consistency is possibly attributable to variations in our definitions of an informative or redundant beginning to a word (bigram/trigram frequency vs. predictability by a cloze task), or to variations in cognitive load imposed by the specific reading task, because we know that foveal load influences the effectiveness of parafoveal information (Henderson & Ferreira 1990), or to variations in the reading skill of the participants being tested (see Everatt et al. 1998). The inconsistency of an effect simply means that we have not yet determined the conditions in which it will appear. Not all words are skipped, and not all short words are skipped all of the time, but there is no suggestion that we should ignore this effect because it does not appear with total predictability. The same should hold for the landing position effect.

The conditions for an information-based landing position effect are that (i) oculomotor programming can be modulated by visually available information, and that (ii) orthographic information can be extracted from words currently in parafoveal vision. The evidence supporting both of these conditions is well established. First, landing positions are sensitive to word length, and some short words sometimes receive no fixation at all (target article, sect. 2.8.1). Second, the parafoveal preview effect has been demonstrated for orthographic information (sect. 2.6). The E-Z Reader model accounts very well for these demonstrations of modulation, and when they are viewed together they make plausible the modulation of the landing position by orthographic information.

The landing position effect is plausible on the basis of lability of oculomotor programming and on the basis of the parafoveal processing of orthographic information. It has been demonstrated in a number of experiments that have used a number of alphabetic languages. How then might the E-Z Reader model be developed to account for it? One possibility is that the first stage of word identification (L_1 in Fig. 3), which in earlier E-Z Reader models was described as performing a familiarity check, could identify predictable sequences of letters at the beginning of word$_{n+1}$. If a highly unfamiliar bigram or trigram started word$_{n+1}$, then a shorter saccade may be programmed. If a predictable sequence were detected, then the signal to the oculomotor system would be to start programming a saccade of increased amplitude. And if the word contained a predictable letter sequence and early visual processing had recognised that it was a short word, then the saccade would skip the word altogether. The model could incorporate this effect and make predictions that would help describe it further. The first task of all model-builders is to identify the essential evidence, and here the E-Z Reader model does not so much fall over as turn its back on the data.

The basic assumptions of E-Z Reader are not well-founded

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Abstract: This commentary focuses on the two basic assumptions of the E-Z Reader model, discussing the possibility that adjacent words in reading may be processed in parallel rather than serially, and presenting evidence against a cognitive control of eye guidance in reading.

Like several recent models of eye guidance in reading, the E-Z Reader model provides a fairly good account of the variability of eye behavior that characterizes reading. From a psychological perspective, however, the performance of a computational model, or how well simulations fit behavioral observations, is not as critical as the reality of the mechanisms and the processes that lead to such performance. From that perspective, E-Z Reader may not be a serious candidate. In this commentary, I present several findings that challenge the two basic assumptions of the model, suggesting, first, that reading may not proceed through sequential attention shifts, and second, that ongoing processing is not the main driving force behind eye guidance.

The first basic assumption of E-Z Reader posits that for the temporal order of the words to be preserved in reading, adjacent words must be processed serially through covert shifts of attention from the fixated word to the parafoveal word(s). This assumption cannot, however, be asserted based on current empirical evidence. First, as noted by Schroyens et al. (1999), the negative influence of the foveal processing load on parafoveal preview benefit is in no way proof that processing of the parafoveal word starts only when the fixated word is identified. As the difficulty of the foveal word increases, a tendency for greater spillover effects in the visible compared to the masked preview condition can be observed, which suggests that the effect may simply originate from an interaction between processing associated with the foveal and parafoveal words. Furthermore, parafoveal preview benefit becomes greater rather than smaller as the fixation duration increases, thereby indicating that parafoveal processing lasts for the whole fixation time, rather than being limited to the delay that remains from the moment the fixated word is identified until the saccade is ready to go.

On the other hand, the fact noted by the authors, that processing of the foveal word remains unaffected in most instances by the lexical and semantic properties of the parafoveal word, does not necessarily mean that adjacent words are processed in sequence. In the framework of a pure parallel hypothesis that makes no recourse to the notion of attention, the presence of parafoveal-on-foveal effects is indeed not obligatory, but rather is conditional on the respective time course of processing associated with both foveal and parafoveal words (see Vitu et al., in press). As more letters from the parafoveal word fall into a region of lower visual acuity, parafoveal processing is relatively slow compared with that associated with the fixated word; and the likelihood that it influences processing associated with the fixated word may be relatively low, unless the word is very easy to process.

Parallel processing therefore remains a serious alternative to the sequential attention shift assumption, and, given that it relies strongly on visual acuity, it may as well preserve the temporal order of the words. Now, it remains an open question whether keeping word order straight is critical to reading. Indeed, several studies suggest that the eye-movement pattern does not always respect word order. This happens, for instance, when a word that is not yet identified is initially skipped. In that case, the word will be fixated only after the execution of a regressive saccade from one of the following words (Vitu & McConkie 2000; Vitu et al. 1998). These particularities of the eye-movement pattern, which are actually not accounted for by E-Z Reader, bring us to the second assumption.

The second basic assumption of E-Z Reader states that ongoing processing is the main driving force behind eye guidance. Ongoing processing would determine when the eyes move, and which word to send the eyes to, while visuomotor processes would produce systematic errors in sending the eyes to specific locations. Three major objections can be raised against this notion. First, the duration of individual fixations, although being correlated with the difficulty of processing associated with the encountered words, is also strongly influenced by the fixation position, with fixation duration being greatest when the eyes are at the center of words (Vitu et al. 2001). This phenomenon, which is opposed to Rayner et al.'s (1996) finding, is very robust since it was found in three different corpora of eye-movement data (based on a total of 153,855 fixations). Besides being interesting, it seriously questions the cognitive assumption, as it is about twice as large as the effect attributable to word frequency and as it cannot be interpreted in terms of ongoing processing. Because a word is most easily identified when the eyes initially fixate its middle, fixation duration should be shortest rather than longest at that position.

A second objection to the cognitive control hypothesis relates to the postulate that ongoing processing determines which word to

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send the eyes to. A recent review confirms that the frequency and the predictability of the words influence the likelihood of word skipping (Brysbaert & Vitu 1998). However, it also indicates that these effects are rather rare, and that when they occur they are smaller than the effects of both word length and launch site. As words get shorter, and the eyes are launched from closer to the beginning of the words, skipping rate increases drastically up to about 90% in the most extreme conditions. Undoubtedly, shorter and closer words are more likely to be identified in parafoveal vision, but this is not what causes them to be skipped more often. Indeed, a comparison between text reading and the scanning of meaningless material (or z-letter strings) reveals that string length and launch site influence string-skipping in the same manner as word length and launch site influence word skipping (Vitu et al. 1995). Such great regularities in the pattern of eye movements – present even when no cognitive processing is involved – strongly suggest that the decision of which word to fixate next is not cognitively determined, but rather, is primarily a function of low-level visuomotor processes.

As a final objection, I question the need to distinguish between two separate *Where* mechanisms, one that selects the next saccade target word and another sending the eyes at about the required location. Given that word length and launch site similarly influence both skipping rate and initial landing sites in words, a single mechanism may determine where the eyes move next. Furthermore, since visuomotor influences strongly deviate the eyes from the center of words, there may be no need to posit that they aim for the center of preselected words. Our assumption is that forward eye movements in reading are not directed to specific target locations, as the eyes would be naturally pulled by peripheral visual information in a center-of-gravity-type manner (see Vitu 1991a). Ongoing word identification processes would only intervene occasionally to modulate the oculomotor scanning pattern, favoring either the lengthening of planned saccades (see Lavigne et al. 2000), or the execution of regressive saccades to specific word locations (see Vitu & McConkie 1998; Vitu et al. 2000).

Authors' Response

Eye movements in reading: Models and data

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Abstract: The issues the commentators have raised and which we address, include: the debate over how attention is allocated during reading; our distinction between early and late stages of lexical processing; our assumptions about saccadic programming; the determinants of skipping and refixations; and the role that higher-level linguistic processing may play in influencing eye movements during reading. In addition, we provide a discussion of model development and principles for evaluating and comparing models. Although we acknowledge that E-Z Reader is incomplete, we maintain that it provides a good framework for systematically trying to understand how the cognitive, perceptual, and motor systems influence the eyes during reading.

R1. Introduction

Before we delve into specific issues and controversies about the issues raised by the commentaries, it might be of some value to try to characterize what we had hoped to accomplish with our model and thus indicate what we feel is the proper context in which it is best discussed and evaluated. Perhaps a good place to start is with a quote from E. B. Huey in the introduction to his classic book on the psychology of reading:

> And so to completely analyze what we do when we read would almost be the acme of a psychologist's achievements, for it would be to describe very many of the most intricate workings of the human mind, as well as to unravel the tangled story of the most remarkable specific performance that civilization has learned in all its history. (Huey 1908)

We hope no one misunderstood our modeling effort as pretending to be an attempt "to completely analyze what we do when we read." We indeed agree with Huey that to completely analyze what we do when we read would be a monumental achievement well beyond our efforts – and certainly well beyond what our field has learned, to date, about reading, the control of eye movements, and language processing.

Instead, we had hoped to develop a model that was a reasonable "zero-order approximation" of how cognitive processes control the eyes in reading. Our first goal was to come up with a model that could explain how ongoing cognitive processes *could* control eye movements during reading, subject to the constraints that it do so in real time and be plausible in terms of what is known about the underlying cognitive processes and the control of eye movements. We think we succeeded at this goal, and that this was a far from trivial task.

Our second goal was to make the model as simple as possible, so that it would be reasonably transparent with respect to how and why it worked. If we succeeded at this goal, then when the model failed to account for a phenomenon properly, it would be clear why the model did not work and, therefore, whether it was merely too simplistic and needed to be further elaborated, or whether it was fundamentally flawed. Put differently, if a model is simple enough, it can be a useful heuristic device, but when it gets too complex, it risks merely being a data-fitting algorithm. Put a third way, if the model is simple enough, it has the chance of generating both testable and interesting predictions about reading (i.e., predictions that can be falsified and that test basic assumptions of how the model explains the reading process).

Consistent with these goals, we tried to delimit our problem carefully so that we would have some chance of success. Most notably, we did not try to explain interword regressions (i.e., regressions to words that had been either previously read or skipped over). The reason for this is that there is ample evidence that many of these regressions are a result of various "higher-level" processing failures (e.g., attributable to general comprehension problems or temporary misparsing of sentences). Another reason is that modeling these kinds of regressions in any detail is several orders of magnitude more difficult than what we have attempted, both because we have a far from adequate cognitive theory of the processes that fail, and because it is quite unclear – given such a failure – exactly what should be targeted by an eye movement responding to this failure. We also did not pretend to have a serious or detailed model of word identification, both because how words are encoded is still a contentious issue that we hoped to bypass, and because a model of word identification (even without

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