to achieve scene interpretation without identifying any of the objects in the scene, let alone identifying them in a certain order (Oliva & Torralba 2001). Moreover, object-background segregation in scenes can be so computationally demanding that object identification precedes figure-ground organization (Vecera & Farah 1997). Thus, object fixation times could reflect processing of object identity as well as background and figure-background relations. Consequently, in scene perception we may have to adopt a more general principle than object identification as the engine behind eye movements. One possibility is that the visual system simultaneously monitors the rate of activation buildup in an object lexicon and in an object localization module: As soon as both rates drop below a criterion level, the current fixation position is deemed to be suboptimal and an eye movement is planned.

Second, E-Z Reader assigns an important role to pre-attentive processing of the upcoming word. Given the rigid serial structure in which information needs to be acquired in reading, this implies that pre-attentive processing is restricted to the word that is about to become the saccade target. In scene exploration, however, there is no inherent spatial order in which objects need to be processed. Therefore, pre-attentive processing occurs for saccade bystanders as well as for the saccade target (Germeys et al. 2002). It will therefore be necessary to determine the spatial and temporal windows within which pre-attentive processing of a saccade bystander can influence that object's fixation duration or skipping probability once it has finally become the saccade target.

Third, E-Z Reader posits that attention shifts and eye movements are decoupled. We wonder whether the sparse and serial stimulus structure inherent in sentences may not be a necessary prerequisite for such a decoupling. In other words, autonomous attention shifts and eye movements may be possible only because the next relevant stimulus component is always easily discriminated on the basis of rudimentary boundary information. In scene perception, however, the next relevant stimulus component could be anywhere in the visual field; a more sophisticated process is required to mark the location of the next saccade target. As demonstrated by behavioral data (Deubel & Schneider 1996) as well as single-cell recordings in LIP (Colby et al. 1996), spatially selective shifts of visual attention appear to be that process, indicating a strong coupling between attention and eye movements. This implies that in scene perception we must invoke different mechanisms when our eye-movement records indicate refixations, spillover effects, and foveal-on-parafoveal effects.

Fourth, E-Z Reader elegantly limits the number of factors influencing fixation duration to visual acuity, word frequency, and word predictability. In object and scene perception these factors are also likely to play a role, although some may not be easy to estimate (e.g., what would constitute a good estimate of object frequency?). The relative importance of these factors is likely to be different in scene perception than in reading. Specifically, because scene identity is available early on in scene exploration (Biederman 1981) more subsequent fixations may show predictability effects than in reading where context develops more gradually. In addition, the list of factors influencing fixation times probably also needs to be extended. For example, ease of object identification has been argued to be a function of object orientation (Boutsen et al. 1998), object size (Theios & Amrhein 1989), and object camouflage (De Graef et al. 1990), all of which may have effects on eye-movement measures.

Fifth and finally, E-Z Reader capitalizes on the incorporation of very task-specific constraints in the model, such as the preferred saccade length in reading English. One could argue that this limits the generality of the model, but we feel such parameters are justified when they accurately reflect eye-movement behavior in the task under study. Moreover, while the parameter value is obviously task-dependent, the parameter itself may not be. Specifically, that preferred saccade length in reading English is estimated to be seven characters may be linked to the fact that the perceptual span for word encoding in reading English extends about eight characters to the right of fixation (Rayner et al. 1982). In other words, readers prefer to saccade to the edge of their perceptual span, a principle which may also apply to much less constrained tasks such as scene exploration (Shioiri & Ikeda 1989). Other task-specific constraints derived from reading data may be less suitable to extrapolate. For example, E-Z Reader assumes that all fixation times are sampled from a unimodal distribution. However, in other tasks, fixation time distributions may be multimodal, raising the question of whether fixation times in the various component distributions can all be modeled in the same fashion (De Graef 1998).

In summary, it would be unwise to extrapolate E-Z Reader to object and scene perception without careful consideration of task-specific differences in the interplay between visual processing, processing goals, attention, and oculomotor control. However, E-Z Reader does provide a valuable framework for thinking about the best design principles for a model of eye movements in object and scene perception.

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Are there two populations of refixations in the reading of long words?

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Abstract: This commentary focuses on the limitations of the E-Z Reader model in its attempt to explain refixation saccades in reading. Listing factors that influence probability of refixating leads the model to assume two sorts of refixations. However, taking into account data on the metrics of refixation saccades allows us to propose an alternative explanation for empirical observations reported in the literature.

In reading, the probability of refixating a word – that is, to read it with two fixations – is known to increase with word length, first fixations landing far from the word center and the decrease of word familiarity (McConkie et al. 1989). The E-Z Reader model accounts for these empirical data by making the following assumptions. The rapid parafoveal integration of the length of the to-be-fixated word results in the preparation of a refixation program. Although it remains implicit, this assumption suggests that the *decision* to refixate long words is taken before landing on the word. The computation of the refixation saccade is then initiated once the eyes land in the word. As the ability of the saccadic system to modify or cancel previous motor plans is now well documented in the literature (since the famous Becker & Jürgens [1979] study; see also Vergilino-Perez & Beauvillain, in press), the target model proposed that the refixation saccade program can be canceled during the first fixation on the word. The cancellation of a refixation saccade program would be more likely in a high frequency word than in a low frequency word because the progression of the first stage of the lexical processing is faster on the former than on the latter. Such an assumption is an elegant explanation for the word frequency effect on refixation probability (Inhoff & Rayner 1986; McConkie et al. 1989).

However, such a scenario does not fit with the classical interpretation of the effect of the first landing position on refixation probability. When the first fixation position was imposed at different locations in an isolated word (e.g., O'Regan et al. 1984), refixation probability increased when locations were far from the word center, a location usually called the optimal viewing position

(OVP). This relationship is expressed by a U-shaped curve. As a similar pattern was found in text reading (e.g., McConkie et al.1989; Vitu et al. 1990), it was popularly assumed that a decision to refixate was made because of errors in the execution of saccades which do not land on the intended saccade target. To integrate these empirical observations, the E-Z Reader model admits that a proportion of refixations is planned because of mislocated initial positions.

We would like to address two questions to the authors. First, whether their model assumes two populations of refixations. Second, whether the presupposed factors that affect the decision to refixate also play a role in the computation of the metrics of refixation saccades. Indeed, even if this model addresses the question of the refixation probability, nothing is said about refixation saccade metrics – for example, what is the target for the refixation saccade?

An experiment was conducted in our lab (Doré-Mazars et al. 2003) to examine these questions further during reading of isolated long words. High- and low-frequency words of 8, 10, and 12 letters were displayed in parafoveal vision. With this procedure, the launch site (eccentricity) and the parafoveal preview were held constant. Critical aspects of early work about the refixation decision are replicated here: both length and frequency effects, and also the classical U-shaped curve describing the relation between the refixation probability and the initial landing position on the word. For each initial landing position, we found an effect of the length and the frequency of the word, the amplitude of the first being more important than the second one.

More interestingly, we provide arguments for the view that refixations do not result from saccadic error but are preplanned and sometimes canceled. We observed that the distribution of landing positions in refixation cases is clearly leftward-shifted relative to single fixation cases. In addition, the examination of the refixation saccade amplitude demonstrates that the saccade is planned on the basis of the word length with no effect of the initial landing position on the word. Indeed, the slope of the linear regression between first and second fixation position close to 1 indicates that the refixation saccade is computed as a fixed motor vector applied irrespective of the initial landing position on the word. We replicate here previous findings indicating that the refixation saccade is preplanned in parafovea relative to the word length integrated at this time (Vergilino & Beauvillain 2000). The absence of a target for refixation saccades stands against refixations as corrective saccades. In such a framework, we interpret the difference in initial landing position on the word between single- and refixation cases found in our experiment as the consequence and not as the cause of the planning of refixation saccades. Of course, because of the inherent variability of the text-reading situation (e.g., in launching sites), some refixations could be caused by mislocated landing positions, but their proportion and metrics remain to be assessed. Moreover, while refixation probability was affected by word frequency, no role of this factor in the computation of the refixation metrics was observed in our experiment. Indeed, we found a frequency effect neither on the mean refixation saccade amplitudes nor on the slope of the linear regression. This result is compatible with the notion that the lexical processing that progresses throughout the first fixation is likely to cancel a preplanned refixation saccade. However, since the frequency effect on refixation probability is around 10%, as usually observed in the literature, we assume that only a small proportion of refixations would be canceled by lexical processing. Word processing plays only the secondary role in refixating of long words.

In conclusion, one of the future challenges of the E-Z Reader model is to take into account not only the factors that influence the decision to make a refixation saccade, but also those that determine its metrics, to better explain refixations in reading.

The game of word skipping: Who are the competitors?

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Abstract: Computational models such as E-Z Reader and SWIFT are ideal theoretical tools to test quantitatively our current understanding of eye-movement control in reading. Here we present a mathematical analysis of word skipping in the E-Z Reader model by semianalytic methods, to highlight the differences in current modeling approaches. In E-Z Reader, the word identification system must outperform the oculomotor system to induce word skipping. In SWIFT, there is competition among words to be selected as a saccade target. We conclude that it is the question of competitors in the "game" of word skipping that must be solved in eye movement research.

In computational models based on the concept of sequential attention shifts (SAS), word skipping is a consequence of a competition between lexical processing and saccade programming (target article; cf. Engbert & Kliegl 2001; 2003; Reichle et al. 1998). This mechanism was proposed first by Morrison (1984). Such an explanation of word skipping is *qualitatively* different from the assumption underlying the SWIFT model (Engbert et al. 2002; 2004; Kliegl & Engbert 2003), that a field of lexical activities builds up during the eyes' random walk over the sentence. It is the relative strength of activity that determines the probability of selecting the next saccade target. The related theoretical framework of competition between targets for action is the dynamic field theory of movement preparation (Erlhagen & Schöner 2002). Consequently, the SWIFT model may be generalized as a model for eye-movement control in situations with many potential saccade targets such as visual search or general scene perception. To compare these differences between SAS models and SWIFT, we investigate the mechanism for word skipping using semianalytical techniques.

In E-Z Reader 7, currently the most advanced SAS model, a new saccade program is initiated at the end of stage 1 of the word identification system (Fig. 3 in the target article). Word skipping occurs if the saccade program is canceled by another saccade command during the labile stage. Such a cancellation will occur if the sum of the durations of L_2 (of the currently fixated word) and L_1 (of the skipped word) is smaller than the average duration of the labile saccade program M_1. To calculate the probability of skipping, we have to consider that saccade program stages are gamma-distributed[1] in E-Z Reader. As a consequence, the probability of skipping is given by an integral over the distribution $q^n_\tau(t)$ of durations of the labile saccade stage M_1,

$$p_{\text{E-Z Reader}} = \int_{L_1+\langle L_2\rangle}^{\infty} q_\tau^{n}(t)\,\mathrm{d}t \qquad (1)$$

where the time constant τ is related to the mean of the labile saccade program by $\tau = M_1/9$. It is important to note that there are two oculomotor parameters, n and τ, in the probability. The integral in Equation 1 can be evaluated analytically. The probability for skipping a word, which needs an average processing time L_1 of the first stage of word identification, is given by

$$p_{\text{SAS}} = \left(\sum_{k=0}^{n} \frac{1}{k!}\left(\frac{L_1+\langle L_2\rangle}{\tau}\right)^{k}\right)\exp\left(-\frac{L_1+\langle L_2\rangle}{\tau}\right) \qquad (2)$$

Since stage L_1 refers to the skipped word, we have to estimate the average processing time during stage 1 by computing means over the five word-frequency classes for L_1. From low to high word frequency (classes 1 to 5) we computed the values 128.0 msec, 100.7