no more reduced when repeated saccades were made to continuously available parafoveal targets, compared to single saccades made to target that elicited a saccade by a sudden onsets.
5. The amplitude of the preceding saccade consistently influenced binocular coordination; more specifically, the greater the amplitude of the preceding saccade the greater the magnitude of the subsequent fixation disparity.
6. The direction of the preceding saccade (i.e. whether to the left or the right) did not influence fixation disparity for adults; however, there was a significant effect of saccade direction for child participants.
7. A similar pattern of results were shown for typically developing children and children with dyslexia during the dot scanning tasks.

In summary, the data reported in Experiment 1 and 2 showed that the visual characteristics of the stimuli have limited influence on binocular coordination. The magnitude of fixation disparity was associated with the amplitude of the preceding horizontal saccade for all participant groups. These data were consistent with the findings of Collewijn et al. (1988) who demonstrated that the preceding saccade amplitude influenced the subsequent vergence velocity during fixation. Binocular fixation disparity, of a similar magnitude, was found to be tolerated during the scanning tasks as was observed in investigations of reading and this was the case for both adults and children. Therefore, consistent evidence regarding the modulation of binocular coordination suggests that top-down cognitive and linguistic processing may not influence binocular coordination; rather, disparity occurs as a consequence of low level oculomotor control during saccadic orienting. Experiment 3 was designed to address this issue.

It was apparent from the findings of Experiments 1 and 2 that the visual system is able to construct a unified visual representation, from frequently conflicting retinal inputs supplied by the binocular coordination system. Clearly, the visual system is not only able to tolerate disparate retinal inputs, but does so, on a fixation-by-fixation basis; where the visual system contends with varying degrees of disparity that can, at times, change millisecond-by-millisecond. This indicates that, a greater degree of flexibility in relation to visual processing is required than would be the case if the magnitude of disparity remained constant across all fixations. Furthermore, the results of Experiment 2 demonstrate that regardless of the participants' reading ability, the developing visual system is adept at dealing with varying degrees of fixation disparity during a non-reading task. Further analyses reported in Chapter 6 (Section 6.2 *Set one: Mixed effect models of binocular coordination during scanning of non-reading stimuli*) showed that while adult's eyes were somewhat less disparate during fixation than children there were no significant difference in the magnitude of disparity between children (with and without dyslexia) and adults. Furthermore, there was no significant difference in the magnitude of fixation disparity between the two groups of children. It has been argued throughout this Thesis, that to support a causal link between dyslexia and poor binocular coordination, it would be necessary to demonstrate a generic binocular coordination deficit, in the absence of linguistic processing. The current results indicate that poor binocular coordination *per se* is not a cause of children's reading difficulties, as problems coordinating the two eyes are not evident during a non-reading task.

During Experiment 3 it was particularly important to consider binocular coordination during fixations, as opposed to saccadic coordination, as it is primarily when the eyes are relatively still that linguistic information is encoded and processed. Therefore, it follows, that, during fixation reading would be most affected. The aim of Experiment 3 was to examine the characteristics of binocular coordination during reading; for adults, typically developing children and children with dyslexia. The same methods were used here to collect and analyse the reading data as in the non-reading study. But this time a set of experimental sentences were constructed, which were designed to be easy for children with and without dyslexia to read.

The experimental sentences were carefully screened with a group of younger children at a local school who did not take part in the eye tracking experiment to ensure that they would be appropriate for the participant groups in the eye tracking experiment. Practice sentences and comprehension questions were also included throughout the eye tracking session. It was very important to demonstrate that all participants, regardless of reading ability, were able to read and understand the sentences. While significant differences were found between adults and children relating to typical measures of oculomotor control during reading, the numerical trends in the data for the two groups of children did not reach significance. The trends in the data however, indicated that while children with dyslexia were reading and comprehending the sentences they found it more difficult to read the sentences than the typically developing children.

Most importantly the pattern of results during reading showed that fixation disparities for the children with dyslexia were much greater than those for the adults and typically developing children. While adults' fixation disparity was found to be significantly greater than 0°, there were no significant differences in disparity for typically developing children compared to adults. However, children with dyslexia had significantly increased magnitudes of fixation disparity compared to adults and typically developing children. Note that this pattern of effects contrasts with that which occurred during the dot scanning task, where no between group difference were found for children with and without dyslexia. Furthermore, children with dyslexia were shown to have a lower proportion of aligned fixations and an increased proportion of uncrossed fixations compared to adults and typically developing children, while reading text. However, for all participant groups if the eyes were unaligned, disparity was more often in an uncrossed direction than crossed direction; this was consistent with the patterns of results for unaligned fixations during the non-reading tasks reported in Experiments 1 and 2.

During fixation all participant groups showed that their eyes were more likely to make small movements than to remain stable. While it was found that adults made more stable fixations than was found for children, there were no differences in the proportion of stable fixations for typically developing children and children with dyslexia. These findings are not consistent with the argument that appropriate maintenance of a stable binocular fixation is not evident for dyslexic individuals (Stein 2001).

For all three participant groups, vergence movements occurred in the majority of fixations. These vergence movements were found to significantly reduce the magnitude of disparity between the start and end of fixation. These movements were most often convergent where the two eyes' points of fixation were verged together in a non-parallel movement, and, as a result, the magnitude of fixation disparity was reduced. As a consequence of the increased proportion of crossed fixations, found for children with dyslexia compared to adults and typically developing children, this group of children were shown to have a significantly increased proportion of divergent eye movements compared to typically developing children and adults. Although children with dyslexia were found to have fewer aligned fixations than was shown for adults and typically developing children, the proportion of aligned (compared to unaligned) fixations was found to increase between the start and the end of fixation for all three participant groups. This indicates that during a fixation the degree of vergence movement was equivalent for the three participant groups. The current findings do not support Stein et al.'s (1988) suggestion that inadequate binocular vergence, which reduces disparity evident at the start of a fixation, plays a causal role in reading difficulties.

From the studies reviewed in Chapter 3 (3.6 *Dyslexic individuals binocular coordination in non-reading tasks* and 3.7 *Dyslexic individuals binocular coordination during reading*), it was clear that previous findings were highly contradictory. Kapoula et al. (2007) found a significant difference in vergence capacity between typically developing children and children with dyslexia. They demonstrated that rather than a generic vergence deficit, children with dyslexia had a divergence limitation. The vergence data reported in this Thesis were inconsistent with the findings of Kapoula et al. It is, therefore, important to consider why the results from the current study and the results reported in Kaploula et al. are inconsistent. An important feature of the current investigations was the fact that the two eyes were simultaneously recorded which provided accurate binocular coordination during the tasks. In the study reported in Kapoula et al. (2007)

binocular eye movements were not recorded; rather ophthalmological tasks and prism assessment were used in which aspects of binocular coordination were inferred regarding the positions of the eyes. The tasks used by Kapoula et al. may differ sufficiently from reading that findings may not generalise to typical binocular coordination behaviour during reading and scanning non-reading stimuli.

Recall that in all of the present sentences a target word was included that was either a high or a low frequency word. These target words were included to investigate whether the difficulty in processing linguistic information modulated the magnitude of fixation disparity. This linguistic manipulation also provided an opportunity to examine whether the possible modulation of processing difficulty on binocular coordination was different between the three groups. No reliable evidence was found to suggest that increased processing difficulty, associated with identifying and comprehending the text, influenced the magnitude of fixation disparity for the adults, the typically developing children or the children with dyslexia. Furthermore, differences between groups remained unchanged independent of the complexity of the reading material.

Throughout this Thesis it has been argued that fixation disparity is a low-level oculomotor effect. While the four visual characteristics of the non-reading task had a limited effect on the magnitude of disparity during a fixation the linguistic stimuli had a differential effect on dyslexic readers compared to skilled readers (both adults and children). Finally, it happened to be the case that 6 of the 9 dyslexic children that were tested during the studies reported in this Thesis took part in both the dot scanning and the reading experiments. Therefore, a within subjects comparison of disparity found to occur in the two experiments was conducted (reported in section 6.4 *Set three: A within participants mixed effect models of binocular coordination during the scanning task and reading*). What was shown through this analysis was that when children with dyslexia were required to read they had a significantly increased magnitude of fixation disparity compared to when they scanned the simple dot targets.

The LME model analyses (presented in Chapter Six 6.4. *Set three: A within participants mixed effect models of binocular coordination during the scanning task and reading*) provide the most compelling evidence to conclude that children with dyslexia have a stimulus specific deficit in regard to binocular coordination. The findings indicate that as a consequence of reading text the magnitude of fixation disparity was increased for children with dyslexia compared to the disparity observed when scanning simple dot strings. Most importantly, as increased binocular disparity is observed for dyslexic children only during reading, it precludes the conclusion that dyslexia is caused by poor binocular coordination; in fact the causal link may be in the opposite direction, where the difficulties associated with processing the linguistic stimuli cause these differences in binocular coordination rather than visa-versa. Given this was the case, this raises the question of what aspect of the stimulus or demands of the task during reading causes fixation disparity to increase compared to fixating during other non-reading tasks.

Let us first consider the visual characteristics of the stimuli. The stimuli created for the two tasks were carefully matched in respect to the oculomotor behaviour required to perform the tasks (see Chapter 2, *2.2 Method*). Saccades and fixations were shown to be equivalent over the two tasks (see Chapter 2, Table 2.3). However, there were differences in the visual characteristics of the stimuli that have been mentioned in *7.1 Potential limitations* (current Chapter). Linguistic stimuli are visually complex stimuli; the dot strings on the other hand are far simpler. Linguistic stimuli incorporate both high and low spatial frequencies; dots strings are comprised of low spatial information. Words are formed of several visual features and these cover a range of orientations; the dot stimuli are comprised of simple curved features each oriented identically to the other. Finally, but only very marginally the luminance value for the two stimuli differ. A row of dot string stimuli comprised of 36 dots was equal to .120 cd/m^2 of luminance, where an average sentence comprised of 39 letters had a luminance value of .089 cd/m^2. We know that the nature of visual stimuli affects fusional limits (Burt & Julesz, 1980; Fender & Julesz, 1967; as cited in Howard, 2002). The literature investigating the influence of the visual characteristics of the stimuli on binocular coordination provides mixed findings. However, the most robust investigation found that adults' binocular coordination was not influenced by the complexity of the text (Juhasz et al., 2006). However, there are currently no studies which have investigated the influence of visual complexity on binocular coordination for children with and without dyslexia; therefore, further research using a similar method of investigation may provide the evidence needed to conclude for or against the suggestion that the differences in the visual stimuli underlie the pattern of effects found in this Thesis.

The two tasks also differed in terms of the cognitive/linguistic processing required by the task. It is therefore, also feasible that the cognitive/linguistic processing demands of reading influenced binocular coordination for children with dyslexia. Processing linguistic stimuli is a complex task, which requires information to be represented and processed to a comparatively "deep" level in order that comprehension might occur. Considerable evidence suggests that children with dyslexia have a difficulty representing and/or mapping phonemes to graphemes; this deficit disrupts typical word processing (e.g. Ramus, 2001). A deficit at some level of processing during reading disrupts oculomotor control in children with dyslexia – for example: longer fixations, more fixations and shorter saccades (Rayner, 1986). Processing difficulties experienced by children with dyslexia may also underlie the observed differences in binocular coordination during reading compared to that observed during the non-reading task. There are several studies however, that have tested the notion that binocular coordination is influenced by the level of difficulty associated with processing the text. Typically, this idea has been tested by including a frequency manipulation in studies testing adult binocular coordination during reading (e.g. Juhasz et al., 2006). An alternative method has been to compare the binocular coordination of adults to that observed in children during reading (Blythe et al., 2006); however, these methods have provided no evidence to support the idea. Arguably, neither of these lines of inquiry fully represents the difference in processing difficulties experienced by children with dyslexia when they read compared to a skilled reader (adult or child).

One suggestion is that processing difficulties lead to a state of disengagement from the stimuli. Following this rational an alternative interpretation of the current findings is that children with dyslexia disengage their attention during reading and this disrupts their binocular coordination. Attentional disorders have been found to affect performance on a range of tasks for dyslexic children (Denckla, Rudel, Chapman, & Krieger, 1985). Again further research is required before any strong conclusions are formed as to the influence of processing difficulties on binocular coordination.

There is a potential line of investigation, however, that may cast more light on the notion that during a stage when participants disengage their attention from the linguistic stimuli, increased fixation disparities may be observed. This line of investigation would involve observing binocular eye movements during "mindless reading" for skilled adult and child readers. Mindless reading refers to the period of time a skilled reader makes eye movements along a line (or even a paragraph) of text, but has failed to process the stimuli to an adequate level to provide a semantic representation of the information. Eye movement behaviour was found to become more erratic during mindless reading than is typical during reading. Also, reading times were found to increased relive to those found for normal reading (Reichle & Reineberg, 2009). Clearly, this along with the other possible explanations of the current effects require further research before they can be considered as anything other than speculation, as is the case at this stage.

There is a considerable amount of work which has demonstrated, during reading, dyslexic populations experience a substantial disruption in typical oculomotor control relative to skilled readers. However, these differences in oculomotor control, typically increased number and duration of fixations, shortened saccade lengths and increased numbers of regressive movements, all of which are considered to reflect the individuals' difficulty with linguistically processing text. The disruption in typical oculomotor control shown for children with dyslexia during reading now includes greater fixation disparity. The current patterns of results observed during non-reading tasks and reading, indicate that poor binocular coordination may also reflect problems associated with processing linguistic information. Clearly, this represents a stimulus specific deficit in regard to binocular coordination.

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