Reward-based decision-making during reading for speed versus for accuracy

Readers make decisions about how fast or how accurately they read a given text. Reinforcement learning characterizes these decisions as originating from either a model-free learning system that repeats previously rewarded actions, or from a model-based system that anticipates future consequences for making decisions. Task context is known to affect eye-movements during reading [1,2]. However, it is unclear how decisions about gaze control are based on explicit valuation of speed versus accuracy, and how learning occurs to optimize outcomes. To investigate these questions, we created two reward conditions where readers received monetary reward either for reading fast, or for answering comprehension questions correctly. We were interested in how readers adapt their eye-movements to achieve these goals. Accurate reading has previously been closely linked to regressive eye-movements, in experimental investigations [3,4,5] and in rational models of reading [6]. We expected that when speed is rewarded over accuracy, readers would reduce regression rates.

Methods: 12 subjects each read 24 paragraphs of natural texts (taken from German novels) and answered eight comprehension questions about each paragraph. We recorded eye-movements during reading using an EyeLink 1000 eye-tracker. We used monetary reward to reinforce high reading speed and correct answers to questions about the text. Reward condition was manipulated within subjects: reading speed yielded higher rewards in 12 paragraphs, and correct responses to comprehension questions yielded higher rewards in another 12 paragraphs. We provided instructions before each paragraph about whether speed or accuracy would be more rewarded.

Results: We found that, as expected, when speed was rewarded participants read faster ($b = 167$ wpm, 95% confidence intervals, CI = [94 240], $p < .001$) and answered less questions correctly ($b = 17\%$, CI = [13 21], $p < .001$) compared to when accuracy was rewarded. In the speed condition, the number of reward points won for each paragraph increased across trials, indicating learning from reward feedback ($p < .001$). In the accuracy condition, the number of gained reward points per paragraph was already high in initial trials, and there was no evidence for a further increase across trials ($p = .199$). Readers adapted eye-movements to achieve high speed versus accuracy (Fig. 1). Participants read fast by skipping words (32% vs. 49%; $p < .001$) and by avoiding repeated fixations on already fixated words (total reading time: 295 ms vs. 227 ms; $p < .001$), in particular on words with low frequency and high length (interaction word length x word frequency x reward condition: $p < .001$). Participants also achieved high speed by making shorter first fixations (200 ms vs. 184 ms; $p < .001$) and less regressive (leftward directed) eye-movements (accuracy: 17%; speed: 14%, $p < .001$). Interestingly, the effect size for regressions was very small (3 percentage points difference). The reward condition influenced reading behavior already in the very first trial (p-values $< .05$; regressions: $p = .062$), before any experience-based learning. The effect of reward condition further increased across trials for skipping ($b = 0.2$, $p < .001$), saccade length ($b = 0.17$, $p = .028$), and first fixation durations ($b = 0.8$, $p = .007$), but not for regression probability ($b = 0.07$, $p = .155$). Moreover, in the speed condition all eye-movement measures were related to reward outcomes (p-values $< .001$; Fig. 2), except for regressive eye-movements, which were not related to obtained reward ($p = .865$).

Conclusion: These results suggest that when reading natural texts for speed, readers only slightly reduce regressive eye-movements. This is in line with the SWIFT model of eye-movement control [7], where regressive eye-movements are triggered by low-level incomplete lexical processing [4]. Alternatively, regressions may be crucial even during fast reading to ensure at least minimal comprehension [5]. The results demonstrate that a model-based decision-system based on instructions can immediately adapt gaze control before the model-free system can learn from experience. Reward-based decision making may provide a paradigm to dissect and test rational decision mechanisms underlying eye-movements during reading.

References: [1] Strukelj, A., & Niehorster, D. C. (2018). Journal of Eye Movement Research. [2] Sanford, A. J., & Sturt, P. (2002). Trends in Cognitive Sciences. [3] Schotter, E. R., Tran, R., & Rayner, K. (2014). Psychological Science. [4] Bicknell, K., & Levy, R. (2011). In Proceedings of the Annual Meeting of the Cognitive Science Society. [5] Metzner, P., Von Der Malsburg, T., Vasishth, S., & Rösler, F. (2017). Cognitive Science. [6] Bicknell, K., & Levy, R. (2010). In Proceedings of the 48th annual meeting of the Association for Computational Linguistics. [7] Schad, D. J., & Engbert, R. (2012). Visual Cognition.

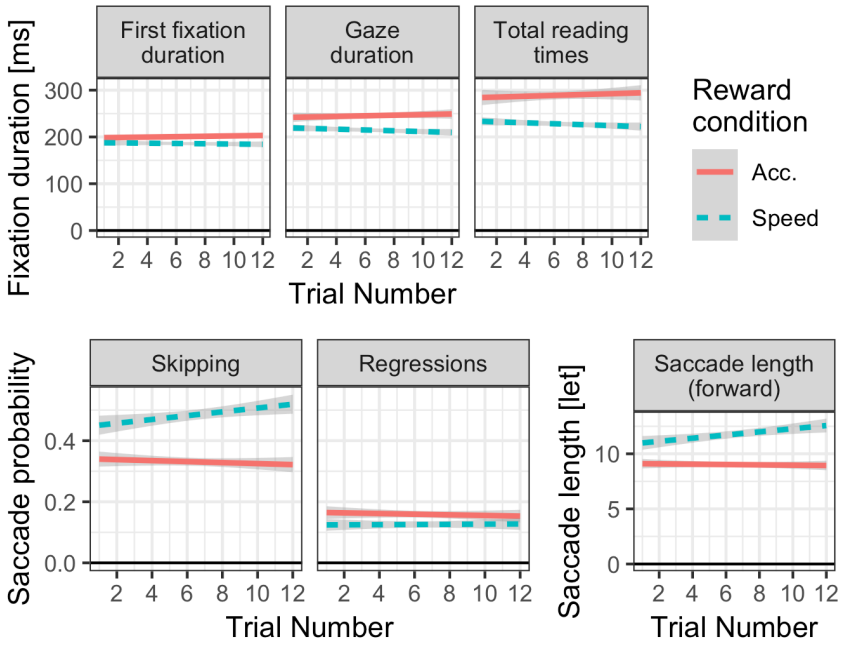

Figure 1. Changes over trials in global measures of gaze for conditions of reward for accuracy (red solid lines) versus for speed (green dashed lines).

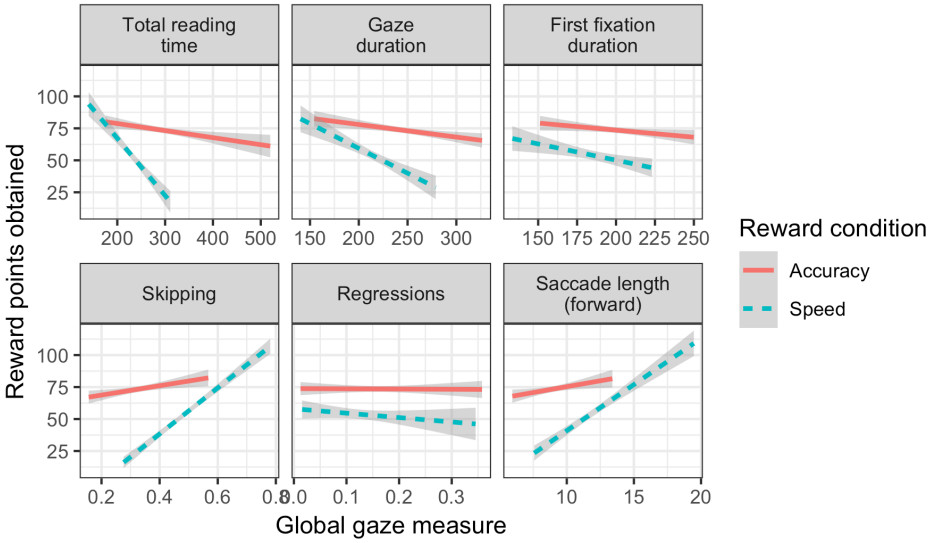

Figure 2. Number of reward points won as a function of global eye-movement measures for conditions of reward for accuracy (red solid line) versus for speed (green dashed line).