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Mislocated fixations during reading and the inverted optimal viewing position effect

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Abstract

Refixation probability during reading is lowest near the word center, suggestive of an optimal viewing position (OVP). Counter-intuitively, fixation durations are largest at the OVP, a result called the inverted optimal viewing position (IOVP) effect [Vitu, McConkie, Kerr, & O'Regan, (2001). Vision Research 41, 3513–3533]. Current models of eye-movement control in reading fail to reproduce the IOVP effect. We propose a simple mechanism for generating this effect based on error-correction of mislocated fixations due to saccadic errors. First, we propose an algorithm for estimating proportions of mislocated fixations from experimental data yielding a higher probability for mislocated fixations near word boundaries. Second, we assume that mislocated fixations trigger an immediate start of a new saccade program causing a decrease of associated durations. Thus, the IOVP effect could emerge as a result of a coupling between cognitive and oculomotor processes.

Keywords: Reading; Optimal viewing position; Mislocated fixations; Saccadic errors

1. Introduction

Fixation durations in reading are sensitive to local processing difficulty, as reflected in effects of word frequency and predictability (i.e., the probability to guess the word from the previous words of the sentence). This well-established link between cognitive processes of word recognition and eye-movement control (e.g., Kliegl, Grabner, Rolfs, & Engbert, 2004; Rayner, 1998) has been implemented in computational models of eye-movement control during reading (see Reichle, Rayner, & Pollatsek, 2003, for a recent review; Engbert, Longtin, & Kliegl, 2002). However, fixation durations are also influenced by low-level nonlinguistic factors like word length. Likewise, fixation durations systematically vary with within-word fixation position (Vitu, McConkie, Kerr, & O'Regan, 2001). It is commonly accepted that within-word landing positions are the result of oculomotor errors (McConkie, Kerr, Reddix, & Zola, 1988). Thus, decisions about where to fixate next, as reflected in landing position distributions, have been largely attributed to the oculomotor plant rather than the cognitive control system of eye movements. The question how oculomotor errors affect fixation durations, however, has so far been neglected in theoretical models.

The word center is typically defined as the optimal viewing position (OVP), operationally defined as the position with a minimum refixation probability (cf., McConkie, Kerr, Reddix, Zola, & Jacobs, 1989, for continuous reading; O'Regan & Lévy-Schoen, 1987, for isolated words). As a consequence, fixation durations were expected to exhibit also a minimum at or near word centers. For gaze durations (i.e., the sum of all fixations on a word, excluding any fixations after the eyes have left the word), such an OVP effect was observed in an isolated word recognition paradigm (O'Regan,

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Lévy-Schoen, Pynte, & Brugaillère, 1984), but not in continuous reading (Vitu, O'Regan, & Mittau, 1990). For continuous reading, however, Vitu et al. (2001, see also O'Regan, Vitu, Radach, & Kerr, 1994) reported several inverted optimal viewing position (IOVP) effects for fixation durations: For example, single fixations (i.e., fixations on words that are fixated exactly once) were longest, not shortest, near the word centers. As an explanation for this counterintuitive effect, we propose that oculomotor errors often lead to mislocated fixations on unintended words. These errors are more likely to result in fixations at boundaries than centers of words. Assuming also that mislocated fixations immediately induce the start of error-correcting saccade programs, we predict that average fixation durations at word boundaries are shorter than at the optimal viewing position. We tested this theoretical explanation with a series of computational analyses; it is also compatible with several mathematical models.

1.1. Cognitive models vs. oculomotor models

Theoretical models of eye-movement control during reading can be classified into two general categories (Rayner, Sereno, & Raney, 1996; Starr & Rayner, 2001): (1) *Cognitive models* are based on the assumption that ongoing cognitive processing drives eye movements during reading, while (2) *oculomotor models* hypothesize that eye movements are mainly controlled by low-level oculomotor or visuomotor processes and are only indirectly related to ongoing cognitive processing. Cognitive models can be further divided into models driven by *sequential attention shifts* (SAS) and models of *guidance by attentional gradients* (GAG) (for details of this classification see also Engbert et al., 2002; Reichle et al., 2003). For SAS models the serial allocation of visual attention from one word to the next is the "engine" driving eye movements. This architecture was first proposed by Morrison (1984). The currently most advanced SAS model is E-Z Reader (Reichle et al., 2003; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 1999). An SAS model with fewer internal states based on advanced stochastic methods was proposed as an alternative (Engbert & Kliegl, 2001; Engbert & Kliegl, 2003). In contrast, GAG models assume that attention is distributed continuously as a gradient. As a consequence, more than one word can be attended to (and processed) in parallel. The SWIFT model (Engbert et al., 2002; Engbert, Kliegl, & Longtin, 2004; Kliegl & Engbert, 2003) is such a GAG variant that assumes spatially distributed lexical processing. In both theoretical frameworks, eye movements are driven by word recognition. In all cognitive models, a specific word is selected as a saccade target. Thus, if oculomotor errors lead to a mislocated fixation, it should affect processing.

The most prominent example of an oculomotor model is O'Regan's strategy-tactics model (1990, 1992; O'Regan & Lévy-Schoen, 1987). In addition, there have been proposals by McConkie et al. (1988), and McConkie et al. (1989). A more recent primary oculomotor model was suggested by Yang and McConkie (2001, 2004). The key assumption of their competition–interaction theory is that the timing of saccades is largely independent of lexical processing. However, processing difficulty can inhibit the oculomotor system from initiating a saccade program.

In principle, the mechanism we propose to account for the IOVP effect is compatible with any theory assuming (1) that reading saccades are directed to a specific target word, and (2) that mislocated fixations are identified and, if necessary, corrected. Cognitive models (e.g., Reichle et al., 2003; Engbert et al., 2002) and most oculomotor models (e.g., O'Regan, 1990; O'Regan & Lévy-Schoen, 1987; oculomotor word-targeting strategies in Reilly & O'Regan, 1998; but see Yang & McConkie, 2004; Vitu, 2003, for a different perspective) assume that an intended target word is specified for each saccade.

1.2. The optimal viewing position

The optimal fixation position for processing a word was originally derived from word identification curves in the isolated word presentation paradigm: The optimal viewing position is defined as the location in a word at which recognition time is minimized. According to O'Regan and Lévy-Schoen (1987), the OVP is slightly left of the center of the word. Due to the rapid drop of visual acuity with distance from the center of the fovea, the letters of a word are most rapidly identified when the eyes are near the word's center. The consequences of making fixations at locations other than the OVP have been extensively studied (for a review, Rayner, 1998). Most importantly, a *refixation OVP effect* was consistently found (e.g., O'Regan & Lévy-Schoen, 1987): The frequency of refixating a word (that is, of making an additional fixation after the initial fixation on the word) is lowest when the eyes initially fixate the center of the word. The refixation OVP effect generalizes to continuous reading (McConkie et al., 1989; Rayner & Fischer, 1996; Rayner et al., 1996; Vitu, 1991; Vitu et al., 1990) and coincides with the OVP determined by word identification times. Therefore, most cognitive and oculomotor models assume that, with their initial saccade, readers target the word center, i.e. the optimal viewing position (e.g., McConkie et al., 1988; Reichle et al., 2003, 1999; but see Vitu, 2003, proposing that the eyes move forward with no specific saccade target).

The current paper is strongly motivated by and related to extensive and seminal studies by McConkie et al. (1988) and Vitu et al. (2001). In their analyses of three large existing corpora of eye movement data