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Testing limits: ERP evidence for word form preactivation during speeded sentence reading

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Abstract

While it is commonly agreed upon that language comprehenders preactivate information at multiple levels, there is less consensus regarding *what* and *when* information is predicted, under which circumstances, and via which mechanism(s). Regarding *when*, Ito, Corley, Pickering, Martin, & Nieuwland (2016) concluded that during sentence processing, word form—unlike semantic—preactivation crucially relies on the time available to generate late-stage predictions via language production mechanisms, setting this limit between 500 and 700 ms/word. The current event-related brain potential (ERP) study tests this proposal at a substantially faster serial visual presentation (SVP) rate of four words/s, on par with normal reading. We utilize the experimental design and replicate the general ERP findings of the two words/s SVP study of DeLong, Chan, & Kutas (2019), with results showing similar N400 reductions to unpredictable sentence continuations whether semantically or orthographically related to contextually predictable words, as well as an increased late posterior positivity to orthographic neighbors. These findings indicate that processing of written word information can be rapidly facilitated through context-based expectancies, establishing that if there is a time constraint for word form preactivation, it must be far less than limits specified by the prediction-by-production comprehension model championed by Ito et al.

KEYWORDS

ERPs, N400, sentence comprehension, timing, word form prediction

1 | INTRODUCTION

Neural prediction is a matter of timing; in other words, it is only *pre*diction if processing is initiated prior to encountering an anticipated physical stimulus. Linguistic predictions may eventually be (in)validated by subsequent input, but before (dis) confirmation, cued forms or features are preferentially neurally activated via context and long-term memory associations. In language processing then, the term *preactivation* is a term favored by some because it reflects the graded, probabilistic nature of early retrieval during comprehension, regardless of the actual stimulus eventually encountered. A wide array of information can be preactivated to varying degrees with incoming linguistic input continually serving to probe and redirect the activation state of mental representations, and in turn, update the prediction landscape. Preactivation subsequently offers potential processing benefits, freeing up resources to allow for, for instance, reallocation of attention, response preparation, ambiguity resolution, signal detection in noisy environments, or any combination of these or other cognitive tasks. We take preactivation to be a default mechanism, continuous and obligatory, and not necessarily under conscious control. However, we favor a view of prediction under which its trajectory may be modulated by individual processing abilities that delimit

available cognitive resources, as well as by particular individual and interacting sources of linguistic and extralinguistic contextual information that may come to bear on variable time scales, ultimately resulting in observable prediction effects only within a limited range of input rates.

When it comes to the timing of preactivation during sentence processing, it has been suggested that word forms can only be predicted at slower input rates (Freunberger & Roehm, 2016) and that word form prediction necessarily trails semantic preactivation, as outlined in certain production-based prediction models (Ito et al., 2016). Broadly, prediction-by-production models contend that prediction during language comprehension relies on the same brain systems as language production, although various production-based models differ in claims of prediction being crucially dependent on the amount of available time and neural resources, and whether or not form prediction invariably trails semantic prediction (e.g., Pickering & Garrod, 2013). In models such as the one outlined by Ito et al. (2016), form prediction is the final step in a chain of unidirectional, several-hundred-milliseconds-long, production-like stages (e.g., as outlined by Indefrey & Levelt, 2004), occurring only when sentence input rates are slowed to allow the processor to advance through to the terminal stage. Ito et al. (2016) argued for such constraints based on their study using an event-related brain potential (ERP) related anomaly paradigm, with highly constraining sentences continued by predictable words (PRED), contextually unexpected words related either semantically (SEM) or orthographically (ORTH) to the predictable word, or unexpected words unrelated to predictable continuations (UNREL). Individuals read sentences one word at a time (e.g., "*The student is going to the library to borrow a book/page/hook/sofa…"*) at both relatively faster (1 word/500 ms) and slower (1 word/700 ms) rates. N400 facilitation was reported for SEM words (*page*) at both rates but for words in the ORTH condition (*hook*) only at the slower rate. The N400 is an ERP component sensitive to an item's contextually grounded predictability and has been considered to reflect the degree to which lexico-semantic information has already been activated. Under the proposal that predictions are made via the language production system, Ito et al. (2016) concluded—based on the absence of a word form (ORTH) prediction effect at the faster presentation rate—that unlike semantic information, word form preactivation during reading depends crucially on the time available to generate predictions, setting this time limit somewhere between 500 and 700 ms per word.

In contrast, DeLong et al. (2019) presented evidence from a similar ERP experimental design, with different results and conclusions. DeLong et al. (2019), consistent with other ERP sentence studies testing orthographic neighbors of predictable words in predictive contexts at presentation rates at or near two words/s (e.g., Kim & Lai, 2012; Laszlo & Federmeier, 2009), reported N400 amplitude reductions to those conditions—results that argue for word form prediction at a faster rate than cited by Ito et al. (2016). Of these several studies, however, only DeLong et al. (2019) used stimuli limited to real words, without the inclusion of pseudoword critical items. Thus, by employing an experimental paradigm and task (reading for comprehension using real word sentences) that directly mirrored Ito et al. (2016), the DeLong results could not be dismissed by attributing them to the experimental use of non-words. Taken together, this body of work points to word forms being predicted more quickly and more commonly than suggested by the staged, time-intensive production model at the heart of Ito et al.'s (2016) comprehension proposal.

While the orthographic neighbor effects reported by DeLong et al. (2019) and others argue for word form prediction being less constrained by input rate than under Ito et al.'s (2016) prediction-by-production model, two words/s serial visual presentation (SVP) input rate still affords more time than is characteristic of natural language processing in young adults. Rayner et al. (2016) place normal reading rates for college-educated adults between 3.3 and 6.6 words per second. ERP research has indicated that readers are capable of processing semantic information at input rates of up to 10 words/s, although at this speed, associated N400 congruency effects are almost 100 ms delayed relative to the canonically stable N400 peak latency (Kutas, 1993). Generally, however, there is relatively little work demonstrating how predictive processing is impacted by input rates faster than two words/s. Dambacher et al. (2012) found delayed and smaller N400 predictability effects for sentences presented with a stimulus onset asynchrony (SOA) of 280 ms compared to slower rates. Wlotko and Federmeier (2015) showed that N400 semantic feature prediction effects were not consistently observed during four words/s SVP sentence reading, but rather were more likely to occur after participants had shown prediction effects during a previous block of sentences read at a slower rate of two words/s. DeLong (2009) also found more limited prenominal ERP evidence for a graded word form prediction effect in only a subset of participants when SVP sentences were presented with a 300 ms SOA. Taken together, these mixed results regarding linguistic prediction at faster input rates, in combination with the conclusions of Ito et al. (2016), led to the current study. Here we set out to assess the time limit for word form prediction by contrasting it with semantic preactivation at an input rate on par with normal reading. We utilized the experimental paradigm and stimuli from DeLong et al. (2019)—a study with proven effects of both types of preactivation at a rate of two words/s—but doubled the presentation rate to four words/s. If no N400 reduction is observed to words orthographically related to predictable continuations, then this would identify a timing limit for word form preactivation and would offer a constraint upon which such predictions could occur. On the other hand, if speeded

presentation yields similar ERP results as with two words/s, this would further complicate arguments favoring word form prediction being the end stage of a time-consuming chain of production-like sub-operations, suggesting that alternative mechanisms for word form preactivation may be involved.

In addition, we also expect words orthographically related (and potentially semantically related or unrelated) to predictable continuations to elicit a posterior post-N400 positivity (pPNP) relative to predictable sentence continuations, similar to DeLong et al. (2019) as well as other studies employing orthographically related continuations at SVP presentation rates near two words/s (e.g., Ito et al., 2016; Laszlo & Federmeier, 2009; Vissers et al., 2006; Kim & Lai, 2012). The functional nature of this effect has been variably proposed to relate to integration difficulty (Brouwer et al., 2012), reanalysis/memory retrieval (Van Petten & Luka, 2012), revision/repair (Kuperberg et al., 2020), and monitoring (Van Herten et al., 2005), with a common thread being that the eliciting conditions do not constitute plausible continuations (see DeLong & Kutas, 2020, for a discussion). For the present study, at issue is whether decreased word reading time impacts the elicitation of this positivity.

2 | METHOD

2.1 | ERP participants

Twenty-four UCSD undergraduate volunteers participated in the ERP experiment for course credit or cash. Participants (16 female, 8 male) were all right-handed, native English speakers with normal or corrected-to-normal vision, ranging in age from 19 to 23 years, with a mean age of 20.4 years. Six participants reported a left-handed or ambidextrous parent or sibling.

2.2 | Stimulus materials and offline tasks and measures

Stimulus materials and offline testing were identical to those used in DeLong et al. (2019) (see for details). Materials consisted of 160 highly constraining sentence contexts with sentence medial critical words from four possible conditions: predictable/best completion (PRED), unpredictable orthographic neighbor of the predictable word (ORTH), unpredictable semantically/associatively related to the predictable word (SEM), or unpredictable unrelated to predictable word (UNREL). See Table 1 for examples. The three unpredictable continuations were selected to be implausible in their contexts. Mean sentence constraint—based on cloze probability for predictable words—was 94% (range 87%–100). Cloze probabilities for unpredictable words were thus very low. Word frequency, a lexical attribute known to influence N400 amplitude, was assessed for the critical words using the Hyperspace Analog to Language (HAL) norms from the English Lexicon Project (Balota et al., 2007). Log transformed word frequencies for the conditions of interest (semantically and orthographically related words) were matched to those of the unrelated condition. No filler sentences were used, and each participant viewed all 160 sentence contexts, with equal numbers of items (40) per experimental condition (4).

2.3 | ERP experimental procedure

ERP experimental procedures were identical to those from DeLong et al. (2019) except that the interstimulus interval for words in the current study was shortened to 50 ms from the original 300 ms. With the duration of SVP words remaining 200 ms, the resultant stimulus presentation rate/SOA was 250 ms (4 words/s). ERPs were recorded in a single session in a sound-attenuating, electrically shielded chamber, with participants sitting one meter in front of a CRT monitor, reading sentences presented one word at a time in the center of the screen for comprehension. Yes/no comprehension questions appeared in their entirety on screen following one-quarter of the sentences and were responded to with one of two hand-held buttons, with response hand counterbalanced across participants and lists. If there was a question, the participant's answer via button-press served to advance to the next sentence: if there was no question, advancement was automatic. There was a 3-s interval of blank screen between sentences. A brief practice session preceded the experimental testing, during which

TABLE 1 Example stimuli

Sentence context	Predictable (PRED)	Form related (ORTH)	Semantically related (SEM)	Unrelated (UNREL)
The Doberman stood its ground and bared its… to the mailman.	teeth	tenth	dentist	report
The woman stashed her wallet in her… for safety.	purse	nurse	snatcher	guest

eye movements were monitored by the experimenter and feedback given to participants. Participants were asked to remain still during testing and to avoid blinking and moving their eyes during sentence presentation.

2.4 | ERP recording and data analysis

EEG recording parameters and data analysis procedures were identical to those described in DeLong et al. (2019). In brief, EEG was recorded from 26 scalp electrodes. Single-trial epochs spanning 500 ms prestimulus to 1,500 ms poststimulus onset were extracted from the continuous EEG. Baseline correction was performed by subtracting the mean amplitude over the 500 ms precritical word onset. Artifact screening was performed by computer algorithm and confirmed by visual inspection, with an average of 14% ($SD = 11\%$) of trials contaminated and excluded prior to averaging.

Mean ERP amplitudes from 300 to 500 and 600 to 1,000 ms time windows were measured over 15 posterior electrodes for the N400 and pPNP analyses, respectively. Repeated measures analyses of variance (ANOVAs) were used to test for effects of relatedness (four levels: PRED, ORTH, SEM, UNREL) on ERP mean amplitude measures across the 24 participants. ANOVA p values are reported with the Greenhouse-Geisser (GG) correction for repeated measures with more than one degree of freedom (df) in the numerator, with the original degrees of freedom. ERP follow-up comparisons were performed with additional repeated measures ANOVAs on subsets of the data. See Figure 1 for a plot of whole head ERPs and graphs of mean amplitude measures.

3 | BEHAVIORAL RESULTS

Participants correctly answered an average of 87.7% (range 75.0 to 97.5%) of the comprehension questions, indicating that they were attending to and comprehending the experimental sentences.

4 | ERP RESULTS

4.1 | N400: 300–500 ms

For N400 mean amplitude measures over 15 posterior channels, overall ERP patterns mirrored those observed at the 500 ms stimulus presentation rate (DeLong et al., 2019). There was a significant main effect of condition [$F(3, 69) = 44.37$, $p_{GG} < .0001$], and a predicted canonical congruity effect was confirmed by PRED items (1.38 μV) displaying the largest N400 amplitude reduction relative to UNREL items (−2.14 μV). Of greater interest for our experimental question, pairwise comparisons revealed that ORTH (−1.39 μV) and SEM (−1.23 μV) items both exhibited statistically significant N400 amplitude reductions relative to UNREL and notably did not differ significantly from each other (see Table 2).

4.2 | Posterior PNP: 600–1,000 ms

Over the 15 most posterior electrodes, there was also a significant main effect of condition in the late positivity time window [$F(3, 69) = 3.80$, $p_{GG} = .0143$]. The late positivity ERP patterns resembled those at the 500 ms presentation rate (DeLong et al., 2019) in that the ORTH condition (2.49 μV) exhibited the largest mean amplitude positivity relative to the other conditions (PRED 1.45 μV, SEM 1.47 μV, and UNREL 1.64 μV). Pairwise tests revealed these differences with the ORTH condition were statistically significant, but that PRED, SEM, and UNREL items did not differ significantly from each other (see Table 2).

4.3 | Summary

The SEM and ORTH conditions showed similar N400 amplitude reductions relative to the UNREL condition, consistent with N400 results from DeLong et al. (2019). In the posterior PNP analysis, ORTH items exhibited increased positivity relative to all other conditions (also consistent with results at the slower presentation rate), with no significant amplitude difference between the PRED, SEM, and UNREL words.

5 | DISCUSSION

The current experiment was designed to test the temporal limits of word form preactivation during online written sentence comprehension. At a reading rate of four words/s, we replicated the ERP prediction effects observed for sentences presented at half the rate (DeLong et al., 2019), with equivalent N400 reductions to unpredictable words either semantically or orthographically related to contextually predictable words, as well as an increased pPNP to the orthographic condition. These results suggest that lexical prediction can occur rapidly and does not necessarily require additional time beyond that needed for semantic preactivation. Our findings also offer strong evidence that form preactivation can be a vital mode of sentence comprehension even when processing resources are more limited, at reading rates typical of healthy, college-educated adults. Also, unlike some previous ERP studies testing for word form prediction using pseudowords or letter strings, the current study relied exclusively on real word sentences, with the only task being to read and answer

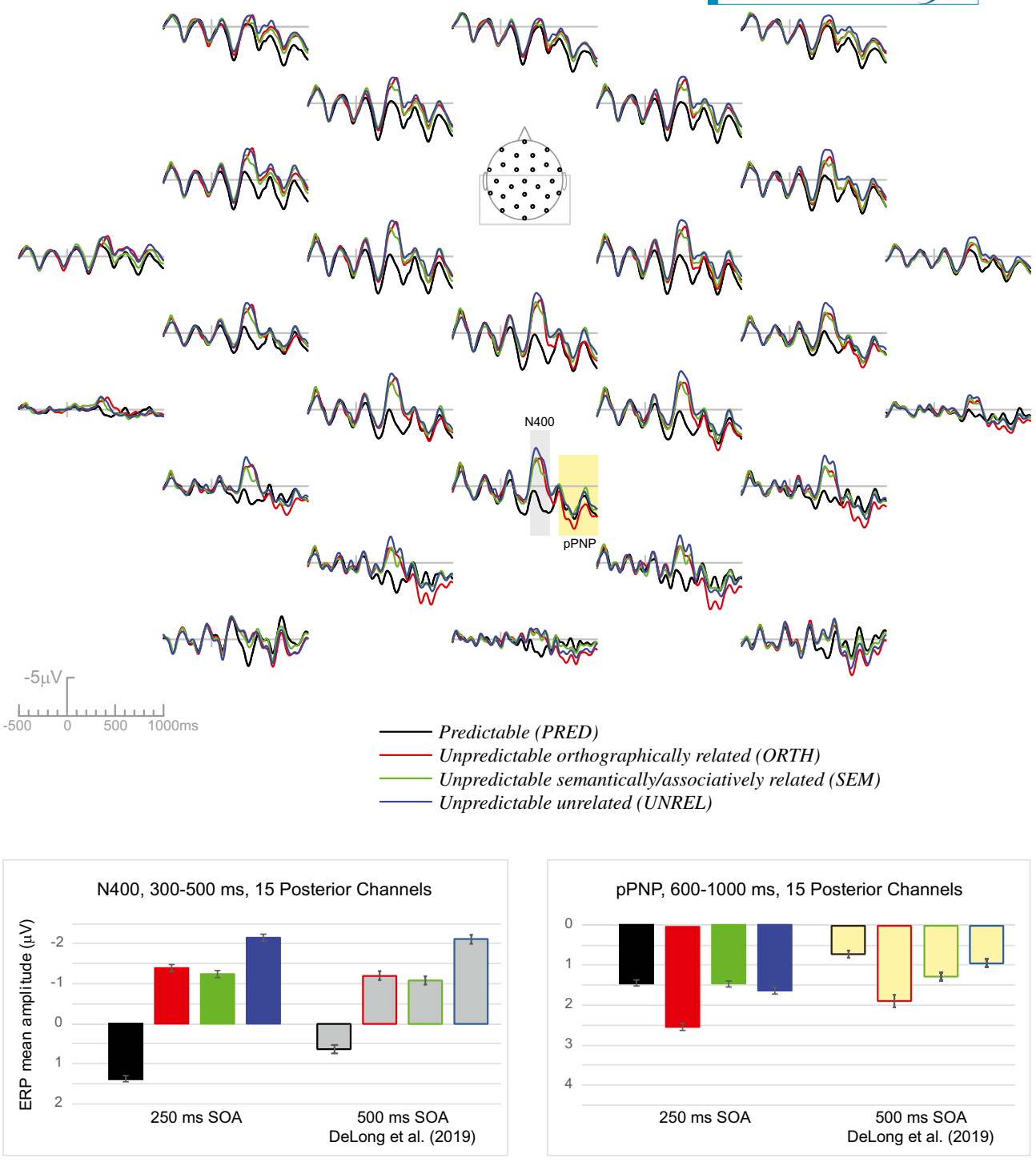

FIGURE 1 Grand average ($N = 24$) ERPs recorded over 26 scalp channels, negative voltage plotted up. The boxed area on the schematic scalp diagram indicates the 15 posterior electrodes included in the N400 and posterior PNP statistical analyses. The N400 analysis time window (300–500 ms) is highlighted in gray and the posterior PNP time window (600–1,000 ms) in yellow. Bar plots of the mean amplitude measures for the conditions in these two time windows are shown, with error bars indicating SEM. Data from the current 250 ms SOA experiment are shown in color on the left portion of each bar graph, and the 500 ms SOA data from DeLong et al. (2019) are displayed to the right.

comprehension questions, thus ruling out word form prediction being attributable to those specific experimental design features. Our finding of a form-related N400 amplitude reduction at a reading rate of four words/s presents a challenge for a prediction-by-production comprehension model like the one proposed by Ito et al. (2016), which posits that even a reading rate of two words/s is too rapid to support word form preactivation. Their timing for word form activation is based on production models like that of Indefrey and Levelt (2004), where up to 600 ms is required to complete a word's

	N400 (300–500 ms)			Posterior PNP (600–1,000 ms)		
ORTH	88.12***			7.54*		
SEM	43.67***	.21 ns		.95 ns	9.76**	
UNREL	160.94***	6.68*	7.02*	.56 ns	4.31*	.22 ns
	PRED	ORTH	SEM	PRED	ORTH	SEM

TABLE 2 *F*-ratios for pairwise comparisons of four levels of condition in two time windows over 15 posterior channels

Note: F-ratios with (1,23) degrees of freedom for each test.
ns $p > .05$, *$p < .05$; **$p < .01$; ***$p < .001$.

phonetic encoding. Clearly, our finding of a form-related N400 reduction between 300 and 500 ms for words presented 4 per second is inconsistent with that proposed timing. The current results are more consistent with results from similar, albeit slower presentation rate, ERP studies (e.g., DeLong et al., 2019; Kim & Lai, 2012; Laszlo & Federmeier, 2009), as well as findings from other experimental paradigms that indicate rapid activation of word form information (e.g., orthographic priming studies and speech error data; see Grainger & Jacobs, 1999, and Meyer, 1992, respectively, for reviews).

The current N400 findings offer some of the clearest evidence to date that word forms, and not just semantic information, can be preactivated at near-normal reading rates. However, it is important to consider this finding in light of other data suggesting a less consistent role for predictive processing with faster input (in particular Ito et al., 2016, but also Wlotko & Federmeier, 2015, and DeLong, 2009). These variable observations of word form prediction suggest that while the brain's processor is *capable* of anticipating predictable upcoming words, it is likely that other factors are mitigating linguistic prediction's engagement, speed, efficacy, or strength. DeLong et al. (2019) list and examine in-depth some of the particular experimental differences between that study and Ito et al. (2016) that could have contributed to the differing data patterns, with the same experimental differences holding for the current study. These included experimental design factors such as the overall stimulus probabilities or explicit or implicit task constraints, and stimulus factors such as critical word lexical properties, sentence structure or length, or critical word position. To this list one might add individual or population variability, due to differences in reading or processing speed, verbal fluency, or language experience—factors that are known to influence prediction; however, this possibility seems less likely, since the current experiment and DeLong et al. (2019) obtained similar results across unique sets of participants. These and potentially other proposals will require further investigation. What such differences do indicate, however, is that input rate alone cannot be the delimiting factor for preactivation of specific word forms—a phenomenon that should be considered in both the broader experimental and extra-experimental contexts.

The other observation made for the form-related words in the current study is that they exhibited a significant posterior post-N400 positivity (pPNP) relative to the other conditions. This pattern was also present in our 500 ms SOA report (DeLong et al., 2019), as well as across multiple studies using orthographic related anomaly paradigms and at a variety of presentation rates (250 ms SOA, current study; 500 ms SOA, DeLong et al., 2019; Ito et al., 2016; Laszlo & Federmeier, 2009; 550 ms SOA, Kim & Lai, 2012; and 700 ms SOA, Ito et al., 2016). Although a functional explanation of this effect remains elusive, its consistency across studies is intriguing. There was, however, no increased pPNP to the SEM condition relative to PRED in the current study, an effect that was observed at the 500 ms SOA (DeLong et al., 2019). While this interexperimental difference could be of potential interest, it is also worth noting that later posterior positivities like the one observed here are generally more subject to individual variation (see Kos et al., 2012).

In conclusion, the current replication of ERP word form preactivation findings at a visual presentation rate of four words/s indicates that the processing of written word form information can be rapidly facilitated through context-based expectancies. These findings also reveal that if there is a time constraint for word form preactivation, it is far less than the 700 ms proposed under some prediction-by-production comprehension models; in fact, the current findings demonstrate that any limit must be less than 250 ms. Ultimately, these results are important because the *absence* of a word form prediction effect at a two word/s input rate was crucial for the predictive comprehension model proposed by Ito et al. (2016). The current findings, in conjunction with those from DeLong et al. (2019), point to the implausibility of such time consuming, production-like stages, indicating that word form prediction must occur via an alternative mechanism—one in which language input can be rapidly processed to facilitate comprehension of predictable words even under timing constraints approximating those of natural reading in young adults.

CONFLICT OF INTEREST

The authors confirm that there are no known conflicts of interest associated with this publication, and there has been no significant financial support for this work that could have influenced its outcome.

AUTHOR CONTRIBUTION

Katherine A. DeLong: Conceptualization; Data curation; Formal analysis; Investigation; Visualization; Writing-original draft; Writing-review & editing. **Wen-Hsuan Chan:** Data curation; Formal analysis. **Marta Kutas:** Funding acquisition; Resources; Supervision; Writing-review & editing.

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