Effects of frequency, predictability, & length in a rational model of eye movements in reading

Klinton Bicknell & Roger Levy (University of California, San Diego)
kbicknell@ucsd.edu

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Eye movement control in reading is one of the best and most naturalistic examples of the adaptive deployment of linguistic knowledge for real-time comprehension. Here we present a model of eye movement control in reading as rational action, which seeks to understand reading behavior as resulting from the efficient way to achieve reader goals. Specifically, we describe empirical benchmarks for the first rational model of eye movements in reading that makes predictions for the full range of the eye movement record. Unlike E-Z Reader (Reichle et al., 2003), SWIFT (Engbert et al., 2005), and Glenmore (Reilly & Radach, 2006), the model directly optimizes its behavior to best achieve the reader's goals, here characterized as accurate and rapid identification of the contents of the text. Unlike Mr. Chips, the only previous rational model in this domain (Legge et al., 1997), the model makes predictions about not only fixation locations but also fixation durations.

In the model, readers use Bayesian inference to combine two sources of information – (1) probabilistic language knowledge (the prior), and (2) noisy perceptual input about the text (the likelihood) – to form and repeatedly update a posterior distribution over possible text contents. At each discrete time step, readers can *continue fixating* the eyes' current position to obtain more perceptual input, *move the eyes* to a position of the model's choice, or *stop reading* and end the trial. The model includes realistic physical constraints including motor error, saccade planning time, and an asymmetric visual acuity curve. Readers obtain noisy letter-identity information (with noise level dependent on visual acuity) and veridical information about word lengths and boundaries throughout the visual span. Model behavior is determined by a number of *parameters* sensitive to the probability distribution over the text at each timestep; the parameter values used in simulations are optimized for speed and accuracy given reader goals, not for fit to human eye movement data.

Simulations reveal effects of word frequency and predictability on diverse reading measures (including first fixation durations, gaze durations, skipping probabilities, and refixation rates) qualitatively reproducing monotonic effects seen in human behavior, and quantitatively provide reasonable fits to human data. An examination of the effects of word length in the model, however, yielded a more complex picture: while skipping and refixation rates were monotonic functions of word length (decreasing and increasing, respectively, as for humans), the model did not produce humanlike monotonic functions of word length on fixation duration measures, but rather a U-shaped function rising with word length between 1–4 characters, but falling with word length above that.

We hypothesized that this length effect was an artifact of the model's simplifying assumption of veridical knowledge of word length, which artificially shrinks orthographic neighborhoods – reducing the visual input necessary for word recognition – of longer words more than of shorter words. We tested this hypothesis by extending the model to include uncertainty about word length as well as letter identity. This change shifted the word-length/fixation-duration relationship exhibited by the rational model much closer to monotonic, human-like patterns.

The success of the model to derive this range of effects from principles of probabilistic inference and rational action suggests that many aspects of human reading behavior can be profitably understood as properties of efficient solutions to the problem of reading.

References

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