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Binocularity during reading fixations: Properties of the minimum fixation disparity

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ABSTRACT

The present study was based on the physiologically reasonable assumption that the binocular system aims for a reduction of fixation disparity during fixation and that the minimum amount of fixation disparity reflects the optimal binocular status. We measured eye movements (EyeLink II) of 18 participants, while they read 60 sentences from the Potsdam-Sentence-Corpus (PSC) at a viewing distance of 60 cm. The minimum fixation disparity was frequently reached directly after the post-saccadic drift, sometimes at the end of fixation and sometimes somewhere in between. Minimum fixation disparity was strongly influenced only by fixation position (within the sentence) while the amplitude of incoming saccade had a negligible effect. Moreover, the effect of fixation position on minimum fixation disparity was correlated with the individual ability to compensate for binocular disconjugacy (due to saccades) while fixating during reading. Generally, we found fixation disparity to be correlated between conditions of reading and fixating single targets, while the reading fixation disparity tended to be more crossed (eso).

1. Introduction

Eye movement research in reading has traditionally been associated with the investigation of visual processing and language comprehension (see, for example: Kliegl, Nuthmann, & Engbert, 2006; Rayner, 1998). Central to the description (and prediction) of eye movement behavior during reading are saccades and fixations, which are traditionally extracted from the movements of only one eye. But we read with both eyes (binocularly), and besides version eye movements, when both eyes move in the same direction, our eyes perform vergence movements, where the eyes move in opposite directions. In other words, binocular vision of the text requires that for each fixation the vergence angle between the two visual axes is adjusted for proper fusion of the two retinal images – even though the viewing distance is not changed during reading. In (theoretically) optimal binocular vision, the principal visual directions (visual axes) of both eyes intersect at the fixation point. Slight deviations – fixation disparities (FD) or vergence errors – from this optimal vergence angle are typically smaller than Panum's area, i.e. the range of disparity where sensory fusion of the two retinal images is performed, thus double vision does not occur. These fixation disparities are called *exo* or *eso* when the visual axes of the eyes converge slightly behind or in front of the fixation point, respectively.

In reading research, the adjustment of vergence was of little relevance to many researchers, since a prevalent assumption was that each eye fixates the same character within a word. During the last decade a number of investigations showed that this assumption is not correct, or at least, not in every fixation during reading (see for an overview: Kirkby, Webster, Blythe, and Liversedge (2008) and Nuthmann and Kliegl (2009)): for example, Heller and Radach (1999) reported that at the end of fixation phases, landing positions of the eyes of eight readers were most often about 1–2 characters apart (character width: 20 min arc). Further, Kliegl et al. (2006) showed that the eyes fixated different letters within a word on 41% of fixations, while the visual axes were more likely to be crossed in front of the plane of presented text. In other words, the majority of fixations of 222 participants who read 144 sentences showed an eso fixation disparity (crossed visual axes) with an amount exceeding one character width. In contrast, Liversedge, White, Findlay, and Rayner (2006) reported proportions of 53% aligned, 8% crossed, and 39% uncrossed fixations, i.e. among the 47% of fixations with crossed and uncrossed visual axes the majority of cases reflected an exo fixation disparity for 15 participants who read 72 sentences (character width: 17.4 min arc). (Note that the classification of fixations as crossed and uncrossed means that the fixation disparity is larger than one character width; smaller fixation disparities are referred to as aligned; see Liversedge, Rayner et al. (2006) and Liversedge, White et al. (2006)). It is currently unclear whether fixation disparity may affect reading parameters like fixation duration. Further, difficulty in cognitive processing may modulate fixation disparity, but there are reports of no effects as well (Heller & Radach, 1999; Juhasz, Liversedge, White, & Rayner, 2006). Thus, the absolute amount or the direction of the fixation disparity as average across a population may be of minor importance for the average reading process. Furthermore, about 50% of fixations are reported to be aligned (relative to character

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width) and this proportion is similar across different studies; these studies from different laboratories only differ with regard to the direction of fixation disparity within the non-aligned fixations, i.e. more crossed than uncrossed fixation (Kliegl et al., 2006; Nuthmann & Kliegl, 2009) and more uncrossed than crossed fixations (Blythe et al., 2006; Liversedge, Rayner, White, Findlay, & McSorley, 2006; Liversedge, White et al., 2006). Up to date these reported differences between the different studies are discussed as to be due to different experimental conditions (see, for example, symposium "Binocularity" at the ECEM2009: http://www.ecem2009.org).

Moreover, an overview of the general vergence movement during reading is found in Nuthmann and Kliegl (2009) or Vernet and Kapoula (2009), which both confirmed previous findings: during saccades the eyes (often) diverge and this saccade disconjugacy is reduced during fixation by the post-saccadic drift in vergence during fixation; for the latter see Hendriks (1996) or Liversedge, White et al. (2006). Due to this vergence drift, which just reflects a slight movement of both eyes towards each other (convergence) or away from each other (divergence), there is an uncertainty regarding the most appropriate moment in time, for which the fixation disparity should be determined. Previous studies differ in this respect. Usually, for analyzing fixation disparity during reading the end of fixations is preferred (see, for example, Liversedge, Rayner et al. (2006) and Liversedge, White et al. (2006)), because the vergence drift (as a disparity reduction) led the binocular fixation point move towards the disparity plane of the text (Nuthmann & Kliegl, 2009). Nevertheless, Vernet and Kapoula (2009) showed that the end of the vergence drift during fixations is reached 48 ms after saccade offset on average, i.e. during the first part of the fixation period; afterwards, only slight movements in vergence occurred throughout the fixation phase.

The primary goal of the present study was to derive a precise description of fixation disparity during the fixation phases. We concentrated on the description of the minimal fixation disparity which was reached during each fixation; this specification of fixation disparity was based on the physiologically reasonable assumption that the binocular system aims for a reduction of fixation disparity during fixation (as shown by Liversedge, White et al. (2006), Vernet and Kapoula (2009, or Nuthmann and Kliegl (2009)) and that the minimum amount of fixation disparity (and corresponding moment in time) reflects the optimal binocular status. As shown by trial examples in Fig. 1a, vergence movements during fixation phases might follow different curves: for example, fixation disparity might be reduced very early and kept stable during fixation, as shown by Vernet and Kapoula (2009); or the process of reducing fixation disparity might continue up to the end of fixation as described graphically by Nuthmann and Kliegl (2009) and suggested earlier by Liversedge, White et al. (2006). Interestingly, we observed in several trials that the minimum fixation disparity was reached somewhere in the middle of the fixation phase and fixation disparity increases afterwards again.

These examples showed that a standard description of fixation disparity at the start or end of fixation may not be the optimal choice. Rather, the moment in time when the minimum fixation disparity is reached theoretically represents the moment of optimal fusion for the actual fixation, i.e. gives an appropriate estimation of binocular fixation accuracy within each fixation. We examined this measure with respect to the fixation disparity observed at the beginning and end of fixation phases. Specifically, we focused on the moment in time the minimum fixation disparity was reached; we also analyzed the amount of minimal fixation disparity and its relationship to other parameters like, for example, fixation duration, fixation position or incoming saccade amplitude. Note that we defined fixation position as actual fixation on a word/letter relative to the center of the screen, i.e. the center of the visual field, for which calibrations of the eye movement measures were obtained and which vertical midline resembled the visual direction of "straight-ahead". Thus, each fixation position reflected the spatial displacement of each fixation relative to the center of the screen. We further examined individual differences, testing the assumption that the minimal fixation disparity or the influences of, for example incoming saccade amplitude, might also depend on the observer.

Different to saccadic movements, vergence movements are not ballistic. Compared to saccadic eye movements, the vergence movement is slower, permanently feedback controlled and the trajectory of vergence is less stereotypic, i.e. the movements show considerable variations from observation to observation (Howard, 2002; Howard & Rogers, 2002). More importantly, the static vergence error, i.e. vergence baseline or starting fixation disparity, differs among observers; the reason why an individual's fixation disparity is eso (crossed visual axes relative to the target plane), exo (uncrossed visual axes relative to the target plane), or ortho (aligned visual axes relative to the target plane) is related to other parameters

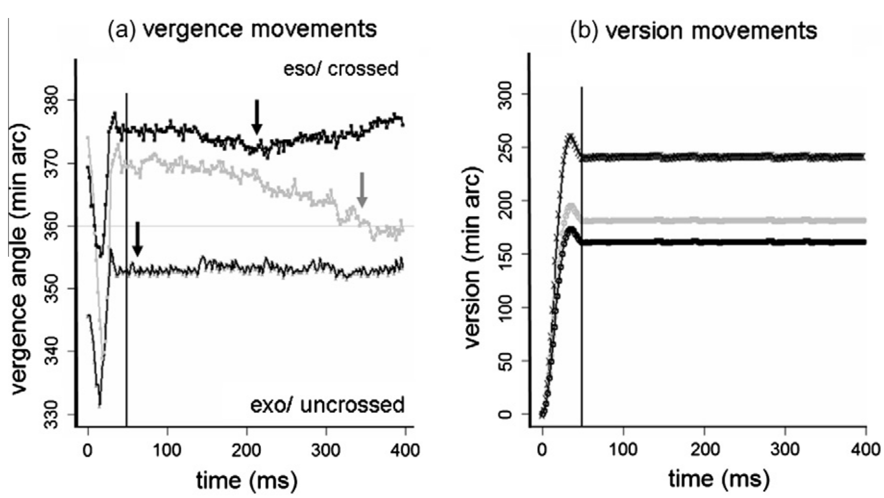

Fig. 1. Examples for single saccades with an adjacent fixation phase. (a) Three different vergence movements during saccade and fixation and (b) the corresponding version movements. The vertical line marks the end of the post-saccadic drift in version, i.e. the defined starting of the fixation. Additionally, in (a) the gray horizontal line marks the theoretically expected vergence angle (360 min arc) and the arrows indicate the moment in time, when minimum fixation disparity is reached. In the upper plot in (a), the minimum fixation disparity is reached in the middle of the fixation period and increases thereafter again, while for the lowest plot, the minimum fixation disparity is reached at the very beginning of the fixation. For the plot in the middle, the minimum fixation disparity is reached near the end of fixation.