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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,

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

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

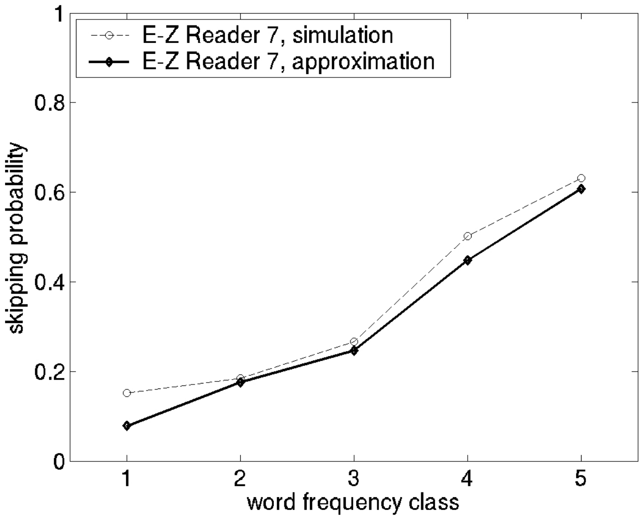

Figure 1 (Engbert & Kliegl). Skipping probability as a function of word frequency class.

msec, 90.8 msec, 60.7 msec, and 44.4 msec for L_1, using Equation 3 and corresponding parameter values given in Reichle et al. The average value of L_2 corresponds to an arbitrary word (the word left of the skipped word). Therefore, we used the ensemble average of L_2 over all words the corpus of sentences,[2] denoted by $\langle L_2 \rangle = 82.3$ msec. For a gamma distribution of order $n=8$ and a mean labile saccade duration $M_1=187$ msec, we obtained $\tau = 20.8$ msec. The resulting estimates for the skipping probability $p_{\text{E-Z Reader}}$ are in good agreement with simulated data from the target article (see Fig. 1).

In SWIFT, a field of lexical activities $a_n(t)$ evolves over time. The probability of target selection is given by the relative lexical activity. As a consequence, no additional assumptions must be made to produce forward saccades, refixations, and regressions. The probability of skipping word_{n+1} is given by the probability to select word_{n+2} as the next saccade target, which is computed by the fraction

$$p_{SWIFT} = \left. \frac{a_{n+2}(t)}{\sum_{k=1}^{n+2} a_k(t)} \right|_{t = \text{target selection}} \quad (3)$$

There is no oculomotor contribution to the skipping probability in Eq. (3) – an important difference to Equation (2) for E-Z Reader. Numerical estimates for p_{SWIFT} can be obtained by evaluating the set of lexical activities at the point in time where target selection occurs in SWIFT (for details see Engbert et al. 2002).

Diverging predictions can be derived from SAS and SWIFT models. In E-Z Reader, the probability of word skipping will depend on oculomotor parameters, because of the competition between saccade programming and word identification. In SWIFT, the competition between words for becoming selected as the next saccade target implies a structural stability of word skipping against oculomotor parameters. Therefore, dynamic models generate highly specific predictions, which might be most stimulating for future research: The current controversy on mechanisms of eye-movement control will still be resolvable by experimental results.

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NOTES

1. The gamma distribution for saccade latencies can be written as $q_\tau^n = \frac{1}{\tau - n!}\left(\frac{t}{\tau}\right)^n \exp\left(-\frac{t}{\tau}\right)$, where τ is a time constant and n is the order of the distribution. Mean value and standard deviation are given by $\mu = (n+1)\tau$ and $\sigma = \sqrt{n+1}\tau$. For a relation of standard deviation to mean of one third (Reichle et al. 1998), we have to choose a gamma distribution of order $n = 8$.

2. This procedure may be interpreted as a *mean field approximation,* that is, using the average processing difficulty of the word left to the skipped word. To compute L_1 and $\langle L_2 \rangle$ according to Equation 3 in the target article, we used word frequencies, predictabilities, and the parameters β_1, β_2, and Δ.