Is the problem of multicolinearity confined to the Schilling et al. (1998) data set? The answer is no. A similar analysis based on our own data (Feng et al. 2003) shows the same pattern of multi-colinearity. The problem stems from two sources.

1. Composite eye-movement measures (see Inhoff & Radach 1998), such as gaze duration and probability of skipping, are statistics computed from individual fixations. Because these statistics are calculated on the same sample of fixations, moderate to strong correlations are expected among them. For example, the fixations counted toward single-fixation duration are a subset of first-fixation duration, which is in turn a subset of gaze duration.

2. These correlations are further concentrated as raw data are aggregated to get a "clean" picture suitable for modeling. For example, in our adult reading data, the correlation between first fixation duration and gaze duration is 0.71 when the unit of analysis is per subject per word ($N = 24,089$). It becomes 0.80 when we average across subjects ($N = 3,599$ words), and 0.95 if we only consider five word frequency levels ($N = 5$) and average across both subjects and words.

As long as only a few means of composite eye-movement variables are used for modeling, the problem of multicolinearity will be unavoidable. Therefore, ingenious and intricate theories such as E-Z Reader will remain untestable. The only solution to this problem is to reinstate the richness of the eye-movement data for modeling. There are at least three approaches to this end:

1. Use less aggregated data.
2. Model distribution functions of eye movement variables (e.g., Feng et al. 2001; 2003; McConkie & Dyre 2000).
3. Use raw data instead of composite eye-movement measures (Feng 2001).

In addition to the multicolinearity problem, there are several important flaws in the parameter estimation procedure shared by all E-Z Reader models (see Reichle et al. 1998, p. 157). Instead of normalizing the difference between model predictions and observed values, the authors erroneously squared the difference. Consequently, fixation duration variables, which have a much larger scale than do probability variables, contributed approximately 100 times as much to the index of model fit as did the probability variables (estimation based on Reichle et al. 1998, Table 1). Another error is the use of the standard deviation in the normalization. Because the comparisons were between observed means and simulated means, the sample standard error should be used in the denominator (see Hayes 1988). As a result, the goodness-of-fit index was shrunk by a factor of the square root of N. Finally, it is disappointing that there was no attempt to test the fit of each model statistically, or statistically compare successive models. Further analyses on the impact of these factors can be found in Feng (2001).

It may seem paradoxical that even though it has serious problems in parameter estimation, E-Z Reader 7 is successful in simulating many well-known reading eye-movement phenomena. A possible explanation is that precisely because the impoverished empirical data could not provide adequate constraints over parameter values, the authors gained more freedom in assigning parameter values that maximize simulation performance. This would predict that the model's simulation performance would be hampered if the data contain more information, something that could be empirically tested.

In summary, the problems discussed here – multicolinearity in data and issues with parameter estimation and model testing – are fairly low-level. However, a model is ultimately only as good as the data and algorithms on which it is based. There is not enough evidence to conclude that E-Z Reader is empirically validated. Nonetheless, we should not throw out the model with the statistical problems. These issues are not difficult to fix. I look forward to seeing an E-Z Reader 8 that is on a solid statistical footing. Meanwhile, future modeling work should fully exploit the richness of reading eye movements and be wary of the limitations of aggregated data.

Serial programming for saccades: Does it all add up?

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Abstract: This commentary analyses the quantitative parameters of Reichle et al.'s model, using estimates when explicit information is not provided. The analysis highlights certain features that appear to be necessary to make the model work and ends by noting a possible problem concerning the variability associated with oculomotor programming.

Reichle et al.'s target article presents a model of eye control during reading that is impressive in a number of ways. It is fully explicit, quantitative, and economical, and it brings in known features of the visual system (differential magnification) and oculomotor system. It provides a good account of a number of observed phenomena and a quantitative fit to data. Its appearance in *BBS* is particularly welcome because if it proves robust against criticism, this must be regarded as a triumph not only for the model itself but also for the serial stage approach to modeling that underpins it.

The duration of fixations are modeled on the basis of a signal traveling through a number of stages that are strictly serial with the visual, lexical, and oculomotor processes taking place sequentially. These stages are shown in Figures 3 and 13 of the target article; and the latter figure in particular suggests that the time-consuming processes leading to saccades are conceived as the time for signals to traverse brain regions. This represents a different tradition and philosophy to the approach of Findlay and Walker (1999), where the emphasis was on specific time-consuming processes of competitive inhibition, particularly in the late oculomotor stages. Some common ground might be found in the separation of the programming of saccade amplitude from the remainder of the programming. This occurs through the direct (dashed line of Fig. 3) pathway from the early stage of visual processing bypassing the word identification system. Section 3.1.3 indicates that this pathway provides the low spatial frequency information needed to program a saccade. However, it would appear that there also needs to be a modulatory influence from the word segmentation process on this pathway, since the whole basis of the model is that saccades are programmed to words.

The remainder of this commentary works through the model in detail, following the commentators' understanding and looking particularly at the time course of events.

The seriality has the consequence that the duration of a fixation can be expressed as a sum of contributions from the component stages

$$\text{FXDUR} = t(V) + L_1 + M_1 + M_2 - (OV_V + OV_L + OV_M) \tag{1}$$

where $t(V)$, L_1, M_1, and M_2 are defined as in the model. OV_V, OV_L, and OV_M are introduced to denote the modifications that occur when the model is working dynamically, since overlap (OV) processes can occur. OV_V and OV_L are savings in the visual and lexical stages, respectively, that can come from peripheral preview. OV_M reflects changes in oculomotor preparation time when saccadic programming stages overlap. All the components are described clearly in the target article and, although the detailed magnitudes can be made only with precise knowledge of the text being read, it is possible to make estimations of the distributions. The

terms in Equation 1 (above) are all stochastic variables and therefore the grand mean of FXDUR must equate to the combination of the means of the various contributing components. How does this work out? Our analysis below ignores refixations but otherwise tries to follow through Reichle et al.'s model.

Section 3.1.1 discusses the variable $t(V)$, which takes values upwards from 90 msec. L_1 is defined in Equation 2 of the target article as a product of two factors. The first ranges from 110 to 228 msec dependent on word frequency, and the multiplier ranges from 0.5 to 1.0 dependent on word predictability. A plausible overall mean value might be 130 msec. M_1 and M_2 are clearly set out to have mean values of 187 msec and 53 msec respectively.

OV_V, OV_L, and OV_M are not defined explicitly and depend on what happens when the model runs. OV_V and OV_L represent savings on the visual and lexical stages through peripheral preview advantage. OV_M represents modifications when saccadic programming stages overlap. Fixation durations are *shortened* when the planning for a saccade is able to take advantage of preparation already made (as with the second fixations in 5D and 5E of Fig. 5). Fixation durations may also be *lengthened* when saccade skipping necessitates a reprogramming of the location-distance stage, as in the first fixation of 5C.

The sum of the means of the first four terms of Equation 1 above is 460 msec. Therefore, to obtain a plausible overall mean, it seems necessary for the OV components to be quite substantial. OV_M can, as far as we can see, only be positive when two conditions are satisfied. First, peripheral preview has allowed completion of the $t(V)$ and L_1 stages of word$_{n+1}$. Second, the triggering signal falls in the 53 msec non-labile stage of the previous saccade preparation or during the saccadic movement itself (25 msec). Therefore, OV_M cannot exceed 78 msec. Whenever this combination of circumstances occurs, OV_L must equal the full value of L_1 (50 msec–228 msec). This suggests that the OV_M component will usually be smaller than OV_L. Our estimates of plausible parameters are as follows: $t(V)$ 90 msec, L_1 130 msec, M_1 187 msec, M_2 53 msec, OV_V 90 msec, OV_L 60 msec, OV_M 30 msec, summing to a mean FXDUR of 280 msec. Of this figure, 70 msec is "visual-lexical" and 210 msec "oculomotor." This reasoning assigns a very considerable role to peripheral preview, and two predictions seem to follow. If preview is prevented, fixations should be considerably lengthened; consequently, we find the 26 msec preview benefit figure given in section 3.2 surprisingly small. Second, the very first fixation on a text should be substantially longer than subsequent ones.

A similar exercise can be carried out with the variance of FX-DUR, which again must be predictable from the variances of the component distributions, taking into account any nonindependence of the terms. How does the variance divide among the various components of the sum, and in particular between the visual-lexical and the oculomotor components? The calculations above suggest that the oculomotor components contribute about 75% to the mean. Unfortunately, the variance of the gamma-distributions from which M_1 and M_2 are drawn are not given in the target article (we very much hope the authors will supply these in their response). However, our rough estimates suggest the oculomotor components must contribute a considerable amount.

If indeed this is the case, it must be reconciled with the fact that in studies of saccades in simple situations, distributions with standard deviations in the 25–30 msec band are often found (Carpenter & Williams 1995; Walker et al. 1995; Wenban-Smith & Findlay 1991). It is, of course, possible that oculomotor variability depends on the circumstances in which the system is used and is higher in reading than in the cases cited. However, it could also be that the serial assumptions of the model are the source of the problem.

Frontal lobe functions in reading: Evidence from dyslexic children performing nonreading saccade tasks

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Abstract: Reichle et al. show that saccades in reading are controlled by linguistic processing. The authors' Figure 13 shows the parietal and frontal eye fields as parts of a neural implementation. This commentary presents data from dyslexics performing nonreading saccade tasks. The dyslexics exhibit deficits in antisaccade control. Improvement of the deficits is achieved in 85% of the cases and results in advantages in learning how to read.

From many different pieces of converging experimental evidence (Fischer 1987) the main components of saccade control have been identified as: (i) fixation, which stabilizes the direction of gaze; (ii) an optomotor reflex, seen under certain conditions as express saccade, when fixation/attention is disengaged; and (iii) a voluntary component, challenged by the instruction to generate antisaccades, that is, saccades in the direction opposite to a visual stimulus (Hallett 1978). Fixation is supported mainly by parietal (Motter & Mountcastle 1980; Robinson et al. 1978) and tectal functions (Munoz & Wurtz 1992), and the reflexes are mediated by the superior colliculus (Schiller et al. 1987; Sommer & Schiller 1992). The voluntary component relies on frontal lobe functions, because successful performance of the antisaccade task is impaired in patients with unilateral frontal lobe lesions (Guitton et al.1985).

Figure 1 shows the basic optomotor cycle consisting of series of periods of fixation (Stop) and saccades (Go). The cycling must not work on its own. It must be controlled by voluntary and/or cognitive processes that make each saccade a meaningful event within the process of active vision. Neurons in the frontal eye fields are activated before purposive saccades – not before any saccade (Bruce & Goldberg 1985).

How can one get more inside, into the relationships between the cognitive processing and the neural systems for saccade control? One possibility is to look at saccade control in nonreading tasks and to compare the corresponding data obtained from subjects who read normally with those of subjects who have reading problems; for example, dyslexics.

Deficits in the acquisition of reading skills may be (and have been) attributed to deficits of a number of different subfunctions within the reading process. One possibility is a deficit in saccade
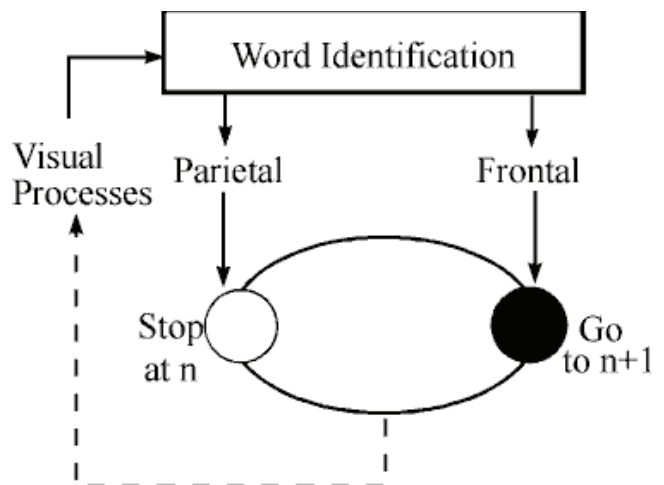

Figure 1 (Fischer).   Schematic drawing of the optomotor Stop-and-Go cycle and its control by parietal (Stop) and frontal (Go) functions.