



Binocular coordination during scanning of simple dot stimuli

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ABSTRACT

We examined the influence of a variety of visual factors on binocular coordination during saccadic orienting. Some experimental conditions placed similar demands on the oculomotor system as those that occur during reading, but in the absence of linguistic processing. We examined whether saccade target extent, preceding saccade magnitude, preceding saccade direction, and parafoveal availability of saccade target influenced fixation disparity. Disparities similar in magnitude and frequency to those obtained in previous binocular reading experiments occurred. Saccade magnitude had a robust influence upon fixation disparities. The results are very similar to those obtained in investigations of binocular coordination during reading, and indicate that similar patterns occur during reading-like eye scanning behaviour, in the absence of linguistic processing.

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1. Introduction

Perhaps the most striking finding from the current upsurge in binocular coordination research is that the points of fixation associated with the two eyes are frequently disparate by a small amount during reading (see Kirkby, Webster, Blythe, & Liversedge, 2008). An important implication of this is that traditional descriptions of the human binocular system, where the two lines of sight fixate the same letter in a word are, at least to some extent, unrealistic. Instead, it appears that movements of the two eyes are coordinated such that each eye fixates within a variable degree of proximity to the other and fusion of the two retinal inputs occurs in order to produce a single unified percept. Thus, given that words are perceived as single, non-diplopic visual units, the visual system must not only tolerate fixation disparity, but must also adapt to varying magnitudes of disparity on a fixation-by-fixation basis (Liversedge, Rayner, White, Findlay, & McSorley, 2006). Liversedge, White, Findlay, and Rayner (2006) have provided a comprehensive description of binocular coordination during reading, reporting both the magnitude and direction of fixation disparity. They found that the two eyes' lines of sight were, on average, 1.9 character spaces disparate when the eyes were unaligned, which accounted for nearly half of all fixations while reading single line sentences. The disparate fixations were further categorised as crossed (8%) and uncrossed (39%), the proportions of which remained relatively consistent across participants.

The majority of research investigating binocular coordination (particularly that investigating binocular coordination during processing of linguistic stimuli) has investigated which characteristics

of text have an influence on binocular disparity (e.g., Blythe et al., 2006; Bucci & Kapoula, 2006; Heller & Radach, 1999; Hendriks, 1996; Juhasz, Liversedge, White, & Rayner, 2006; Liversedge, Rayner, et al., 2006; Liversedge, White, et al., 2006; Nuthmann & Kliegl, 2009). Hendriks (1996) recorded the binocular eye movements of adult participants while they read prose passages or lists of unrelated words. The velocities of the vergence movements made during fixations were found to be higher while reading prose than unrelated word lists. Hendriks argued that during processing of prose readers used semantic context to constrain lexical identification to a greater degree than was possible when reading word lists. Thus, she suggested that in the word list condition readers would be more dependent on the visual input itself than when reading prose, and she suggested that this might be the cause of the increased vergence velocities for prose compared to word lists. Perhaps the most important point to note from this study is that Hendriks considered that binocular coordination (in this case vergence movements) may be influenced by the properties of the text being read.

Heller and Radach (1999) directly investigated how the properties of text modulated fixation disparity during reading. To do this they compared binocular coordination during reading of MiXeD cAsE tEXt compared with that for text presented normally. They reported that the magnitude of disparity was reduced for mixed case text than for normal text and that subsequent vergence velocities were decreased. Heller and Radach argued that larger magnitudes of disparity may be tolerated when reading less visually demanding (i.e., normal) than more demanding text (i.e., mixed case).

Bucci and Kapoula (2006) investigated task-related modulation of binocular disparity. They compared the magnitude of disparity between the points of fixation of the two eyes when adult and

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child participants made eye movements to isolated words or to a light-emitting diode (LED). While differences in binocular coordination between adults and children occurred (see Blythe et al. (2006) for similar results), no differences between tasks were found for either participant group (adult or child). These results are inconsistent with Heller and Radach's (1999) and Hendriks' (1996) findings, and provide evidence that linguistic as compared with non-linguistic stimuli did not influence the magnitude of disparity between the two eyes' lines of sight during saccadic orienting.

Juhász et al. (2006) also investigated the influence of the properties of the text on binocular disparity during reading. As in the study by Heller and Radach (1999), participants were presented with sentences of either normal or mixed case text. No difference between the two conditions in terms of binocular coordination was found and they argued that visual processing difficulty associated with mixed case did not affect the magnitude or direction of binocular disparity observed during reading. Furthermore, Juhász et al. also included a condition in their experiment in which participants were presented with rows of six equally spaced Xs (where no linguistic processing was required). Fixation disparity during scanning of these stimuli was very similar to that observed during reading. Finally, Juhász et al. also included high or low frequency target words within their experimental sentences. Low frequency words are more difficult to identify than high frequency words, thus, this constituted a manipulation of linguistic processing difficulty. Consistent with their other findings, Juhász et al. found no influence of linguistic processing difficulty on binocular coordination during reading. A similar finding was reported by Blythe et al. (2006), where there was no effect of word frequency on the binocular coordination of skilled adult readers.

Finally, 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; Juhász et al., 2006; Liversedge, Rayner, et al., 2006; Liversedge, White, et al., 2006). Quite why crossed and uncrossed disparities are more or less prevalent in different studies is currently unclear and we will consider this question in more detail in Section 4.

To briefly summarise, a number of studies have been carried out to investigate how visual and linguistic processing difficulty influences binocular coordination during reading tasks. All these studies share a common characteristic in that they include manipulations that examine binocular coordination during fixations in relation to some aspect of linguistic processing. The focus on aspects of binocular coordination during fixations is not surprising, given that fixation durations reflect underlying cognitive processes, and the modulatory influence of such processes on binocular coordination has been an issue under investigation in these studies. It is apparent that the findings from these studies are mixed; earlier studies appear to indicate that disparity is modulated by processing difficulty, whereas more recent studies suggest that it is not.

Simple non-linguistic, visual stimuli have been regularly used in studies that have investigated saccade disconjugacy and post-saccadic vergence (e.g., Collewijn, Erkelens, & Steinman, 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 between 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 stimuli¹ are not usually manipulated. Such studies have shown that temporal and spatial disconjugacy is inherent in binocular saccades (Erkelens et al., 1989; Zee, Fizzibon, & Optican, 1992). 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, Crawford, Cadera, & Vilis, 1992; Collewijn et al., 1988; Hering, 1977; King & Zhou, 2000; von Helmholtz, 1962; see Liversedge, Rayner, et al. (2006), for 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), or differing synaptic delays, or even differences in the mechanical dynamics of the muscles that control the two eyes (Bains et al., 1992).

It should be clear from the discussion above that 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 complementary (see Kirkby et al., 2008). For present purposes, note that, to date, there have been very few, if any, studies that have been carried out to investigate how binocular coordination is affected by the manipulation of the visual characteristics of non-linguistic stimuli. We set out 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 (Collewijn, Erkelens, & Steinman, 1997; Yang & Kapoula, 2003). In both these investigations the same simple dot stimuli (LEDs) were presented to participants either at near viewing distances (~15 cm and 20 cm, respectively) or far viewing distances (~75 cm and 150 cm, 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, Collewijn 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. Collewijn et al. found a very small effect of viewing distance on binocular coordination, while 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 we manipulated the horizontal extent of the saccade target to assess its influence on binocular coordination whilst viewing distance was held constant. In other of our experimental condi-

¹ We use the term "visual characteristics" here to refer to properties of the visual stimulus that are non-linguistic but may affect eye movements. Such characteristics include horizontal extent, stimulus direction and eccentricity relative to fixation, stimulus availability over time, etc. This term may be contrasted with "linguistic characteristics" which is often used in reading research to refer to linguistic properties of visual stimuli (words or sentences) that are known to influence oculomotor control. Such characteristics include word frequency, word predictability, plausibility, etc.

tions, we were also keen 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 we wished to assess the magnitude of any observed fixation disparities in relation to the magnitude of similar effects observed during reading (e.g., Blythe et al., 2006). Note also that in the present study we used identical hardware and software for the acquisition and analysis of the data to those used by several preceding studies (e.g., Blythe et al. 2006; Liversedge, Rayner, et al., 2006; Liversedge, White, et al., 2006), thereby precluding the possibility that any differences we obtained might be caused by such factors. Finally, we examined the data from the present study to assess binocular coordination both during fixations and during saccades (c.f., Kapoula, Vernet, Yang, & Bucci, 2008).

There were three experimental testing sessions in the present experiment. In the dot string task (Task 1) participants were presented with horizontal arrays of dot stimuli that were grouped into strings of the same length within each trial (i.e., strings of two, four, or six 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 as well as variability of target length within any one trial. 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. We wished to examine whether the characteristics of binocular coordination when scanning simple dot stimuli would be similar to the documented binocular eye movement behaviour observed during reading. Grouping the dots into strings and gradually increasing the horizontal spatial extent of the unit of visual information (i.e., from single dots to two, four, and then six dots) provided an opportunity to investigate the influence of the horizontal extent of the target on binocular coordination. Also, using strings of dots rather than words allowed us to construct horizontal arrays of stimuli that were all of the same horizontal extent. 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 horizontal extent of the target 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.

Task 1 provided a very valuable opportunity to examine variability in binocular landing positions on horizontal dot strings of different lengths. Clearly, 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. The experimental conditions in Task 1, therefore, allowed us to assess whether there is increased variability in binocular landing positions, in terms of increased binocular disparity for longer compared to shorter dot strings. On the assumption that greater precision of saccadic targeting will occur for targets with smaller compared to larger horizontal extent (based on increased variability in saccadic targeting for long compared with short words; for a recent example see Joseph, Liversedge, Blythe, White, and Rayner (2009)), then we might expect reduced disparity for short compared to long dot strings. Alternatively, if disparity is not influenced by the horizontal extent of the target to which the saccade is made, then we should observe little, if any, relationship between horizontal extent of the target and binocular disparity for

fixations on the target. These were the primary experimental hypotheses that we examined in Task 1.

In the second testing session (Task 2) we were interested to investigate binocular coordination during a series of successive saccades made between two single dot stimuli presented horizontally separated on the presentation monitor. Such stimuli are parafoveally available prior to direct fixation. Participants were required to make saccades between these two continuously available dots in time with a metronome. This procedure is very similar to that employed by Lemji and Collewyn (1989) who found that participants' saccadic accuracy was enhanced when looking back and forth between two stationary dot targets that were continually visually available in the parafovea, 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 next appear. Note, however, that Lemji and Collewyn considered only monocular eye movements, and no examination of binocular coordination under these conditions was undertaken. We considered that binocular disparity may be reduced when repeated saccades are made between two continually available targets relative to saccades made to target onsets.

In our third testing session (Task 3) single dots were presented at one of four bi-lateral horizontal locations, at near or far eccentricities from a centrally presented cross. After a central fixation cross disappeared, a 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 Task 3 were designed to allow the systematic examination of the joint influence of saccade amplitude and direction on binocular coordination during fixations. While the studies reported in Hendriks (1996) and Heller and Radach (1999) showed 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 and the direction of fixation disparity in relationship to the amplitude of the preceding saccade. 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 in 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 that 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 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 jointly influence the alignment characteristics of the two eyes during the subsequent fixation.

2. Methods

2.1. Participants

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

2.2. Apparatus

Two Dual Purkinje Image eye trackers were used to record binocular eye movements. Eye positions were monitored every milli-

second. A Pentium 4 computer interfaced with the eye trackers and all stimuli were presented on a Philips 21B582BH 21" monitor. The stimuli (dots) were presented at a viewing distance of 1000 mm. Each dot covered $.29^\circ$ 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.

2.3. Stimuli

The study employed three separate eye tracking tasks. Task 1 consisted of horizontal rows of dot targets, which were presented simultaneously and remained visible throughout the trial. The stimuli consisted of a row of five single dot targets, or dots were grouped into strings of two, four and six. 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. Thus, by offsetting the length of each dot string with the number of dot strings presented, the stimuli always covered the same horizontal extent on the monitor (to within 3 mm). Task 2 consisted of two single dot targets, (again, of diameter $.29^\circ$) presented on the horizontal axis about the screen centre. The dots were presented simultaneously and separated by 5.5° . 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. When one dot was presented the luminance value for the screen was $.062 \text{ cd/m}^2$ and when two dots were present $.064 \text{ cd/m}^2$. The luminance of the screen was $.069$, $.128$, $.105$, and $.120 \text{ cd/m}^2$ for rows containing five individual dots, six strings of six dots, 12 strings of two dots, and eight strings of four dots, respectively.

2.4. Procedure

In Task 1 (the presentation of a horizontal row of dot targets) participants were instructed to fixate a cross, presented on the left side of the screen for 1 s. 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., 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; 10,000 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. Stimuli were presented as blocks of six trials for each horizontal extent of dot string (i.e., one, two, four and six).

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

During Task 3 (the presentation of single dots in isolation) a central fixation cross appeared and participants were required to fixate the cross until it disappeared and a single target dot appeared. The presentation location of the target dot 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 fixation cross, which indicated the start of a new trial. The entire task consisted of six trials in each of the four positions, a total of 24 trials. The order of presentation for the three tasks was counterbalanced across participants. All instructions for each of the tasks were given both verbally and in writing prior to calibration. Participants were allowed to ask questions prior to the beginning of the experiment if they did not understand any of the instructions.

2.4.1. Calibration

Left and right eye calibrations were performed monocularly (e.g., when calibrating the left eye the right eye was occluded and vice versa). In our view, this is the preferred procedure in relation to obtaining veridical binocular recordings (c.f., Nuthmann & Kliegl, 2009). The horizontal calibration range was 11.42° . 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. Under monocular viewing conditions, the calibration of each eye was visually checked for accuracy across the three calibration points by the experimenter. 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 if this proved necessary.

2.5. Analysis

Fixations were manually identified in order to avoid contamination by dynamic overshoots (Deubel & Bridgeman, 1995; Liversedge, White, et al., 2006). A custom-designed software package was utilised to analyse all data. The analyses were based on all valid fixations and saccades recorded during the experiment. Disparity was calculated at fixation onset and offset so that changes in disparity (vergence movements) could be compared across conditions. Blinks were excluded from the data stream in the initial stage of analysis, during the segmentation of data into fixations and saccades. Fixations with duration of more than 80 ms were considered valid; no upper cut-off was applied due to the experimental instructions to maintain an extended fixation at the end of each trial. Additionally, fixations were deleted if the absolute disparity during that fixation was more than 2 standard deviations from the mean for that individual participant. Fixations with durations of less than 80 ms, along with the subsequent saccade, that were excluded from the analyses (3.8% of the data). A further 4.1% of 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 4.7% of fixations were excluded due to an absolute disparity of greater than 2 SD from the mean for each participant at fixation onset. Therefore the final data set consisted of 4169 fixations and saccades.

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), we categorised fixations 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 ($.29^\circ$). Therefore an una-

ligned fixation represented an absolute disparity of more than one dot (greater than $.29^\circ$). Unaligned fixations were further categorised 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. Given that Liversedge, White, et al. (2006) showed that there was no systematic change in disparity across the horizontal extent of the display screen we, similarly, did not anticipate any modulation of disparity effects for fixations with increased eccentricity relative to the centre of the screen.

3. Results

3.1. 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, Rayner, et al., 2006; Nuthmann & Kliegl, 2009). We calculated fixation disparity 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. We also computed the mean difference in saccade amplitude for the two eyes (these data presented in Tables 1–3 relate exclusively to Task 1, scanning of horizontal rows of dot stimuli). These are shown in Table 1.

At fixation onset the mean binocular disparity was $.24^\circ$, and by fixation offset this had reduced to $.22^\circ$. These disparities are consistent with those reported by Blythe et al. (2006), who reported disparity magnitudes of $.24^\circ$ 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 binocular disparity through the course of a fixation, though for two participants a small increase in fixation disparity occurred. In addition to fixation disparity, we computed the mean absolute difference in the saccade amplitude for the two eyes, which was $.1^\circ$. Thus, consistent with previous studies (e.g., Collewijn, Erkelens, & Steinman, 1988), we found that all participants demonstrated a degree of asymmetry in their binocular saccade amplitudes.

Next we considered the alignment proportions of all valid fixations. The mean proportions of aligned, uncrossed and crossed fixations at the start and end of fixations are presented in Table 2.

Table 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 ($^\circ$)	Absolute disparity magnitudes at fixation offset ($^\circ$)	Absolute differences in saccade amplitudes for the two eyes ($^\circ$)
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)

Table 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, we made comparisons of the probability of making an uncrossed fixation against chance (50%). 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. In the current task, while residual disparity was observed at the end of a fixation, it was no more likely to be uncrossed than crossed.

Previous research has demonstrated that the two eyes make asymmetric saccades during reading (Hendriks, 1996; Vernet & Kapoula, 2009; see also Heller & Radach, 1999), and the present results were again consistent with this finding. In task one, the disconjugacy between the two eyes accounted for between 8% and 10% of the absolute total saccade amplitude (see Table 3), with larger amplitudes for the abducting eye (the eye moving temporally, $M=1.19$, $SD=1.13$) than the adducting eye (the eye moving nasally, $M=1.13$, $SD=1.12$; $t(8)=16.99$, $p<.01$).

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 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 and 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.

Table 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 and the number and duration of fixations. Standard deviations are in parentheses. Note that absolute saccadic disconjugacies do not equal the difference in mean saccade amplitudes due to a small proportion of trials in which nasal saccades were greater than temporal saccades.

	Saccade amplitude for the adducting eye (°)	Saccade amplitude for the abducting eye (°)	Disconjugacy in the two eyes' saccade amplitudes (°)	Percentage of saccade amplitude (%)	Maximum saccade amplitude (°)	Mean number of fixations per trial	Fixation duration (ms)
Five, single dot targets	1.64	1.70	.13 (.03)	8	8.09	7	549
Twelve, two dot strings	.86	.91	.09 (.03)	11	5.32	15	505
Eight, four dot strings	1.05	1.09	.09 (.03)	9	8.21	9	525
Six, six dot strings	1.23	1.30	.12 (.04)	9	7.33	6	468

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

In the next set of analyses we considered the influence of the horizontal extent of the target (one dot, two dot, four dot and six dot strings) on binocular coordination. In the current analyses, we were particularly interested to determine whether binocular disparity was increased for targets with a greater horizontal spatial extent than for those with reduced horizontal extent. To reiterate, our 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, we predicted increased fixation disparity with larger horizontal extent of the target.

To examine the effect of target extent we computed fixation durations, absolute fixation disparities and differences in the absolute saccade amplitude for the two eyes, in all target extent conditions. Here we considered all the fixations made as participants scanned the arrays of dots during Task 1 (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 $M = 561$ ms, $SD = 106$; two dots $M = 498$ ms, $SD = 92$; four dots $M = 517$ ms, $SD = 145$; and six dots $M = 489$ ms, $SD = 95$; $F(3, 24) = 2.15$, $p = .12$). 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 (e.g., in reading fixation durations relate directly to linguistic processes associated with text comprehension, Liversedge & Findlay, 2000; Rayner, 1998). 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.

We then examined absolute disparity magnitudes as a function of the horizontal extent of the target. Contrary to our 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 $M = .30$, $SD = .18$; two dot $M = .20$, $SD = .05$; four dot $M = .24$, $SD = .16$; six dot $M = .27$, $SD = .12$) or at the end of fixations ($F(3, 24) = .82$, $p = .50$; one dot $M = .25$, $SD = .15$; two dot $M = .19$, $SD = .06$; four dot $M = .22$, $SD = .13$; six dot $M = .24$, $SD = .10$). Indeed, the numerical trends that exist within the data are in the opposite direction to our expectations. The smaller the target extent, the greater the magnitude of disparity found, though again, these effects were not significant. In addition to these analyses, we conducted ANOVAs 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 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) \times two (sample point of fixation: start vs. end) repeated measures ANOVA. We obtained no reliable effects in these analyses (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). Although we are reporting null effects here, in our view, these results are still important since some researchers have argued that the visual characteristics of stimuli directly influence the degree of variability observed in binocular coordination (e.g., MiXeD cAsE text vs. normal text, Heller & Radach, 1999; though see Juhasz et al., 2006).

Table 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 we aimed to determine whether, as is the case in 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. We again conducted repeated measures ANOVAs 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 (c.f., Nuthmann & Kliegl, 2009).

3.3. 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 categories were identified (based on those of Liversedge, White, et al. (2006)). (1) Stable, where both eyes moved less than (or equal to) 10% of a dot's diameter (.03°). (2) Drift, 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 $.03^\circ$. (3) Convergence, where the point at which the two eyes' lines of sight cross moves nearer to the viewer. This can be due to both eyes moving in different directions (left eye moves right, right eye moves left). Alternatively, due to one eye only moving (the left eye moves right or instead the right eye moves left). Alternatively, this could arise due to both eyes moving in the same direction (i.e., drift), but one eye moves further than the other. For example, if drifting to the left then the right eye moves further than the left eye, and conversely, for a rightwards drift the left eye moves further than the right eye. 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 $.23^\circ$ 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 $t_s > 2$). During 10% of all fixations made to dot targets along a horizontal array, the disparity between the two eyes' lines of sight remained constant while both the eyes' lines of sight made drift movements in the same direction. These fixations were also, on average, $.23^\circ$ disparate at fixation onset.

While scanning horizontal arrays of dot groups, 60% of all fixations were found to demonstrate convergent movements, where the focal point 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). 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 $.25^\circ$ 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 = $.30^\circ$).

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 $.19^\circ$ and $.22^\circ$ 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.

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

To address this question, we initially investigated the probability of making a vergence movement (either convergent or divergent), contingent upon start of fixation alignment (aligned vs. unaligned). 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 we compared the probability of making convergent movements during fixation, contingent on whether the eyes were aligned, crossed or uncrossed at fixation onset. The 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 when participants were scanning the simple dot stimuli (see also Nuthmann & Kliegl, 2009). 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.

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

In all conditions, during fixations the two lines of sight were significantly more likely to converge ($F_s > 25.0$) than be 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 the greater the amount of vergence that occurs during fixation. Again these findings are consistent with Liversedge, White, et al. (2006).

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

Recall that the third testing session involved the random presentation of a single dot task (Task 3), 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 posi-

tions 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 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, we categorised fixations on targets in each of four possible positions (far left, near left, near right and far right targets). Far target fixations were preceded by a 5.5° amplitude saccade; near target fixations were preceded by a 2.1° amplitude saccade. Our 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. We found that preceding saccade amplitude did 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, our analysis also showed that the direction of the preceding saccade had no reliable influence on fixation disparity ($F(1, 8) = .10, p = .76$).

We also assessed the influence of saccade direction and distance on the nature of fixation alignment. The proportion of fixations that were aligned at the onset of a fixation were compared with the proportions of unaligned fixations. Further we categorised those fixations that followed a leftward or rightward saccade that were to a target that required a saccade of different amplitudes (5.5° or 2.1°). Perhaps unsurprisingly, given our 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 ($F_s < 1$). We did find 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 categorised 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, White, et al. (2006).

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

In the second experimental testing session (Task 2), 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 session, 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 us to directly compare 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 third testing session. We hypothesised that repeated saccades of similar magnitude between omnipresent targets may well result in reduced binocular 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.

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 binocular disparity was comparable regardless of whether saccades were made to single target onsets ($M = .23^\circ$ SD = $.14^\circ$), or were directed repeatedly between targets that were continually available in the parafovea ($M = .22^\circ$ SD = $.16^\circ$) ($t(8) = .90, p = .39$). Furthermore, the proportion of aligned fixations at fixation onset (shown in Table 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 ($t(8) = 2.09, p = .07$). Thus, it appears that binocular coordination was very largely constant under these different experimental conditions.

4. Discussion

During all the tasks and conditions, at the start of fixation all participants had, on average, $.24^\circ$ of disparity between the points of fixation of the two eyes. The eyes were more often aligned than unaligned (within one dot space, measuring $.29^\circ$). 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). We 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 $.20^\circ$ at the end of a fixation. A key

Table 5

Mean alignment proportions at the end of fixation in the saccade magnitude manipulation (note all data is rounded to the nearest whole number).

		Aligned (%)	Uncrossed (%)	Crossed (%)
End of fixation	Preview	86	13	1
	No preview	83	9	8
Start of fixation	Preview	73	26	0
	No preview	80	14	5

Table 4

Mean absolute fixation disparity and mean preceding saccade amplitude (in degrees) for saccades to the left and the right.

Saccade direction	Distance to centre of target ($^\circ$)	Adducting eye saccade amplitude ($^\circ$)	Abducting eye saccade amplitude ($^\circ$)	Start of fixation absolute disparity ($^\circ$)	End of fixation absolute disparity ($^\circ$)
Left	5.5	4.83	4.90	.22	.16
Left	2.1	1.87	1.94	.21	.18
Right	2.1	1.80	1.95	.19	.20
Right	5.5	4.56	4.84	.25	.15

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 the current non-linguistic 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, our findings are still informative for a number of reasons. Examining binocular coordination using novel manipulations in non-linguistic tasks enabled us to ascertain the degree to which four basic visual characteristics of the stimuli modulated fixation disparities. We chose our particular paradigms as they allowed us to examine 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. We were particularly interested to examine whether binocular coordination during fixation was influenced by these factors as they have not been systematically investigated in a general scanning task prior to the current study and, in our view, based on our previous work, such factors were likely to modulate binocular disparity. We will now discuss each one of these in turn.

The influence of the horizontal extent of the visual stimuli was examined. By increasing the horizontal spatial extent of the dot strings, we increased the number of potential landing sites for each eye on the target. Thus, we considered that, 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, we reasoned that disparity, on average, would be greater for dot strings that were longer than for those that were shorter.

However, we found no evidence to suggest that the horizontal extent of the target influenced the magnitude or alignment (aligned, uncrossed or crossed fixations) of binocular disparity during scanning of simple dot stimuli. 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 our 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. We considered there to be the likelihood for greater binocular coordination (i.e., reduced disparity) 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, Lemji and Collewyn (1989) showed that repeated saccades between continually available targets were more spatially accurate than saccades made to target onsets with limited parafoveal availability. We assessed whether there was in-

creased 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. We found no evidence to suggest that binocular 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. Binocular disparity metrics appear to be consistent across single target availability, and recurrent oculomotor responses associated with repeated saccadic targeting of continuously available targets.

By 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), we were also able 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 (Collewyn et al., 1988, Liversedge, White, et al., 2006; Nuthmann & Kliegl, 2009), our manipulation allowed us to assess 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 binocular 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.

We found that the amplitude of the preceding saccade consistently influenced binocular coordination. Specifically, we found 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 Collewyn et al. (1988), Liversedge, White, et al. (2006) and Nuthmann and 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, 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 us to examine reading-like eye movement behaviour in the absence of linguistic processing. Furthermore, during the current experiment 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, Rayner, et al., 2006; Liversedge, White, et al., 2006). Thus, the consistency of experimental set up readily allows for compar-

ison of the findings. Despite other differences across experiments (e.g., differing font sizes and viewing distances), the magnitude of binocular disparity demonstrated during the present non-linguistic tasks was quite similar to that observed in the reading research (Juhász 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 (Bucci & Kapoula, 2006; Juhász et al., 2006).

However, although there is considerable agreement concerning the basic characteristics of binocular coordination across a number of reading studies (see Kirkby et al., 2008), 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, Nuthman, & Engbert, 2006; Nuthmann & Kliegl, 2009), while others have obtained a majority of uncrossed disparities (e.g., Blythe et al., 2006; Juhász et al., 2006; Liversedge, Rayner, et al., 2006; Liversedge, 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 (Kirkby et al., 2008; 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).² Researchers in several laboratories, including our own, are currently carrying out investigations to establish which, if any, of these or other possibilities adequately explains the different patterns of effects that have been published.

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 tasks relative to that observed in investigations of reading. It appears, therefore, that cognitive or linguistic processing do not modulate aspects of binocular coordination. Rather, binocular 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.

² In a recent presentation at the 15th European Conference on Eye Movements data were presented from an experiment to investigate whether differences in the prevalence of crossed and uncrossed disparities were caused by different eye tracking devices and associated software (Dual Purkinje Trackers vs. an EyeLink 2000 Tracker). The data for the two different experimental arrangements and methods of analysis were very similar, indicating that any differences in the proportion of crossed and uncrossed disparities reported across different experiments and laboratories is unlikely to be due to different data acquisition devices (Blythe, Kirkby, Drieghe, Benson, & Liversedge, 2009).

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