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Do successor effects in reading reflect lexical parafoveal processing? Evidence from corpus-based and experimental eye movement data

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ABSTRACT

In the past, most research on eye movements during reading involved a limited number of subjects reading sentences with specific experimental manipulations on target words. Such experiments usually only analyzed eye-movements measures on and around the target word. Recently, some researchers have started collecting larger data sets involving large and diverse groups of subjects reading large numbers of sentences, enabling them to consider a larger number of influences and study larger and more representative subject groups. In such corpus studies, most of the words in a sentence are analyzed. The complexity of the design of corpus studies and the many potentially uncontrolled influences in such studies pose new issues concerning the analysis methods and interpretability of the data. In particular, several corpus studies of reading have found an effect of successor word ($n + 1$) frequency on current word (n) fixation times, while studies employing experimental manipulations tend not to. The general interpretation of corpus studies suggests that readers obtain parafoveal lexical information from the upcoming word before they have finished identifying the current word, while the experimental manipulations shed doubt on this claim. In the present study, we combined a corpus analysis approach with an experimental manipulation (i.e., a parafoveal modification of the moving mask technique, Rayner & Bertera, 1979), so that, either (a) word $n + 1$, (b) word $n + 2$, (c) both words, or (d) neither word was masked. We found that denying preview for either or both parafoveal words increased average fixation times. Furthermore, we found successor effects similar to those reported in the corpus studies. Importantly, these successor effects were found even when the parafoveal word was masked, suggesting that apparent successor frequency effects may be due to causes that are unrelated to lexical parafoveal preprocessing. We discuss the implications of this finding both for parallel and serial accounts of word identification and for the interpretability of large correlational studies of word identification in reading in general.

Introduction

One of the major debates in reading research concerns the extent to which upcoming words can be processed before they are fixated (i.e., what is the extent of parafoveal

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preprocessing?). This question closely aligns with the issue of how many words a reader can process in parallel. Since only one word can be fixated at a time, and since there is only limited evidence that readers keep processing words after they have moved their gaze away from them (Binder, Pollatsek, & Rayner, 1999; Rayner, Well, & Pollatsek, 1980), readers processing multiple words at once must be engaging in parafoveal processing. Thus far in the literature, there have been two general approaches to answering this question: experimental manipulations and large corpus correlational techniques.

Evidence that readers are able to process parafoveal words at all was shown by McConkie and Rayner (1975; for a recent review of their research see Rayner, 2014), and since then a number of studies have converged to estimate that the area from which readers can obtain useful visual information (the *perceptual span*) extends up to 14–15 letter spaces to the right of fixation (usually including the current and next word). A different paradigm, the gaze-contingent boundary paradigm, which was introduced by Rayner (1975), provides insight into which properties of an upcoming word can be pre-processed. In this paradigm, unbeknownst to the reader, an invisible boundary is placed to the left of a target word of interest, which remains masked before the boundary is crossed. After the boundary is crossed, the display changes to reveal the actual target word. Subjects are usually not aware of this experimental manipulation. By varying how similar the mask is to the target word, researchers can infer which properties of the target word can be processed parafoveally; previews that are more similar to the target lead to faster reading time once the target is fixated (i.e., they yield preview benefit; for reviews, see Schotter, 2013; Schotter, Angele, & Rayner, 2012). In contrast to these experimental approaches, parafoveal processing is assessed in corpus analyses by entering properties of the upcoming word into a statistical model; if properties of the upcoming word account for variance in first-pass reading time on the current word, researchers infer that the reader was processing the upcoming word before fixating it (i.e., in parallel with processing of the current word).

The different accounts of parafoveal and serial/parallel processing are best summarized in the context of current computational models of eye movement control in reading. These models can be divided in two groups: Serial attention shift (SAS) models assume that attention can only be allocated to one word at a time. Usually, this means that attention (i.e., lexical processing) is initially allocated to the currently fixated word and then shifted to upcoming parafoveal words while the language processing system is waiting for the oculomotor system to plan and execute a saccade. The most prominent representative of SAS models is the E-Z Reader model (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Pollatsek, & Rayner, 2006; Reichle, Warren, & McConnell, 2009). In contrast to SAS models, processing gradient (PG) models assume that, during normal reading, attention can be spread over multiple words in a sentence, with processing speed being determined by the distance of each letter from the center of fixation (i.e., by its eccentricity). As a consequence, PG models predict that readers should be frequently engaging in lexical parafoveal processing of several upcoming words (although recent models have placed some limitations on which words can be processed in a given situation, e.g. Schad & Engbert, 2012). Prominent examples of PG models are the SWIFT model (Engbert, Longtin, & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl, 2005; Schad & Engbert, 2012) and the Glenmore model (Reilly & Radach, 2006).

While these two classes of models are similar in many respects (and consequently make similar predictions for most of the benchmark effects in reading), the detailed implementations of both the serial and parallel accounts of word identification in reading have stimulated a great deal of research aimed at testing their divergent predictions (for thorough reviews of this research, see Rayner, 1998, 2009a; Schotter et al., 2012). Here, we will focus on research addressing the most important difference between the models' predictions: parafoveal-on-foveal (PoF) effects. PoF effects are defined as effects of the linguistic properties (e.g., word frequency) of the upcoming word (word $n+1$) on the ongoing processing of the currently fixated word (word n) as reflected by eye movement measures such as fixation time and, to a lesser extent, fixation probability. PoF effects are similar to but theoretically distinct from successor effects (although they have often been discussed similarly; see further discussion below). Since PG models assume that parafoveal words are constantly being processed (until completion), while SAS models predict parafoveal processing only after saccade programming away from word n has already begun, PoF effects are considered to be more compatible with PG models than with SAS models. Importantly, despite this generally accepted dichotomy, neither SWIFT nor E-Z Reader currently implement a mechanism that would allow parafoveal input to have an influence on the duration of the ongoing fixation.[1] Still, it could be argued that such a mechanism would be easier to implement in SWIFT than in E-Z Reader. We now turn to an important caveat regarding the debate surrounding parafoveal processing of words: the experimental methods and statistical approaches used to test for its presence.

The difference between PoF and successor effects

The difference between correlational and the experimental approaches can be described as follows: in the experimental approach, the variables of interest are controlled or manipulated a priori in the experimental design (e.g. by holding word length constant or varying it across conditions) whereas in correlational approaches the variable of interest is investigated post hoc by entering the word's property into the statistical analysis (e.g., by entering word length as a predictor variable in a regression model). In practice, one could argue most studies of reading include some degree of both approaches by manipulating some variables a priori while entering others into the

[1] SWIFT may allow an effect of parafoveal processing on refixation probability and thereby gaze duration. Additionally, first fixation duration and single fixation duration may be influenced to some degree by changes in the saccade-target selection (Risse, Engbert, & Kliegl, 2008; Schad & Engbert, 2012).