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A comparative analysis of vertical and horizontal fixation disparity in sentence reading

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ABSTRACT

Humans have two, frontally placed eyes and during reading oculomotor and sensory processes are needed to combine the two inputs into a unified percept of the text. Generally, slight vergence errors, i.e., fixation disparities, occur but do not cause double vision since disparate retinal inputs fall into Panum's fusional area, that is, a range of disparity wherein sensory fusion of the two retinal images is achieved. In this study, we report benchmark data with respect to the mean magnitude and range of vertical compared to horizontal fixation disparities for natural reading. Our data clearly fit to an elliptical pattern of Panum's fusional area that corresponds with theoretical estimates. Furthermore, when we examined disparity-driven vergence adjustments during fixations by comparing monocular with binocular reading conditions, we found that only horizontal fixation disparities increased significantly under conditions of monocular stimulation. Also, no significant vertical fine-tuning (vergence adjustment) was observed for vergence eye movements during reading fixations. Thus, horizontal and vertical fixation disparities and vergence adjustments during reading showed quite different characteristics, and this dissociation is directly related to the functional role of vergence adjustments: vertical fusion – and vertical vergence – subserve the maintenance of a single percept and stereopsis by keeping the eyes in register and allowing for horizontal fusional processes to successfully operate over a vertically aligned input. A reliable and stable vertical alignment is, thus, a pre-requisite over which horizontal fusional responses (and depth perception) can work most efficiently – even in a task like reading.

1. Introduction

Humans have frontally placed eyes and when reading text on a screen or in a book, we typically make use of both of our eyes which constantly perform yoked, rapid eye-movements. Between these saccades the eyes pause and fixate selected information for approximately 200–300 ms (Rayner, 1998; Rayner, 2009). During fixations in reading, additional fine-grained oculomotor adjustments are made via vergence movements that serve to maximize correspondence in retinal activation between the two eyes (Blythe, Liversedge, & Findlay, 2010; Blythe et al., 2006; Jainta et al., 2010; Jainta & Jaschinski, 2012; Liversedge, Rayner, et al., 2006; Liversedge, White, et al., 2006), even though slight vergence errors (i.e. fixation disparities) are typically observed at the end of reading fixations (for review, see Kirkby, Webster, Blythe and Liversedge (2008)). These vergence eye movements are part of the binocular fusion process and are thought to be a pre-requisite for subsequent sensory fusion and even later stages of visual and cognitive processing (Howard & Rogers, 2002; Jainta, Blythe, & Liversedge, 2014; Schor & Ciuffreda, 1983; Steinman, Steinman, & Garzia, 2000). Research investigating binocular coordination during reading has primarily focused on horizontal aspects of binocular fusion (Blythe, Liversedge, & Findlay, 2010; Blythe et al., 2006; Jainta, Blythe, & Liversedge, 2014; Jainta et al., 2010; Jainta & Jaschinski, 2012; Liversedge, Rayner, et al., 2006; Liversedge, White, et al., 2006; Nuthmann & Kliegl, 2009; Vernet & Kapoula, 2009), since reading requires predominantly horizontal saccades. Note that while Nuthmann and Kliegl (2009) did report a vertical misalignment of the two eyes, to date no studies have systematically investigated vertical motor fusion in reading.

Aspects of horizontal binocular fusion have been shown to be critical for lexical processing. Blythe, Liversedge, and Findlay (2010) showed that lexical decisions were slowed down when horizontal disparities were introduced for target word presentations. In addition, lexical identification was less efficient

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when sentences were read monocularly, that is, when no binocular input was provided at all (Jainta, Blythe, & Liversedge, 2014). In this context, a precise examination of vertical fixation disparities and possible vertical vergence drifts in natural sentence reading is timely. It is important to better understand aspects of the fusion process in relation to binocular vision since it is necessary for efficient delivery of visual information required for reading.

Generally, vergence eye movements occur as horizontal, vertical or cyclovergence (the latter will not be addressed in the present study). Existing studies in non-reading tasks indicate that horizontal and vertical vergence contributions to fusion show substantial differences (Leigh & Zee, 2006; Schor & Ciuffreda, 1983; Steinman, Steinman, & Garzia, 2000): horizontal vergence reacts to horizontal disparity of the object to be foveated and thus changes fixations from one depth plane to another, allowing for some degree of voluntary control. Vertical vergence reacts to vertical misalignments of the image of one eye relative to the other eye without any voluntary control and is not specifically related to localized disparities of foveal inputs or viewing distances (Howard, 2012).

After the initial motoric component of fusion, sensory fusion of the two inputs (one from each eye) occurs, and this can take place over a range of fixation disparities. These remaining misalignments of the eyes are small and do not lead to double vision (Howard & Rogers, 2002) as they fall within Panum's fusional area. Panum's fusional area is a range of disparities within which sensory fusion of the two patterns of retinal stimulation can be achieved even though there is not exact and direct correspondence (Ogle, 1954). In non-reading tasks, Panum's fusional area is suggested to be elliptical, such that it is broader in the horizontal than in the vertical dimension. The width of this ellipsis is dependent on the shape of the stimulus under fixation, its contrast, luminance gradient, and spatial and temporal frequency structure, among other characteristics (Leigh & Zee, 2006; Ogle & Prangen, 1953; Schor & Ciuffreda, 1983; Schor, Heckmann, & Tyler, 1989; Schor & Tyler, 1980; Schor, Wood, & Ogawa, 1984; Steinman, Steinman, & Garzia, 2000). Given the elliptical nature of Panum's fusional area, it is unsurprising that the area over which disparity is observed during fixations is also, correspondingly, elliptical, thus, it has been widely argued that humans have a much reduced vertical fixation disparity range relative to their horizontal range and this has been suggested to impact on the extent to which fusion is achieved. Against this background, it is somewhat surprising that Nuthmann and Kliegl (2009) reported vertical disparities that were very comparable to horizontal disparities in reading. Estimated from their graphical representation of horizontal and vertical disparity at the end of fixation (see Fig. 3a; page 7), vertical fixation disparities ranged from $-1°$ to $1°$ (i.e., a range of $2°$), with the majority found between $-0.4°$ and $0.2°$, and similarly, horizontal fixation disparities ranged between $-1.5°$ and $0.5°$ (i.e., a range of $2°$), with a majority of crossed fixations ranging between $-0.5°$ and $0.1°$. Thus, although the data were linearly translated, the magnitude and variability of the horizontal and vertical disparities were extremely similar. It is important to mention that Nuthmann and Kliegl's findings regarding fixation disparity were purely descriptive and they made no claims as to the extent of any vertical vergence adjustments during fixations.

Given this theoretical background, the present study had two aims. First, we set out to undertake a precise examination of vertical fixation disparities and possible vertical vergence adjustments in natural sentence reading. It may be the case that the vertical fixation disparities show a range almost as broad as that for the horizontal fixation disparities, as reported by Nuthmann and Kliegl (2009). If such a pattern was to occur, then it would be important to consider which aspects of reading processes might cause such disparities, especially since no vertical misalignment is typically introduced by horizontal saccades made during reading. Vertical misalignments, at least potentially, might impact upon horizontal vergence control (Howard, 2012; Schor & Ciuffreda, 1983) which itself is known to affect the efficiency of lexical processing (Blythe, Liversedge, & Findlay, 2010; Jainta, Blythe, & Liversedge, 2014). Alternatively, we may obtain an asymmetric, elliptical, pattern of fixation disparity reflecting a greater range of horizontal than vertical fixation disparities consistent with patterns reported in non-reading studies (Howard, 2012; Schor & Ciuffreda, 1983; Steinman, Steinman, & Garzia, 2000). If this pattern of effects is observed, it will allow us to precisely quantify vertical fixation disparities that typically occur relative to horizontal fixation disparities during reading.

Second, we set out to examine vertical vergence adjustments that occur during normal reading in experimental conditions that do not offer the possibility of binocular motoric and sensory fusion. To achieve this we included a monocular reading condition, thereby eliminating disparity-driven vergence adjustments (see Fig. 1; Howard and Rogers (2002), Leigh and Zee (2006), Schor and Ciuffreda (1983), Steinman, Steinman, and Garzia (2000)). In reading, and more generally, horizontal saccades inherit a disconjugacy (a transient vergence eye movement) that is due to a difference in the horizontal movements of the two eyes (Collewijn, Erkelens, & Steinman, 1988; Collewijn, Erkelens, & Steinman, 1995; Collewijn, Erkelens, & Steinman, 1997; Heller & Radach, 1998; Yang & Kapoula, 2003). This horizontal saccade disconjugacy is usually divergent, and is followed by a compensatory horizontal (typically convergent) vergence movement during the subsequent fixation (Blythe et al., 2006; Jainta & Jaschinski, 2012; Jainta et al., 2010; Nuthmann & Kliegl, 2009; Vernet & Kapoula, 2009). Monocular reading represents an optimal experimental situation for examining vergence adjustments that occur in the absence of any disparity manipulation within the stimulus itself. It has been previously shown that the coupling of the two eyes during saccades becomes weaker in monocular reading; more importantly, and regarding vergence eye movements, horizontal fixation disparities increase and horizontal vergence adjustments decrease (Jainta & Jaschinski, 2012). Thus, even though some coordination of the eyes may have been passively restored in the early phases of each fixation (Jainta et al., 2010; Leigh & Zee, 2006; Vernet & Kapoula, 2009), overall horizontal vergence adjustments seem to be disparity-driven in binocular reading and absent in monocular reading (Jainta & Jaschinski, 2012). To date, nothing is known about vertical vergence adjustments in monocular reading. If vertical fusional responses share functional characteristics with horizontal fusional responses, as indicated by Nuthmann and Kliegl (2009), and thus, show disparity driven properties, we would accordingly expect larger vertical fixation disparities and reduced vergence adjustment in monocular reading compared to binocular reading. Again, if such a pattern occurs, it will be necessary to consider which aspects of reading processes might cause such deviations compared to the patterns of effects found in non-reading tasks.

2. Methods

2.1. Participants

The 16 participants were adults aged 18–32 years with good visual acuity in each eye (better than 0.8 in decimal units). Stereo acuity was assessed using the TNO random dot test and ranged from 40 arc s for most participants to 80 arc s for one participant. No participant wore glasses during the experiment and only two wore their prescribed contact lenses. Eye dominance was assessed using a sighting dominance test (all participants we tested were right eye dominant). Three participants were excluded