130 to 150 msec after the beginning of a fixation. Alternatively, the completion of early visual processing or attentional selection in the visual system might trigger saccade programs. Indeed, preliminary analyses indicate a linear increase in microsaccade rate from 90 to 200 msec (Kliegl & Engbert 2003), which is after early visual processing but already before the completion of *L1*. We speculate that, aside from effects related to the spatial position, some of these microsaccades represent traces of inhibited saccade programs as postulated in SWIFT, but any reliable link between perceptual or lexical processing and microsaccade rate or orientation will provide important constraints for attentional and ocular control during reading.

Reading as a special case of dynamic attention allocation. Obviously, attention and ocular control did not evolve for reading, but reading is a special application of the attentional/ocular control system. Indeed, the highly constrained spatial nature of the reading process represents an ideal testbed for the further development of theories of attentional/ocular control models. We argue that SWIFT can be ported more readily to nonreading situations (such as visual search) than E-Z Reader, because it does not make any reading-specific assumptions with respect to target selection; indeed a variant of the model was applied to searching for a target in a display of Landoldt rings (Engbert & Trukenbrod 2003). Moreover, the combination of target selection via attentional gradient and parallel processing of words within the perceptual span allows us to generate all types of reading eye movements from the same underlying mechanism. In contrast, in E-Z Reader some reading eye movements require special assumptions (i.e., word skipping or refixations) and others are not even part of the present framework (i.e., interword regressive movements). SWIFT may actually be too flexible, given emerging empirical constraints. For example, it may be necessary to constrain parallel processing within the perceptual span to lexical preprocessing to reduce semantic parafovea-on-fovea effects. Such constraints, however, can be implemented and tested in nested models.

Conclusion. Although E-Z Reader 7 and SWIFT differ in core assumptions, it does not seem insurmountable to introduce flexibility of saccade triggering in E-Z Reader and to constrain parallel processing and possibly autonomous timing in SWIFT. Therefore, E-Z Reader may need to abandon the assumption that all saccades are canceled or triggered by the completion of lexical processing stages; SWIFT may need to restrict parallel processing to visual/lexical preprocessing. Such adjustments, if necessary, will be forced by experimental results. The purpose of a computational model is to provide a coherent perspective on a complex set of empirical results and generate new hypotheses. Computational models of attentional and ocular control of reading already live up to this expectation.

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NOTE

1. We replicated longer fixation durations following a skipped word. Also, skipping saccades started closer to the end of $word_n$ and landed closer to the beginning of $word_{n+2}$ compared with matched movements from $word_n$ to $word_{n+1}$, as expected from oculomotor control theories.

Psycholinguistic processes affect fixation durations and orthographic information affects fixation locations: Can E-Z Reader cope?

Simon P. Liversedge and Sarah J. White

Centre for Vision and Visual Cognition, Department of Psychology, University of Durham, Durham, DH1 3LE, United Kingdom.

s.p.liversedge@durham.ac.uk s.j.white@durham.ac.uk

http://psychology.dur.ac.uk/staff/details.asp?name=LIVERSEDGE

www.dur.ac.uk/s.j.white/

Abstract: This commentary focuses on two aspects of eye movement behaviour that E-Z Reader 7 currently makes no attempt to explain: the influence of higher order psycholinguistic processes on fixation durations, and orthographic influences on initial and refixation locations on words. From our understanding of the current version of the model, it is not clear how it may be readily modified to account for existing empirical data.

E-Z Reader 7 provides an impressive account of the processes that determine when and where fixations are made during reading. The eye movement patterns that the model predicts are remarkably similar to the observed data. Furthermore, the model is based on quite simple, fundamental principles. In this commentary, we would like to consider two central aspects of the model that we believe may require reconsideration if future versions of the model are to explain data that currently exist in the literature. First, there is evidence to show that processing beyond the level of orthographic identification can influence the duration of fixations. The second issue is that there is growing evidence to suggest that the orthographic characteristics of words can influence where they are first fixated and refixated. It is possible that future versions of the model could account for these additional phenomena and, therefore, our criticisms are intended to be constructive in nature.

Our first point is that Reichle et al. limit their model to explaining lexical and visual influences on fixation duration. In the E-Z Reader model, L_1 is a stage of orthographic identification that is influenced by word frequency and predictability. Completion of this stage of processing is the primary determinant of fixation duration. However, studies have shown that processing beyond orthographic identification does influence initial fixation durations on words (e.g., Murray & Liversedge 1994; Rayner et al. 1983a). To account for these higher-level influences on the duration of fixations whilst retaining the underlying mechanisms of the model, such processes must, it seems to us, modulate the time required to complete L_1. That is, L_1 must be redefined as being processing which includes full lexical access, syntactic processing, and perhaps even thematic and semantic processing.

However, it is not clear whether such depth of processing may be realistically achievable within existing L_1 time constraints. If not, then it may be necessary to extend the L_1 stage of processing, thereby providing sufficient time for higher order processing to occur during this period. Such a modification would result in more plausible timings for the occurrence and influence of higher order cognitive processes on fixation durations. Note, however, that since eye-movement programming can begin only after completion of L_1, this will necessarily reduce the time allocated to program a saccade (M_1 and M_2). As the authors note in section 3.1.4, given existing data (e.g., Rayner et al. 1983b), the mean eye-movement programming time cannot be much shorter than is currently specified in the model. Consequently, such a modification may not be viable. Note also that if this modification were made, it is then unclear what type of processing would occur during L_2 (the stage in which readers currently perform full lexical access and which triggers the attention shift). L_2 is central to the mechanism for decoupling of eye movements and attention, and abandoning this stage would constitute a major change to the model.

An alternative possible modification is to substantially alter the fundamental mechanism for the initiation of eye-movement programming. That is, completion of L_1 would not serve to trigger the initiation of an eye movement. In such a situation, higher-level processing could take place in parallel with the labile stage of saccadic eye movement programming. Cognitive processing could then affect this labile stage at any time to influence when the eyes move. Such an alteration may overcome some of the time constraint problems identified above; however, the nature of L_2 would still have to be respecified. Furthermore, the authors may consider such a modification to be too radical a departure from the existing mechanistic processes by which E-Z Reader 7 currently operates.

The second point that we wish to make about E-Z Reader 7 concerns what determines specifically where words are first fixated. Within E-Z Reader 7, the visual system extracts low spatial frequency information from the visual periphery and the oculomotor system uses this visual information, apparently exclusively, to target saccades. While the authors suggest that word shape information may be provided by the visual system and this in turn could affect saccade targeting, within their simulation, the only information that is used to guide saccade extent is word length. As noted by the authors (Note 5), a number of studies have now shown that the frequency of letter sequences at the beginning of words influences where words are first fixated (see also Radach et al. 2003; White & Liversedge, in press). Furthermore, evidence also suggests that the characteristics of words can influence the direction (White & Liversedge, in press) and length (Hyönä 1995a; White & Liversedge 2003) of refixation saccades. While it may be possible to explain such effects through processing of low spatial frequency word shape information, how such processes would operate is not currently specified. Moreover, studies using artificial tasks (Beauvillain & Doré 1998) and recent results from our laboratory investigating normal reading (White & Liversedge 2003) have shown that orthographic information influences where words are first fixated and refixated for upper case text. Uppercase text does not have visually distinctive differences in word shape to the same degree as lower-case text. Therefore, it is not clear how E-Z Reader 7 could explain such results on the basis of low spatial frequency information alone.

To conclude, E-Z Reader 7 impressively explains a wide range of eye movement behaviour during reading. In its present form, it makes no attempt to explain existing evidence for higher-level influences on fixation durations and growing evidence for orthographic influences on where words are initially fixated and refixated. We believe that these aspects of eye-movement control during reading are important and that an attempt to account for such oculomotor behaviour would strengthen future versions of the E-Z-Reader model.

Basic assumptions concerning eye-movement control during reading

George W. McConkie[a] and Shun-Nan Yang[b]

[a]*Beckman Institute, University of Illinois at Urbana-Champaign, Urbana, IL 61801;* [b]*Brain Science Institute, Riken, 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan.* **gmcconk@uiuc.edu** **syang3@brain.riken.go.jp**

Abstract: Reichle et al. specify two assumptions as being basic to E-Z Reader: Words are sequentially attended during fixations, and saccades are triggered by a cognitive event. We point out that there is little evidence for the first assumption and counterevidence for the second. Also, the labile/nonlabile stage distinction in saccade preparation seems to be contrary to current evidence. An alternative explanation of saccade onset times in reading assumes that saccades are strategically generated, independent of language processing, but are delayed on a probabilistic basis by processing difficulties.

The development of E-Z Reader is a notable intellectual accomplishment. In its detail, scope, and ability to account for many established results, it sets a new standard for what a theory of eye-movement control should accomplish. At the same time, there is reason to doubt some of the basic assumptions that lie at its heart. Here we discuss the two that Reichle et al. list as being the "central assumptions" of the model: (1) words are attended sequentially during the fixation (here called the sequential attention assumption), and (2) the signal for moving the eyes is the occurrence of some stage in word identification (the cognitive saccade triggering assumption).

The sequential attention assumption, as proposed earlier by Morrison (1984), provides a way to employ the findings of "parallel programming" of saccades by Becker and Jürgens (1979) to drive the oculomotor engine. Becker and Jürgens observed that if a saccade target is displaced at critical times following its onset, the resulting saccade is modified in its amplitude or direction. By assuming that the critical event in those studies was a shift of attention to the new target location, Morrison had only to further assume that covert attention shifts occur from word to word during fixations in reading, to then invoke this mechanism as a model for driving the eyes during reading: Shifting attention occurs when the system is ready to consider the next word; this shift triggers preparation for a saccade; and if another shift occurs soon enough, it cancels or modifies the current saccade program.

Actually modeling this mechanism indicates that timing constraints within Morrison's model are contradictory, which has forced modifications in the more recent implementation of E-Z Reader; for example, a saccade currently is assumed to be initiated by some cognitive event that occurs before attention shifts. However, there is very little empirical support for the proposed sequential attention assumption during reading, in spite of direct attempts to experimentally reveal it (Blanchard et al. 1984). It is quite possible that Becker and Jürgens obtained their results only because of the stimulus displacement, and that no such discrete attention shifts occur during the reading of stable text. Reichle et al.'s model also postulates two distinctive stages of saccade programming, labile and nonlabile, that are used in accounting for the occurrence of word skipping. However, in parallel saccade programming, there is actually a dynamic modification of the amplitude of the initial saccade toward the second target position, indicating a summing of signals from both steps. Even after a saccade is in flight, it can still be modified by a later-programmed saccade, thus contradicting Reichle et al.'s distinction as they describe it.

Evidence is clearer with regard to the cognitive saccade triggering assumption. We (McConkie & Yang 2003; Yang & McConkie 2001; in press) have conducted a series of experiments in which the text is replaced by alternative stimulus patterns (strings of Xs, random letters, patterns with spaces filled, etc.) for occasional single fixations as people read, to observe the effect on the saccade onset time. The stimulus changes occur during saccades so that the stimulus motion that normally signals such changes is not perceived and does not produce the type of saccadic inhibition observed with changes during fixations (Reingold & Stampe 1999). A stimulus pattern consisting of wordlike random letter strings would be expected to produce characteristic changes in saccade initiation times (fixation durations) in an E-Z Reader mechanism or any other mechanism in which the saccade onset is triggered by some cognitive event at a level higher than simply achieving a clear visual image. Because this is a low-frequency stimulus pattern, its evaluation should be slow, and any cognitive event depending on word identification will fail to occur. Thus, we would expect that the durations of fixations would be increased because the triggering event is delayed or missing. Figure 1 shows frequency distributions of fixation durations for three conditions: a control condition, the random letter condition, and a condition in which wordlike units are removed by replacing spaces with letters (Yang & McConkie 2001; in press). The figure shows that if fixations are long enough, the following saccade is indeed delayed. However, nonwords have very little effect on saccade onset time (that is, the experimental condition curve is similar to that of the control condition) until 175 msec after the onset of the fixation; and many fixations after that appear unaffected. A large propor-

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