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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.

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.

Juhasz 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 text did not affect the magnitude or direction of binocular disparity observed during reading. Furthermore, Juhasz 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, Juhasz 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, Juhasz 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; Juhasz 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 stimuli[1] are not usually manipulated. Such studies have shown that temporal and spatial disconjugacy is inherent in binocular saccades (Erkelens et al., 1989; Zee, Fizgibbon, & 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 ($\sim$15 cm and 20 cm, respectively) or far viewing distances ($\sim$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, 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, 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.