trol that were part of the training program (Fischer & Hartnegg 2000a).

Finally, a group of 20 dyslexics with deficits in saccade control was divided into a test and a control group. Only the test group was given the antisaccade training. Then both groups were recombined and received six weeks of reading instruction. The test group reduced their reading error rate by about 49%, the control group by only 19% ($p=0.01$). The improvement of saccade control facilitates the learning process but does not replace it.

Among the executive functions of the frontal lobe is the execution of saccadic eye movements during reading. An impairment of this function does not imply that reading is completely impossible, only that the chances of reading errors due to inappropriate saccades are increased. It is suggested that a neural implementation of the E-Z Reader model does indeed include the frontal lobe, and that the model could also serve as a model of dyslexia.

Dimensionality and explanatory power of reading models

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Abstract: The authors' review of alternative models for reading is of great value in identifying issues and progress in the field. More emphasis should be given to distinguishing between models that offer an explanation for behavior and those that merely simulate experimental data. An analysis of a model's discrete structure can allow for comparisons of models based upon their inherent dimensionality and explanatory power.

The authors are to be congratulated for their structural analysis and comparison of several widely varying models of eye-movement control during reading. The emphasis on the basic structures and assumptions of the models is welcome, as is the authors' recognition that the ability to simulate experimental results is not the only measure of a model.

This commentary presents a further evaluation of reading models in terms of their discrete structures and dimensionalities, which represent the inherent expressive power of the model. It is seldom necessary to consider the output of computer simulations, using specific formulae, to understand the range of phenomena that can be predicted. Moreover, a focus on structure distinguishes the facets of a model that offer explanatory relationships from those that only quantitatively simulate data.

We begin with an example of such a discrete, structural explanation with regard to the spillover effect, then consider two notions of the dimensionality for reading models.

Two lexical stages accommodate the spillover effect. The ability of the E-Z Reader model to correctly predict the "spillover effect," under which the difficulty of one word can lengthen the fixation on the next, has nothing to do with specific formulae or simulations but is inherent in the separation of lexical processing into two stages. In Morrison's earlier model (Morrison 1984), of which E-Z Reader is an elaboration, lexical processing is considered as a single unit, and the signal to generate a saccade originates only after this process is complete. This basic structural assumption implies that the difficulty of processing the current word can have no influence on the following fixation. Therefore, Morrison's model cannot possibly account for the spillover effect.

In contrast, the E-Z Reader model has a second stage of lexical processing following the signal to generate a saccade. This automatically gives the possibility of a spillover effect of various amplitudes, because the duration of this second stage can contribute to the *following* fixation. Therefore, the ability of E-Z Reader and the inability of Morrison's model to account for the spillover effect does not in any way depend upon the specific equations but is implicit in the models' structures.

If the model is fundamentally correct, the requirement of two degrees of freedom in the lexical processing system must be reflected in physiological processes. In this way, the dimensionality of a model of sensorimotor function has implications for physiological organization.

Dimension as the measure of the space determining average fixations or individual fixations. There are various ways of assessing the dimensionality of a model, depending on the facets of interest. Here we give two examples of ways to make dimensional assessments based on a model's ability to predict fixation durations.

One notion of dimensionality is the average number of input variables determining fixation durations in a sequence. In Morrison's model, for example, the sequence of fixation durations is determined by the sequence of lexical processing times for each word. This is an average of one variable per fixation, giving the model a dimension of one. In the E-Z Reader model, the sequence of fixation durations depends on the durations of both stages of lexical processing for each word, as well as the word lengths (which determine early processing rates). This is an average of three variables per fixation, so E-Z Reader has dimension three.

Alternatively, dimension can be determined as the potential number of variables affecting the duration of an individual fixation. In Morrison's model, the length of the fixation is determined by either the duration of lexical processing on the fixated word $L(0)$ or by this duration plus that of lexical processing on the next word $L(+1)$, in case the next word is skipped. A graph of the possible contributions of these variables to the duration of a single fixation is given in Figure 1A. This is a two-dimensional subset of real two-space, giving Morrison's model a dimension of two. A similar analysis shows that with the E-Z Reader model (excluding early processing), individual fixations are determined from the durations of L_2 on the preceding and fixated words and L_1 on the fixated and following words. A graph of possible contributions of $L_1(0)$, $L_2(0)$, and $L_1(+1)$ to a fixation duration is shown in Figure 1B. This three-dimensional graph gives E-Z Reader a dimension of four when the possible contribution of L_2 on the previous word is included.

Both estimates of dimensionality show E-Z Reader to be more complex than Morrison's model, as expected, but they do give different numbers. The reason is that, because of parallel processing of saccades, an individual fixation can involve more cognitive processes and more free variables than does the average fixation. Note that if some fixations have more than average freedom of determination, then others necessarily have less! This is reflected in Figure 1 by the lower-dimensional components of the graphs. The two-dimensional measures are not incompatible but emphasize different aspects of the models.

Conclusion. The essential complexity and expressive power of a model can be represented in a discrete, schematic way. A correctly designed discrete model indicates all of the variables influencing the system, and all the ways in which values of one parameter can constrain those of another. Given the discrete model, simulations can be generated by constructing formulae that provide the best "fit" to the data. However, a focus on simulations can obscure the fundamental properties of the model by presenting results in a form similar to experimental data.

We feel that it is of great importance to distinguish those parts of a model that offer an explanation for behavior and physiology from those parts that merely simulate data. E-Z Reader offers real explanations for how the brain controls saccade timing, while its handling of saccade lengths and refixations is explicitly constructed for purposes of quantitative fit. Other models show their strengths in other areas, as can be seen from the excellent analysis of the target article. Our understanding of reading would be best served by attention to the dimensionalities necessary to explain observed sensorimotor behaviors and their implications for physiological processes.

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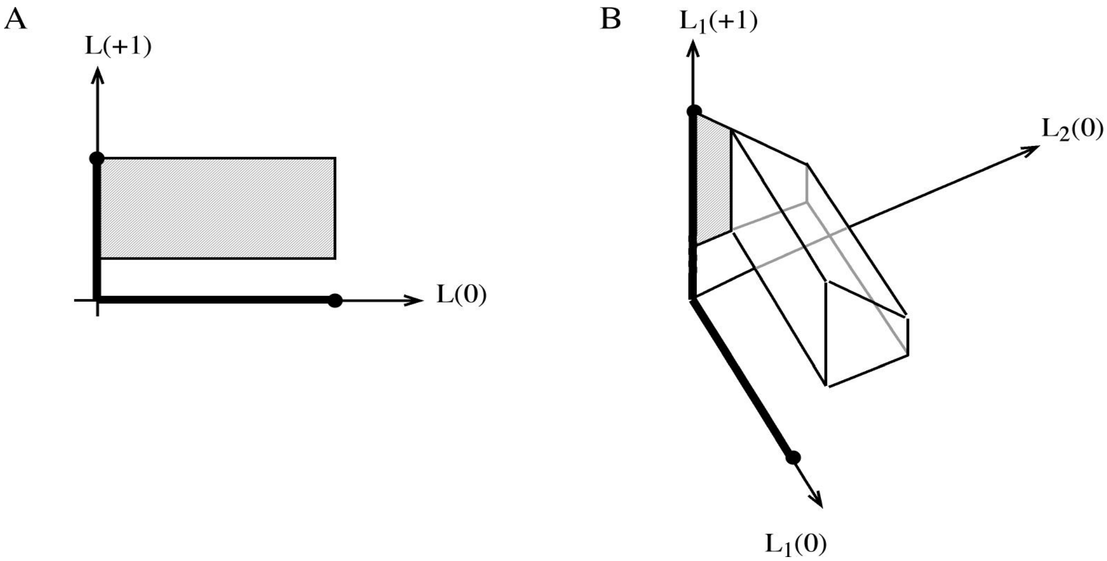

Figure 1 (Hanes & McCollum). A. Values of the pair (L(0), L(+1)) that can determine a fixation duration in Morrison's model. B. Values of the vector ($L_1(0)$, $L_2(0)$, $L_1(+1)$) that can determine a fixation duration in the E-Z Reader model. L(0) and L(+1), lexical processing time on fixated and following words, respectively; $L_1(0)$ and $L_1(+1)$, durations of first stage of lexical processing on fixated and following words, respectively; $L_2(0)$, duration of second stage of lexical processing on fixated word. Enclosed three-dimensional regions, shaded planar regions, and thick line segments are included in the graph.

Visual word recognition and oculomotor control in reading

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Abstract: A central component in the E-Z Reader model is a two-stage word processing mechanism made responsible for both the triggering of eye movements and sequential shifts of attention. We point to problems with both the verbal description of this mechanism and its computational implementation in the simulation. As an alternative, we consider the use of a connectionist processing module in combination with a more indirect form of cognitive eye-movement control.

The E-Z Reader suite of computational models is characterized by the role played by lexical processing in the complex system that guides the eyes through text during reading. The word identification module of E-Z Reader 7 is seen as the "engine" that drives the whole process, determining both the dynamics of saccade generation and the assumed sequential shifting of attention. Although the section on word identification occupies only a modest proportion of the target article, there is no denying that this is a central component of the model.

As argued by Grainger (2003), the time is ripe for a fruitful interaction between research on visual word recognition and research on eye movements in reading. Including a word identification component in a model of eye-movement control in reading is already a significant step in the right direction, and Reichle et al. are to be congratulated for their pioneering work towards this goal. However, there are several ways to go about generating such an interaction. One is to examine how a given model of visual word recognition, motivated by research using isolated word presentation techniques, could be integrated into a more global reading system that includes oculomotor control. Another way is to define a minimalist model of visual word recognition that, when coupled with a model of oculomotor control, optimally fits the data collected using eye-movement paradigms. Reichle et al. have adopted the latter approach, with some unfortunate consequences.

E-Z Reader 7 implements a two-stage approach to word identification. An early stage (L_1) is assumed to play a crucial role in the identification of the orthographic form of the word, whereas a second stage (L_2) is rather related to phonological and semantic processing. Completion of the first stage initiates the preparation of a saccade to the next word, and completion of the second stage initiates an attention shift to the next word. However, an examination of the verbal description of this part of the model and its mathematical implementation reveals a number of problems with this approach.

As the authors note, the major motivation for the two stages in the word identification component of E-Z Reader 7 is the decoupling of eye movements and attention in the model, and the fact that this allows E-Z Reader to capture a wide range of eye-movement data. In the mathematical implementation of E-Z Reader 7, it is apparent that only two empirically observed variables are used to model the various types of processing associated with each stage: word frequency and predictability (see equations for $t(L_1)$ and $t(L_2)$ below). This is because the model was designed to capture the influence of word frequency and predictability on the various measures obtained in eye movement recordings.

$$t(L_1) = [\beta_1 - \beta_2 \ln(\text{frequency})]\ (1\text{-}\theta \text{ predictability})$$

$$t(L_2) = \Delta[\beta_1 - \beta_2 \ln(\text{frequency})]\ (1\text{-predictability})$$

Two problems come immediately to mind. First, the only difference between these two processing stages concerns the relative weight assigned to frequency compared to predictability. In the first stage, the influence of predictability is reduced and that of word frequency enhanced, compared with the second stage. Second, the relationship between these variables and the orthographic, phonological, and semantic processing described in the verbal model, is left unspecified.

The verbal model is said to be partly motivated by the activation-verification model (AVM) of Paap et al. (1982). It is true that the AVM can be described as a two-stage (activation and verification) model of visual word recognition, but the analogy between

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