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

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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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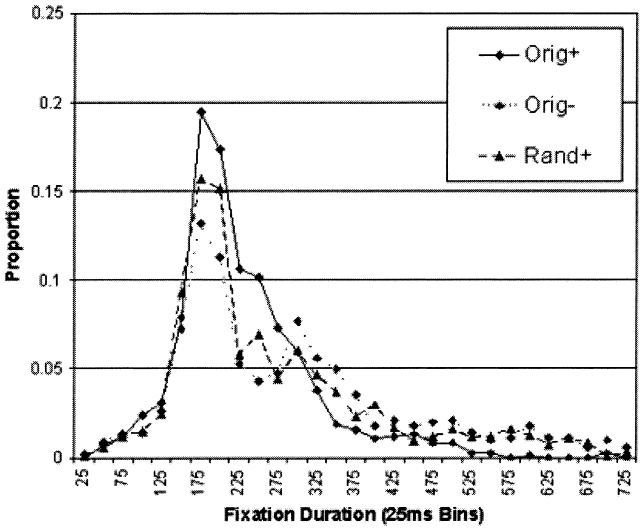


Figure 1 (McConkie & Yang). Fixation duration frequency distributions for people reading under three conditions defined by the nature of the text present during critical fixations: Orig+ (original text with spaces: control condition), Rand+ (letters replaced by random letters, but with spaces remaining in the text), and Orig− (original text but with spaces replaced by letters). Data from Yang & McConkie (in press).

tion, perhaps even a majority, of saccades occur at their normal time regardless of whether the text consists of words. Furthermore, as Figure 1 shows, a large proportion of saccades occur at their normal times even when there are no perceptual word units to which to shift attention or direct saccades. While E-Z Reader and other cognitive saccade triggering theories may expect a small set of preprogrammed early saccades, it is unclear how they can account for so many saccades occurring uninfluenced by such aberrant stimulus patterns. Triggering a saccade must not depend on word-based processes.

We have proposed an alternative explanation for saccade generation in reading, in which saccades are produced on a strategic basis, not directly determined by the language processes (see also Engbert & Kliegl 2001; Engbert et al. 2002). However, when processing difficulty occurs, the saccadic system is inhibited, reducing the likelihood of saccade generation. The nature of the processing difficulty determines the onset time and severity of the inhibition, with a given saccade being delayed only if it has not occurred by the time of the inhibition (a horserace model). Earlier and strong inhibition delays more saccades, resulting in a longer mean fixation duration. There is ample evidence that such autonomous saccades are generated in situations requiring repetitive or predictable eye movements (Basso & Wurtz 1997; 1998; Fischer & Ramsperber 1984; Vitu et al. 1995). Our proposal suggests that cognitive events inhibit saccades rather than triggering them during reading. We do not rule out the possibility that in reading, saccades can be triggered based on the guidance of cognitive information, but evidence suggests that these saccades will take much longer time to take place (Yang & McConkie, in press).

The primary strength of E-Z Reader is its ability to reproduce many previously observed phenomena. However, if further research confirms that its basic assumptions are incorrect, this may raise questions about the value of this type of evidence – and raise the interesting question of what the tests of E-Z Reader have actually been tests of. Much of the framework of the model could be preserved while changing these basic assumptions, but would it then be E-Z Reader? The future of this model will be interesting to watch.

The eye-movement engine

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Abstract: E-Z Reader fits key parameters from one corpus of eye movement data, but has not really been tested with new data sets. More critically, it is argued that the key mechanism driving eye movements – a serial process involving a proportion of word recognition time – is implausible on the basis of a broad range of experimental findings.

Reichle et al. provide an appealing, explicit, and, to a first approximation, accurate model of eye-movement control. One problem with being fully explicit is that it encourages nit-picking concerning details of the formulation. But Reichle et al. do a pretty good job of justifying the existence of, and appropriate values for, most of their mechanisms and free parameters. However, it seems a terrible pity that this model (and others) have been developed and "tested" using a single, rather limited, corpus of data. A real test involves setting parameters and then testing the model on another corpus.

I will, however, focus here on whether the conceptual properties of E-Z Reader 7 seem appropriate, given what we know. Let's look at the engine that drives fixation timing in the model: a process that serially identifies successive words in text. Or, more specifically, a serial mechanism sensitive to some proportion of that process. This is a constant (67%) for unpredictable words but increases with predictability. In no case, however, is it greater than the time required for word recognition. Nor does it ever encompass the recognition – or even part thereof – of more than one word. Partial or even complete recognition of a subsequent word can proceed after that engine is engaged and while the gears drive the saccade into motion, but these factors cannot influence engagement of the engine.

How plausible is this? It leads to conclusions that appear to be at variance with much of what we know about eye movements. First, obviously, is the question of whether processing is strictly serial. The authors concede that two "attention gradient" models (SWIFT and GLENMORE) do a similarly good job of accounting for critical phenomena. (To say that these models "fail" to account for some phenomena that they have never attempted to model is no damning criticism.) Others, I am sure, will point out the accumulating mass of evidence pointing to the *possibility* of parafoveal difficulty influencing fixation duration. Indeed, the authors point to some of it themselves – while suggesting that it occurs only if the task "isn't quite reading." I'll content myself with the observation that well-established, uncontroversial phenomena often come and go across experiments that clearly involve "reading" (see below). The same is true of parafoveal effects in "reading-like" tasks: Murray and Rowan (1998; see also Murray 1998) found effects of the pragmatic plausibility of a yet-to-be-fixated word. The effect was replicated by Kennedy et al. (in press), but not by Rayner et al. (2003), using a different procedure. The effect was also not replicated with the same procedure but differently structured items, by Murray and Clayes (1998). However, using the same task, and items of the same structure as Murray and Clayes, but differing semantics, Murray et al. (1999) found evidence for a parafoveal pragmatic effect. It appears not to be either the task or the items that drive it, but a complex interplay of these factors – and possibly others. The same, as we will see, is true of other, less controversial, effects. To dismiss effects as coming from "non-reading tasks," as the authors are inclined to do, appears to be missing the point: The mechanism "normally" used for reading (whatever that means) is just as likely to be applied to the processing of a piece of text forming a paragraph, a line, a single sentence, a phrase, or indeed any concatenation of words; and it is just as likely to be applied when the task involves "understanding" a piece of text, as when it is to decide if this text is the same as an-

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