Predictive pre-updating: Converging evidence from electrophysiology and eye-blink rate

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Introduction: Prediction during sentence processing was suggested to involve two qualitatively distinct mechanisms: "pre-activation" of representations in long-term memory (LTM), and "pre-updating" of the context's representation in working memory (WM) to include the predicted content [1]. Unlike pre-activation, pre-updating has hardly been studied. In a recent event-related potentials (ERP) study [2], pre-updating was demonstrated as an increased P600 amplitude prior to a highly predictable word, indicating integration of the predicted word prior to its appearance. The effect was greater for participants with higher WM capacity, suggesting a higher tendency to pre-update. Here we present converging evidence for pre-updating, and for the influence of WM capacity, from two additional experiments. We also explore the circumstances under which pre-updating occurs, establishing a plausible architecture for the interface between LTM and WM.

Methods: Experiment 1: 48 participants read strongly and weakly constraining sentence fragments (i.e. fragments that lead or do not lead to a strong prediction, 156 sentences, see Table 1), presented word-by-word. ERPs were measured on the verb at the end of the fragment, where the prediction is generated. Participants were then prompted to complete the sentence aloud as quickly as possible (the production prompt was separated from the verb by the Hebrew accusative case marker, to prevent ERP artifacts). This design allowed us to test whether pre-updating, indicated as an increased P600 amplitude on the verb [2], depends on the participant's specific completion, i.e. whether she produces the most probable completion (highest cloze-probability) or not. It also enabled looking for a correlation between the P600 effect and production onset.

Experiment 2 (N=40) employed an event-based eye-blink rate (EBR) methodology. Research has shown that EBR is an indirect measure of dopamine activity in the striatum [3] and increases when WM is updated [4], in line with the prefrontal cortex basal ganglia WM model [5,6]. Experiment 2 used 160 two-word phrases with the first word either highly predictive of the second (e.g. *global warming*) or not (e.g. *vegetable soup*). In highly predictive phrases, upon updating the first word into WM, if pre-updating occurs then the predicted second word is also updated. No additional updating is needed upon presentation of the second word, and reduced EBR is predicted.

In both experiments, participants' WM capacity was assessed via a reading span (RS) task.

Results: Experiment 1: Behavioral data replicated previous findings [7], with higher cloze probability as well as higher constraint leading to shorter production onset (analysis as detailed in [7], p's < .001). In the ERP data, high constraint trials were divided based on the produced word, forming three conditions: HH (High constraint, High cloze word produced), HL (High constraint, Low cloze word produced), L (Low constraint). A P600 effect was observed in both HL and HH conditions (relative to L). Words produced faster were preceded by a larger P600 (Figure 1a,b). Experiment 2: EBR was decreased in the high vs. low constraint condition (Figure 2a). Both the P600 and EBR effects were greater for participants with higher RS (Figures 1c, 2b).

Discussion: Experiment 1 replicated the P600 effect at the verb [2], and showed that this effect exists regardless of whether the participant's prediction in the specific moment is the most probable completion. Additionally, this effect was correlated with production onset, suggesting that the likelihood of pre-updating depends on the time needed for a predicted word to be retrieved. These results support an architecture with a retrieval threshold at the interface between LTM and WM. This threshold is usually reached by bottom-up activation (i.e. when the word appears in the input). Pre-updating occurs when top-down activation is strong enough, and fast enough, to reach this threshold prior to realization of the word in the input. In Experiment 2, pre-updating manifested as decreased EBR when the second word did not require additional gating and updating, thus providing additional evidence for pre-updating. In both experiments, pre-updating effects were greater for participants with higher RS, thus strengthening the claim that these effects reflect WM updating. The influence of WM capacity could be mediated by a lower threshold for participants with higher WM capacity, leading to a higher likelihood of pre-updating.

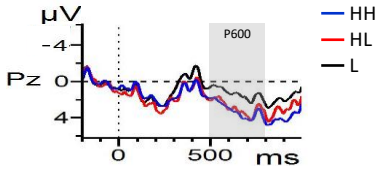
Table 1: Example set for experiment 1

Constraint	Sentence fragment
High	*biglal še-ofir lo makir et ha-sifria, ha-safranit azra lo* ***limco*** *et* ___ since that-ofir not know ACC the-library, the-librarian helped him **to-find** ACC ___ 'Since Ofir isn't familiar with the library, the librarian helped him **find** ___'
Low	*ofir xipes ve-xipes bemešex šaot, aval lo ecliax* ***limco*** *et* ___ ofir searched and-searched for hours, but not succeeded **to-find** ACC ___ 'Ofir had searched for hours, but he couldn't **find** ___'

Note: Sentences were presented in Hebrew. ACC = accusative marker.

Figure 1: ERP results

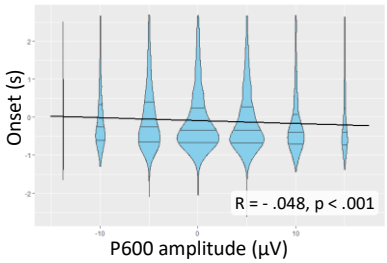
(A)



P600 at a representative electrode

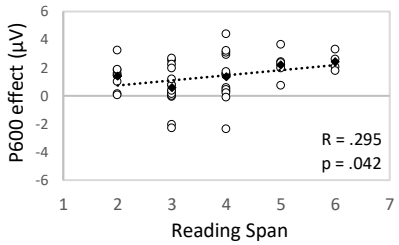
Analysis over posterior electrodes:
Main effect of Condition ($F(2,94) = 12.842$, $p < .001$).
Pairwise contrasts:
HL and L differ significantly ($F(1,47) = 18.970$, $p < .001$).
HH and L differ significantly ($F(1,47) = 28.181$, $p < .001$).
HL and HH do not differ significantly ($F(1,47) = 0.755$, $p = .389$).

(B)



By-trial correlation between P600 amplitude and production onset (Pearson correlation = -.048, N = 7022, p < .001)

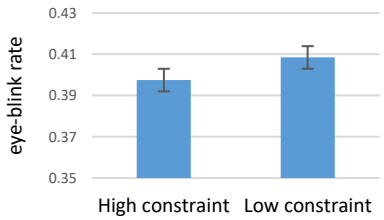
(C)



By-participant correlation between RS and the P600 effect (Pearson correlation = .295, N = 48, p = .042)

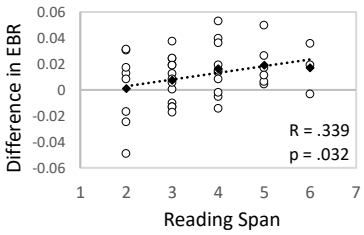
Figure 2: ebEBR results

(A)



Decreased EBR in the high (relative to low) constraint condition ($t(39) = -3.276$, $p = .002$).

(B)



By-participant correlation between RS and the EBR effect (Pearson correlation = .339, N = 40, p = .032)

References: [1] Lau, E. F., Holcomb, P. J., & Kuperberg, G. R. (2013). Dissociating N400 effects of prediction from association in single-word contexts. *Journal of Cognitive Neuroscience, 25*, 484-502. [2] Ness, T. & Meltzer-Asscher A. (2018). Predictive pre-updating and working memory capacity: Evidence from event-related potentials. *Journal of Cognitive Neuroscience*, 30, 1916-1938. [3] Jongkees, B. J., & Colzato, L. S. (2016). Spontaneous eye blink rate as predictor of dopamine-related cognitive function—A review. *Neuroscience & Biobehavioral Reviews,* 71, 58-82. [4] Rac-Lubashevsky, R., Slagter, H. A., & Kessler, Y. (2017). Tracking real-time changes in working memory updating and gating with the event-based eye-blink rate. *Scientific reports*, 7, 2547. [5] D'Ardenne, K., Eshel, N., Luka, J., Lenartowicz, A., Nystrom, L. E., & Cohen, J. D. (2012). Role of prefrontal cortex and the midbrain dopamine system in working memory updating. *Proceedings of the National Academy of Sciences*, 109, 19900–19909. [6] Hazy, T. E., Frank, M. J., & O'Reilly, R. C. (2006). Banishing the homunculus: making working memory work. *Neuroscience*, 139, 105-118. [7] Staub, A., Grant, M., Astheimer, L., & Cohen, A. (2015). The influence of cloze probability and item constraint on cloze task response time. *Journal of Memory and Language,* 82, 1-17.