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Not fixating at the line of text comes at a cost

Antje Nuthmann

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Abstract Previous research on eye guidance in reading has investigated systematic tendencies with respect to horizontal fixation locations on letters within words and the relationship between fixation location in a word and the duration of the fixation. The present study investigates where readers place their eyes vertically on the line of text and how vertical fixation location is related to fixation duration. Analyses were based on a large corpus of eye movement recordings from single-sentence reading. The vertical preferred viewing location was found to be within the vertical extent of the font, but fixations beyond the vertical boundaries of the text also frequently occurred. Analyzing fixation duration as a function of vertical fixation location revealed a vertical optimal viewing position (vOVP) effect: Fixations were shortest when placed optimally on the line of text, and fixation duration gradually increased for fixations that fell above or below the line of text. The vOVP effect can be explained by the limits of visual resolution along the vertical meridian. It is concluded that vertical and horizontal landing positions in single-sentence reading are associated with differences in fixation durations in opposite ways.

Keywords Reading · Eye movements · Vertical fixation positions · Preferred viewing location · Fixation durations

Introduction

When reading, we move our eyes across the page of text, mainly because of visual acuity limitations. Fine visual discriminations can be made only within the foveal region of the visual field, typically defined as the central 2º of vision. Thus, visual acuity is best in the fovea, and it rapidly decreases toward the parafovea and periphery (see Strasburger, Rentschler & Jüttner, 2011, for a review). Acuity drops faster along the vertical than along the horizontal meridian (Weymouth, Hines, Acres, Raaf & Wheeler, 1928).

A. Nuthmann (✉)
Psychology Department, University of Edinburgh, 7 George Square, Edinburgh EH8 9JZ, UK
e-mail: Antje.Nuthmann@ed.ac.uk

A. Nuthmann
Center for Interdisciplinary Research (ZiF), Bielefeld University, Bielefeld, Germany

Viewing position effects in reading

Eye movements during reading are generally considered to be the result of two classes of decisions, one spatial (*where* to move the eyes) and one temporal (*when* to move the eyes). The temporal aspect of eye movement behavior, the "when" decision, is captured by fixation-duration measures. The durations of individual fixations have been found to reflect ongoing perceptual and cognitive activity, providing a powerful method for investigating underlying perceptual and cognitive processes (Rayner, 1998). Concerning the spatial aspect of eye guidance in reading, there are several well-documented findings related to landing positions in words (see Vitu, 2011, for a review). First of all, there are systematic tendencies with respect to where the eyes typically land within a word (the preferred viewing location [PVL]). In addition, landing position influences the likelihood of within-word refixations (the optimal viewing position [OVP] effect) and the duration of fixations (the inverted OVP [IOVP] effect).

Landing positions of forward saccades into words tend to cluster at word center or slightly left of it, honoring the PVL (Rayner, 1979). For words of a given length, the distribution of landing positions resembles a truncated Gaussian distribution, and the PVL may be indexed by the mean of the fitted normal curve. The phenomenon has been replicated many times (e.g., McConkie, Kerr, Reddix & Zola, 1988; Nuthmann, Engbert & Kliegl, 2005; Vitu, McConkie, Kerr & O'Regan, 2001). The variance in landing positions around word center is thought to be due to visuomotor constraints (McConkie et al., 1988). The observation of a PVL has been taken as strong evidence for word-based eye guidance (see Vitu, 2011, for critical discussion).

OVP effects were first reported for isolated words, which are more easily and more quickly identified when the eyes initially fixate near the center of the word (see Vitu, Lancelin & d'Unienville, 2007, for a review). As a relevant example, Kajii and Osaka (2000) investigated the OVP in horizontally and vertically presented Japanese words. In both conditions, word recognition was best when the word center was fixated. Performance was generally better for horizontal words than for vertical words, which is in line with the results in Weymouth et al. (1928). Collectively, the results from single-word reading studies suggest that visual acuity is a major determinant of the OVP phenomenon. In text reading, a related effect has been described as the refixation probability OVP effect. The likelihood of making more than one fixation on a word before moving to another word is lower when the eyes initially fixate the middle of the word than when they first fixate the beginning or end of the word (e.g., McConkie, Kerr, Reddix, Zola & Jacobs, 1989; Nuthmann et al., 2005; Vitu et al., 2001). The occurrence of refixations is related not only to visual acuity constraints, but also to ongoing processing demands (McConkie et al., 1989). Given these findings from single-word and text reading studies, word center is thought to be the optimal position for word processing.

If central fixations afford optimal visual processing, fixation durations should be shortest when the eyes are located near the center of a word. Empirical data from various studies present, however, the reverse pattern. When the eyes are placed at word center, fixation durations are longest, rather than shortest (e.g., Hyönä & Bertram, 2011; Nuthmann et al., 2005; Vitu et al., 2001; White & Liversedge, 2006). This IOVP effect has been attributed to perceptual-economy principles (e.g., Vitu et al., 2001) and/or mislocated fixations (e.g., Nuthmann et al., 2005) (see below).

Research on viewing position effects in reading has exclusively considered horizontal fixation locations. The present study extends this research by investigating where readers fixate vertically on the line of text and how vertical fixation location modulates fixation duration. The interest in vertical landing positions in reading goes back to Huey (1908), who reasoned that the fixation point is likely to vary between the vertical extent of the font but may not wander perceptibly above or below the line.

Predictions on vertical fixation locations

Reading left-to-right languages is typically seen as requiring only horizontal eye movements—principally left to right. The exceptions are return sweeps (from one line to another), which show as oblique saccades. With regard to vertical fixation positions on the line of text, we can expect that both the *optimal* viewing position (i.e., the position where readers *should* fixate) and the *preferred* viewing position (i.e., the location where readers *do* fixate) fall close to the middle of the vertical extent of the text. Eye-tracking data suggest that the upper part of words in reading is more important for word recognition than the lower part (Perea, 2012). We may therefore specify our hypothetical OVP as a location in the upper part of the line of text. With regard to readers' actual eye movement behavior, variability in vertical landing positions is expected such that some fixations will fall above or below the line of text, because saccade programming is subject to oculomotor aiming errors (McConkie et al., 1988).

Predictions on vertical fixation durations

Both the horizontal and the vertical locations of fixation potentially affect fixation duration. The horizontal IOVP effect, discussed above, considers fixation durations as a function of horizontal (i.e., within-word) landing position of the eyes. Any effect of vertical fixation location is a function of distance from some meridian, such as the lower boundary of the text. Horizontal landing positions are expressed in terms of letters within words, whereas vertical landing positions will be determined as deviations (in degrees of visual angle) from the lower boundary of the text. In the following, the main explanations for the horizontal fixation duration IOVP effect are reviewed briefly. If applicable, predictions concerning the influence of vertical fixation position on fixation duration are derived.

Visual acuity account

Visual acuity rapidly drops with increasing horizontal and vertical retinal eccentricity. Therefore, a pure visual acuity account would predict longer fixation durations for fixation positions that (1) deviate to the left or right from word center and (2) deviate vertically from the line of text. The fixation-duration IOVP effect described above is inconsistent with the first hypothesis. The second prediction will be tested with the present data.

Perceptual-economy account

It has been argued that, for perceptual-economy reasons, fixations are held longer when the eyes are estimated to be at optimal locations where greater amounts of information are anticipated (Vitu et al., 2007; Vitu et al., 2001). On a more speculative note, Vitu and colleagues proposed that perceptual-economy principles may be universal in the sense that they may be at work in any task that involves visual information intake (Vitu et al., 2007). With regard to vertical landing positions in reading, optimality may be confined within the lower and upper boundaries of the text. The following prediction of a vertical IOVP effect can be derived from the perceptual-economy account: The duration of eye fixations should be longest for fixations that are placed optimally on the line of text, as compared with fixations placed above or below the line of text.

Mislocated fixation explanation

The mislocated fixation explanation suggests that mislocated fixations are the primary source of the fixation-duration IOVP effect (e.g., Engbert, Nuthmann, Richter & Kliegl, 2005; Nuthmann et al., 2005; Nuthmann, Engbert & Kliegl, 2007). Using modeling techniques, it was demonstrated that a considerable number of fixations are mislocated such that they do not fall on the intended target word, due to undershoots and overshoots of the oculomotor system (Nuthmann et al., 2005). Failed skippings of short words and unintended refixations of long words are particularly common (Engbert & Nuthmann, 2008). It was proposed that the eyes respond to mislocated fixations with the start of a new, potentially error-correcting saccade program. Because mislocated fixations occur most frequently at word boundaries, this mechanism generated the typical inverted *u*-shaped pattern for fixation durations as a function of landing position. In brief, the general idea of the mislocated IOVP model is that landing on the wrong word interferes with word processing and, therefore, needs correction (Nuthmann et al., 2005). Technically, fixations above or below the line of text may also qualify as mislocated fixations. However, missing the intended target word on the line of text by some vertical offset is likely to be less disruptive to reading than is fixating an entirely different word (horizontally). Moreover, corrections of small vertical errors do not appear to be an efficient oculomotor strategy. In line with this view, the directional distribution of microsaccades during reading fixations shows a horizontal preference (Nuthmann, Engbert & Kliegl, 2003, analyzing a subset of the present data). Thus, the notion of quick responses to mislocated fixations is not readily applicable to vertical eye positions in reading. Therefore, if a vertical fixation-duration IOVP effect is observed, it cannot be explained by a fast corrective response to mislocated fixations.

Method

Participants, materials, and apparatus

Analyses were based on eye movement data from the Potsdam Sentence Corpus (Kliegl, Nuthmann & Engbert, 2006), which contains 1,138 words in 144 single sentences. Data from 225 readers contributed to the analyses. All participants had normal or corrected-to-normal vision. Sentences were presented one at a time in black Courier New font on a white background on the centerline of a computer screen. At a viewing distance of 60 cm, letters subtended 0.38º. For binocular eye movement recording, EyeLink I and II systems (SR Research, Ottawa, Ontario, Canada) were used (absolute error of less than 0.5º, which corresponds approximately to the size of a single letter in the experimental setup). A 9-point system-controlled EyeLink calibration procedure was used. Further details on participants, sentence material, apparatus, and procedure are provided in Nuthmann and Kliegl (2009).

Analyses

For binocular saccade detection, a velocity-based detection algorithm was used (see Appendix A in Nuthmann & Kliegl, 2009, for details). Sentences containing blinks were removed. No data cleaning or correction procedures were applied; in particular, vertical eye positions were not corrected. Analyses were based on the average of all position samples during the fixation, obtained separately for the horizontal and the vertical dimensions. First and last fixations in a sentence were excluded from analyses. In addition, fixation durations shorter than 50 ms and longer than 750 ms were removed. Data were analyzed with linear mixed models, using the *lmer* program of the *lme4* package (Bates, Maechler & Bolker, 2012) supplied in R.

Results

For analyses of vertical fixation locations, the lower vertical boundary of the text served as reference point (0 on the *x*-axis in Fig. 1). Relative to this reference, eight equally spaced bins to either side (to the top vs. to the bottom) were considered, with a bin width of 15 min arc. Analyses showed that vertical landing position distributions were Gaussian in shape (Fig. 1a). For both eyes, distributions peaked within the vertical boundaries of the text. The mean of the distribution is termed the vertical PVL. The analyses further demonstrate that readers frequently fixated above or below the actual line of text (right eye, 53.1 %; left eye, 55.7 %).

Figure 1a reveals a subtle difference in distributions for the two eyes: The left-eye distribution was more centered on the line of text than was the right-eye distribution. It is known that the two eyes do not always fixate exactly the same location (Liversedge, White, Findlay & Rayner, 2006). Previous analyses of the Potsdam Sentence Corpus data established vertical fixation disparity in that, on average, the right eye tended to fixate somewhat below the left eye (Nuthmann & Kliegl, 2009). The present data substantiate these findings by taking the vertical sentence boundaries into account. Vertical fixation positions for the left and right eyes were analyzed separately—that is, as independent events. Nonetheless, the obtained distributions further illustrate the direction of the observed average vertical fixation disparity: Relative to the left-eye distribution, the distribution for the right eye was slightly shifted downward (i.e., to the right in Fig. 1a).

A second analysis considered how fixation durations varied as a function of vertical landing position. As a novel finding, fixation durations showed a vertical optimal viewing

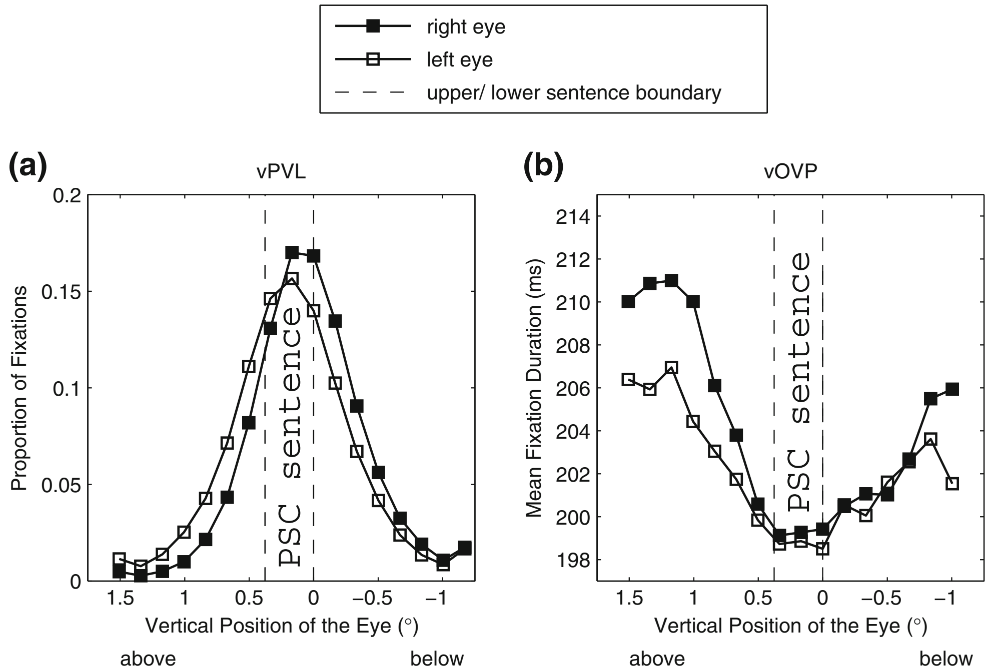

Fig. 1 Vertical eye movement data in left-to-right reading. Participants read single sentences presented at the vertical midline of the screen. **a** Distributions of vertical landing positions. **b** Mean fixation durations as a function of vertical landing position. In both panels, zero on the *x*-axis represents the lower vertical boundary of the text. Data from the right eye (full squares) are contrasted with data from the left eye (open squares). PSC=Potsdam Sentence Corpus

position (vOVP) effect: When the eyes fixated on the line of text, fixation durations were shortest. The more the vertical fixation location deviated from the line of text, however, the longer the fixation duration was. For statistical evaluation, piecewise linear mixed models with by-subject random intercepts were specified, using the upper and lower sentence boundaries (b_{up} and b_{low}) as breaking points. The first two models (one for each eye) each regressed fixation duration on deviations in fixation position from the upper sentence boundary ($x > b_{up}$). The second pair of models did the same for deviations from the lower sentence boundary ($x < b_{low}$). Accordingly, the fixed-effect estimates for the intercept in Table 1 represent the mean durations for fixations placed at the upper and lower sentence boundaries, for a given eye (cf. Fig. 1b). Importantly, for each model the fixed-effect estimate for the slope was significant ($|t|>2$), confirming that fixation duration reliably increased as readers fixated further away from the line of text.

Discussion

The present study investigated where readers place their eyes vertically on a line of text and how these vertical fixation

Table 1 Fixed effects estimates on fixation durations from piecewise linear mixed models

	Fixation Positions Above the Line of Text					
	Left Eye			Right Eye		
	Estimate	*SE*	*t-value*	*Estimate*	*SE*	*t-value*
Intercept	199.3	1.743	114.36	200.3	1.79	111.85
Slope	0.104	0.036	2.87	0.173	0.05	3.46
	Fixation Positions Below the Line of Text					
	Left Eye			Right Eye		
	Estimate	*SE*	*t-value*	*Estimate*	*SE*	*t-value*
Intercept	198.1	1.738	114	198.8	1.74	114.28
Slope	−0.127	0.036	−3.53	−0.087	0.034	−2.56

Note. SE=standard error.

locations are associated with differences in fixation durations. Analyses were based on a large corpus of binocular eye movement recordings from 225 readers (Kliegl et al., 2006). Results showed that, contrary to Huey's (1908) intuition, readers frequently fixated above or below the actual line of text. Distributions of vertical landing positions were normal in shape and peaked on the line of text. Results by Perea (2012) suggest that the upper part of words is more important for reading than the lower part of words, confirming Huey. The present data add to this by showing that there was no preference for fixating the upper part of the line of text in particular.

In addition, a vOVP effect for fixation durations was found: Fixation durations were shortest when fixation was on the line of text and systematically increased for fixations slightly above or below the line of text. The data suggest that vertical and horizontal landing positions are associated with differences in fixation durations in opposite ways. Previous research has established a horizontal IOVP effect; fixation durations are longest when optimally placed at word center and decrease toward the beginnings or ends of words (e.g., Nuthmann et al., 2005; Vitu et al., 2001). In contrast, the vOVP effect reported here suggests that fixations are shortest, rather than longest, when placed optimally on the line of text. As compared with the horizontal IOVP effect (see Fig. 2 in Nuthmann et al., 2005, for the Potsdam Sentence Corpus data), the vOVP effect is relatively small, about 10 ms in size. The effect is, however, very systematic in that the fixation-duration profile shows as a precisely shaped trough (Fig. 1b). This clear-cut pattern also suggests that fixations above or below the line of text (Fig. 1a) are not an artifact due to the limits in spatial accuracy of the eyetracker, or due to poor calibration.

How does the reported vertical fixation-duration OVP effect relate to theoretical explanations concerning the functional relation between fixation duration and horizontal landing position? The perceptual-economy account advocates that fixations are held longer when the eyes are estimated to be at locations in words where greater amounts of information are anticipated (Vitu et al., 2007; Vitu et al., 2001). In reading, the horizontal center of a word is such an optimal location. The perceptual-economy account can therefore explain the IOVP effect for horizontal landing positions: Fixations that are placed near word center are longer than fixations that fall near word boundaries (Vitu et al., 2001). This idea can be extended for vertical landing positions: Fixations that are placed optimally on the line of text should be longer than fixations that fall beyond the vertical boundaries of the text. The present data show, however, the reverse pattern.

The mislocated fixation IOVP model presents an alternative explanation for the horizontal fixation-duration IOVP effect, drawing on the observation that a considerable proportion of saccades appear to miss the intended word (e.g., Engbert et al., 2005; Nuthmann et al., 2005, 2007). As was outlined in the Introduction, the notion of quick responses to mislocated fixations does not apply to vertical fixation positions in single-sentence reading.

It appears that visual acuity limitations are a major determinant of the observed vOVP effect for fixation durations. Visual acuity rapidly drops with increasing distance from the center of the fovea. It decreases systematically for both the vertical and the horizontal meridians, but the drop of acuity with eccentricity is stronger in the vertical than in the horizontal meridian (Weymouth et al., 1928). Thus, the letters of a word are most rapidly identified when the eyes are on the line of text. As the vertical distance from the line of text increases, fixation duration increases. Of special note from Fig. 1b is that the fixation-duration profile indicates a flat trough when the eyes fixate within the vertical sentence boundaries, suggesting that there was no loss of visual resolution within the vertical extent of the line of text.

Future research should explore factors that may modulate or contribute to the phenomena reported here. For example, readers exhibit longer fixation durations during intervals of mindless reading (e.g., Schad, Nuthmann & Engbert, 2012), but their eye movements may also be less accurate.[1] It would also be interesting to investigate where patients with central vision loss fixate relative to the line of text and whether this is associated with differences in fixation duration.

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[1] I thank Sarah White for pointing out this possibility.

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