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Direct lexical control of eye movements in reading: Evidence from a survival analysis of fixation durations

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ABSTRACT

Participants' eye movements were monitored in an experiment that manipulated the frequency of target words (high vs. low) as well as their availability for parafoveal processing during fixations on the pre-target word (valid vs. invalid preview). The influence of the word-frequency by preview validity manipulation on the distributions of first fixation duration was examined by using ex-Gaussian fitting as well as a novel survival analysis technique which provided precise estimates of the timing of the first discernible influence of word frequency on first fixation duration. Using this technique, we found a significant influence of word frequency on fixation duration in normal reading (valid preview) as early as 145 ms from the start of fixation. We also demonstrated an equally rapid non-lexical influence on first fixation duration as a function of initial landing position (location) on target words. The time-course of frequency effects, but not location effects was strongly influenced by preview validity, demonstrating the crucial role of parafoveal processing in enabling direct lexical control of reading fixation times. Implications for models of eye-movement control are discussed.

1. Introduction

The human visual system compensates for its lack of high resolution outside of the fovea by making eye and head movements. During the performance of complex visual tasks such as reading,

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high-velocity saccadic eye movements, during which vision is largely suppressed (Matin, 1974), serve to align the fovea with the part of the text that is being encoded by the reader. Reading saccades, which occur at an average rate of 3–4 per second, are separated by fixations during which the eyes are relatively still and perceptual information is extracted (see Rayner (1998, 2009a) for reviews).

Given the vital role of eye movements in selecting the location of the text to be foveated (i.e., fixation position within words) as well as delimiting the duration of each foveation (i.e., fixation duration), researchers have examined the factors that influence *when* the eyes move as well as *where* they move. Over the past three decades, this investigation of the nature of eye-movement control in reading generated a substantial body of findings as well as considerable controversy (see Rayner (1998, 2009a) and Starr and Rayner (2001) for reviews). Early models of eye movement control in reading differed dramatically with respect to the hypothesized role of ongoing *lexical* and comprehension processes in controlling eye movements. *Oculomotor* theories (e.g., McConkie, Kerr, Reddix, & Zola, 1988; McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; O'Regan, 1990, 1992) assumed that *non-lexical*, low-level visual information and oculomotor constraints jointly determine eye-movement control in reading. In contrast, *processing* theories (e.g., Henderson & Ferreira, 1990; Just & Carpenter, 1980; Kennison & Clifton, 1995; Morrison, 1984; Rayner & Pollatsek, 1989) advocated a critical role for lexical and attentional processes.

In addition to the lexical vs. non-lexical dichotomy, models of eye-movement control of fixation times in reading often refer to the distinction between *direct* vs. *indirect* control. Direct control refers to the assumption that the processing of the properties of the fixated word ($word_n$) influences the timing of the saccade terminating that fixation, regardless of whether this processing was initiated while $word_n$ was foveated or when it was parafoveally processed during fixations on the pre-target word ($word_{n-1}$). Consequently, direct control is by definition an *immediate* fixation-by-fixation adjustment based on the properties of the *local* stimulus (i.e., $word_n$). Direct control of fixation times is often contrasted with a variety of indirect control mechanisms that are assumed to cause the eyes to continue to move forward at a rate that (on average) allows enough time to encode the text. Importantly, if the triggering of the saccade that terminates a fixation on $word_n$ was caused by indirect control, then the duration of that fixation is assumed not to be influenced by any lexical or non-lexical properties of $word_n$. Thus, in order to allow for optimal encoding of the text, indirect control is often postulated to involve a *delayed* adjustment (i.e., non-real-time) of fixation times that is typically based on the average processing difficulty encountered by the reader and other contextual factors (i.e., *global* control). Thus, in the context of the eye-movement control literature, the direct/indirect dichotomy often incorporates the immediate/delayed and local/global distinctions. It is important to note that the above use of the terms "direct" and "indirect" is not consistent with the more colloquial use of the terms to refer to whether or not some behavior is mediated by intervening stages or mechanisms. Given that there is an unknown number of synaptic junctions between the cortical systems that support cognition and the brainstem circuitry that is ultimately responsible for moving the eyes, our usage of the direct/indirect distinction reflects our decision to remain agnostic about the degree to which the mechanisms that control eye movements in reading are direct or indirect in the more colloquial sense (i.e., non-mediated vs. mediated).

The nature of the debate concerning the eye-movement control of fixation times in reading has become more complex in recent years with several models incorporating a combination of direct and indirect control mechanisms (sometimes referred to as *mixed* control models; e.g., Rayner & Pollatsek, 1981). Furthermore, although it is now generally accepted that fixation times are influenced by lexical and/or linguistic variables such as word frequency (Inhoff & Rayner, 1986; Rayner & Duffy, 1986; see White (2008) for a review), contextual constraint or predictability (Ehrlich & Rayner, 1981; Rayner, Ashby, Pollatsek, & Reichle, 2004; Rayner & Well, 1996), lexical ambiguity (e.g., Duffy, Morris, & Rayner, 1988; Rayner & Duffy, 1986; Sheridan, Reingold, & Daneman, 2009; see Duffy, Kambe, and Rayner (2001) for a review) and age of acquisition (e.g., Juhasz & Rayner, 2006), there remains an intense disagreement as a result of differing assumptions concerning both the time course of lexical influences and the proportion of reading fixations that are impacted by lexical processing. Specifically, recent models advocating primarily visual/oculomotor control of fixation times in reading (e.g., Deubel, O'Regan, & Radach, 2000; Feng, 2006; McConkie & Yang, 2003; Yang, 2006; Yang & McConkie, 2001) assume that lexical effects are limited to a small subset of long fixations and that the vast majority of reading fixations are unaffected by these variables. In marked contrast, other recent models suggest that lexical and linguistic processes play a non-trivial role in controlling fixation times in