HHS Public Access

Author manuscript

Cortex. Author manuscript; available in PMC 2016 July 01.

Published in final edited form as:

Cortex. 2015 July ; 68: 20–32. doi:10.1016/j.cortex.2015.03.014.

Time for prediction? The effect of presentation rate on predictive sentence comprehension during word-by-word reading

Edward W. Wlotko[a,1] and **Kara D. Federmeier**[a,b,c]

Kara D. Federmeier: kfederme@illinois.edu

[a]Department of Psychology, University of Illinois, 603 E. Daniel Street MC 716, Champaign, IL 61820

[b]Beckman Institute, University of Illinois, 603 E. Daniel Street MC 716, Champaign, IL 61820

[c]Program in Neurosciences, University of Illinois, 603 E. Daniel Street MC 716, Champaign, IL 61820

Abstract

Predictive processing is a core component of normal language comprehension, but the brain may not engage in prediction to the same extent in all circumstances. This study investigates the effects of timing on anticipatory comprehension mechanisms. Event-related brain potentials (ERPs) were recorded while participants read two-sentence mini-scenarios previously shown to elicit prediction-related effects for implausible items that are categorically related to expected items (*'They wanted to make the hotel look more like a tropical resort. So along the driveway they planted rows of* PALMS/PINES/TULIPS.'). The first sentence of every pair was presented in its entirety and was self-paced. The second sentence was presented word-by-word with a fixed stimulus onset asynchrony (SOA) of either 500 ms or 250 ms that was manipulated in a within-subjects blocked design. Amplitudes of the N400 ERP component are taken as a neural index of demands on semantic processing. At 500 ms SOA, implausible words related to predictable words elicited reduced N400 amplitudes compared to unrelated words (PINES vs. TULIPS), replicating past studies. At 250 ms SOA this prediction-related semantic facilitation was diminished. Thus, timing is a factor in determining the extent to which anticipatory mechanisms are engaged. However, we found evidence that prediction can sometimes be engaged even under speeded presentation rates. Participants who first read sentences in the 250 ms SOA block showed no effect of semantic similarity for this SOA, although these same participants showed the effect in the second block with 500 ms SOA. However, participants who first read sentences in the 500 ms SOA block continued to show the N400 semantic similarity effect in the 250 ms SOA block. These findings add to results showing that the brain flexibly allocates resources to most effectively achieve comprehension goals given the current processing environment.

Corresponding author: Edward W. Wlotko, phone: (217) 333-0631, fax: (217) 244-5876, ewwlotko@alumni.pitt.edu.
1Present address: Department of Psychology and Sackler School of Graduate Biomedical Sciences, Tufts University, 490 Boston Avenue, Medford, MA 02155, phone: (617) 627-3523, fax: (617) 627-3181

Keywords

prediction; sentence processing; timing; event-related potentials; N400

Introduction

The ability to learn and exploit regularities in the environment is a fundamental feature of the nervous system (Bar, 2011). As such, the anticipatory use of sensory information in a context-sensitive manner underlies neural responses associated with many levels of processing, from early perceptual effects through complex higher level cognition. Indeed, a great deal of evidence has accumulated pointing toward prediction as a core component of normal human language processing. The use of contextual cues in the language stream can allow the pre-activation of features of likely upcoming input at multiple levels and grains of representation (see, e.g., Kutas, DeLong, & Smith, 2011). In this study, we examine the role of timing in the ability of predictive processing to affect on-going semantic processing during sentence comprehension.

Event-related brain potentials (ERPs) have provided key evidence for anticipatory language processing mechanisms. As a direct measure of neural activity with millisecond-level temporal resolution, the technique provides a view of ongoing brain activity as it occurs in real time. Furthermore, ERPs can be measured continuously and without an overt secondary task over and above attending to and comprehending language. Therefore, brain responses can be measured before, during, and downstream from experimental manipulations of predictability.

In a series of ERP studies designed to probe interactions between contextual influences on word processing and the structure of semantic memory, Federmeier and colleagues showed that two-sentence mini-discourse contexts that constrain for a particular sentence completion can lead to pre-activation of semantic features of expected words (Federmeier & Kutas, 1999a,b, 2002). For example, given the context, *'They wanted to make the hotel look like a tropical resort. So, along the driveway, they planted rows of…'* many people[1] would expect the sentence to end with the word *'palms'*. Consistent with all ERP studies of sentence comprehension, brain responses showed an effect of semantic context, evident in a comparison between expected words and words that violate expectations. In Federmeier et al.'s studies, message-level expectations were violated with words of a different semantic category than expected words, such as the completion *'tulips'* in the example sentence. This effect was apparent on the N400 component of the ERP, a neural measure of the demands on semantic processing. An observed reduction in the amplitude of the N400 is interpreted as evidence of facilitated semantic processing (for a complete discussion see Kutas & Federmeier, 2011). Thus, expected words elicit smaller N400 amplitudes than words that violate contextual constraints, taken as an indication that the context has 'eased' processing of the meaning of the expected word.

1In studies of prediction in sentence comprehension, expectancy is typically operationalized by cloze probability (Taylor, 1953), the empirically estimated proportion of individuals who would complete a particular context with the same word.

The critical manipulation in this paradigm is a third type of stimulus that also violates message-level expectations but that overlaps significantly in semantic features with the word expected in each context. This condition was created by choosing words from the same semantic category as the expected word (e.g. *'pines'*). These 'within-category' violations elicited N400 amplitudes intermediate in size compared to the expected words and the 'between-category' violations. Thus, brain responses showed simultaneous effects of contextual expectations and the out-of-context structure of semantic memory. Importantly, this pattern provides evidence that the brain can use context to pre-activate semantic features of upcoming words. The logic of this inference rests on the observation that both within- and between-category violations disconfirm message-level expectations, so that neither type of word is an appropriate completion to the context. The reduction in N400 amplitude for the within-category violations, therefore, is due to the contextual pre-activation of semantic features of the expected (but never presented) words, which overlap to a greater degree with the features of the within-category violations compared to between-category violations. Further support for this interpretation of the results was provided by an examination of constraint: this semantic similarity effect was larger in strongly constraining (more predictable) contexts compared to less constraining contexts.

In addition to providing evidence for contextual pre-activation of semantic features, ERP studies have also demonstrated that the brain can generate predictions of orthographic, grammatical/syntactic, and phonological features of words (Laszlo & Federmeier, 2009; Wicha, Moreno, & Kutas, 2004; Van Berkum, Brown, Zwisterlood, Kooilman, & Hagoort, 2005; DeLong, Urbach, & Kutas, 2005). Similar findings have been reported in studies using other paradigms and methodologies, such as behavioral decision times and eye-tracking (Schwanenflugel & LaCount, 1985; Kamide, Altmann, & Haywood, 2003).

In light of this large body of evidence, the predictive nature of typical language comprehension is well established. However, prediction is not necessarily engaged to the same extent across all processing circumstances. For example, recent work on second language acquisition suggests that native-like prediction may depend on factors such as proficiency and similarity of the first and second languages (Foucart et al., 2014; cf. Martin et al., 2013; Kaan, 2014). Additionally, age-related changes may lead to decreased reliance on contextual pre-activation for older adults (see Wlotko, Lee, & Federmeier, 2010). Recently, we have demonstrated that monolingual young adults, too, fail to pre-activate predictable words when placed in an environment that reduces the validity of contextual cues for predicting a specific word in a given context. For example, when strong predictions are violated with synonyms of the predictable words, electrophysiological signs of prediction are diminished (Wlotko & Federmeier, 2011). This flexibility in the implementation of anticipatory comprehension mechanisms suggests that predictive processing is at least partially resource-dependent.

We have argued that predictive comprehension arises through production-like mechanisms (Federmeier, 2007; cf. Pickering & Garrod, 2013; MacDonald, 2013). That is, neural systems that subserve language production are engaged during ongoing language comprehension. This view was motivated in part by exploring hemispheric asymmetries in context effects[2] (reviewed in Federmeier, 2007; Federmeier, Wlotko & Meyer, 2008). We and others have observed that although "typical" comprehension patterns often manifest as a blend of the responses from each hemisphere (Wlotko &Federmeier, 2007, 2013; Ayedelott et al., 2012), effects attributable to prediction are observed only with left hemisphere (LH) biased processing. In contrast, right hemisphere (RH) patterns are consistent with what has been termed "integrative" comprehension: rather than pre-activating representations in advance of occurrence, context effects are based on the integration of each word with the prior message-level representation as it is encountered.

These distinct comprehension mechanisms may be distributed across the hemispheres because production mechanisms are strongly left-lateralized in the large majority of right-handed adults. Therefore, robust top-down connectivity between frontal and posterior language regions is instantiated to a greater degree in the left hemisphere (Catani et al., 2007; Glasser & Rilling, 2008). Such anatomical and functional connections may underlie contextual effects based on prediction in language comprehension.

Further support for this framework is provided by evidence that older adults with higher verbal fluency scores — a measure of language production ability — tend to show younger-like predictive effects in comprehension (Federmeier et al., 2002, 2009, 2010). Additionally, for both older and younger adults, individuals that show larger effects attributed to anticipatory processing are less likely to elicit brain responses associated with reinterpretation of prior context (Wlotko & Federmeier, 2012a).

Taken together, these findings reveal that predictive mechanisms are malleable based on age-related, individual, and situational factors. Our framework suggests that contextual pre-activation during comprehension is dependent on top-down processing rooted in neural systems supporting language production. If such resources are unavailable (e.g. in older adults, especially those with lower verbal fluency ability) or are unable to appropriately affect ongoing processing (e.g. when the predictive validity of contextual cues is reduced), the brain may rely on a non-predictive mode of comprehension. As such, not all context effects are attributable to contextual pre-activation. For example, sentence congruency effects are observed in all cases in which evidence for pre-activation is diminished, including for older adults and RH-biased processing. Thus, we have argued that multiple neurocognitive pathways can lead to successful comprehension (Wlotko & Federmeier, 2012b).

These distinct modes of comprehension can result in different processing advantages or disadvantages across circumstances. The proclivity of the language system to use context predictively is thought to result in increased processing efficiency when predicted stimuli are encountered. This 'head-start' on processing may be one way the brain contends with the many challenges of language processing, including multifaceted ambiguity and a high degree of noise in which the signal is embedded (e.g., Van Petten & Luka, 2012; Kuperberg,

2In most cases, this type of inference relies on exploiting the contralateral organization of the visual system. These studies use the visual half-field (VF) technique, in which stimuli are presented in the left or right half of the visual field, preferentially stimulating and biasing processing to the contralateral hemisphere (Banich, 2002). Patterns of response variables (e.g., reaction times or ERP amplitudes) are compared as a function of VF of presentation. Differences in these patterns lead to inferences about underlying hemispheric asymmetries.

2013). Thus, predictive processing may contribute to the experience of seemingly effortless use of language in everyday comprehension circumstances.

However, in order for anticipatory comprehension to yield such processing benefits, predictions must be generated in advance of the predictable input. Therefore, timing may impact the likelihood that predictive processing can affect ongoing comprehension. Investigations of timing on sentence processing mechanisms, using speeded word-byword visual presentation or time-compressed speech, generally show minimal effects of input rate on behavioral or neural responses, or similar response patterns that are delayed relative to those obtained in "normal" processing conditions (Adank & Devlin, 2010; Vagharchakian, et al., 2012). However, such contrasts are typically based on simple comprehension questions or overall congruency effects. Here, we focus specifically on anticipatory comprehension mechanisms. If prediction in language comprehension relies on production-like mechanisms, as we propose, then context effects associated with pre-activation of predictable input may be more likely to be affected by presentation rate.

To assess the impact of timing on sentence processing mechanisms, we use the same design manipulating contextual fit and semantic similarity that Federmeier and colleagues have shown many times to robustly elicit N400 effects associated with contextual pre-activation of semantic features. Sentence presentation rate was manipulated in a blocked design. In one condition, word-by-word sentences were presented with a stimulus onset asynchrony (SOA) of 500 ms (2 words/second), as in prior studies using this paradigm. In the other condition, words appeared with an SOA of 250 ms (4 words/second).

As the 500 ms SOA is a direct replication of past studies, N400 amplitudes should follow the graded pattern observed previously: largest for between-category violations, smallest for expected words, and intermediate for within-category violations. The primary question of this study is whether N400 patterns vary as a function of presentation rate. A within-subjects design allows an examination of both the overall N400 expectancy effect and the prediction-related N400 semantic similarity effect in the same participants for the two presentation rates. As overall context effects are often robust to speeded presentation rates, we expect little influence on the N400 expectancy effect, such that N400s for expected words should be smaller than for violation words in both SOA conditions.

However, speeded presentation may have a greater effect on prediction-based context effects. One possibility is that top-down mechanisms crucial for generating predictions act too slowly for semantic features to become activated in time to affect ongoing word processing at fast presentation rates. Alternatively, speeded presentation may tax the comprehension system such that fewer resources are allocated to top-down mechanisms. In either case, the prediction-related semantic similarity effect would be smaller with sufficiently fast presentation rates. Thus, a failure to observe evidence for predictive processing with speeded presentation in the same participants who show such effects at slower rates would establish that qualitatively different mechanisms of comprehension can be engaged as a function of time.

As N400 latency is typically stable across experimental manipulations (Federmeier & Laszlo, 2009), these hypotheses are focused on patterns of N400 amplitude. However, speeded presentation could alter the overall latency of the N400 component or the timing of N400 context effects under some circumstances (e.g. Kutas, 1987). Therefore, we examine peak latencies of N400 components and N400 effects across the two presentation rates to determine whether the SOA manipulation affects the timing of the processes indexed by the N400.

Finally, SOA block order was counterbalanced between subjects. Examining whether timing effects are dependent on block order potentially provides some insight into whether the impact of timing on prediction is absolute or may be dependent on recent experience.

2. Method

2.1. Subjects

Twenty-four native English speakers were recruited into the experiment at the University of Illinois at Urbana-Champaign. Two additional volunteers participated in the study, but their data were not included in the final analysis due to unacceptably high levels of EEG artifact. Potential participants were screened for the exclusionary criteria of exposure to other languages before age 5, history of psychiatric or neurological diagnoses or injury, and use of any neuro-active medications within the previous 6 months. Mean age was 19.2 years (range 18–23 years); 13 subjects were female and 11 were male. All participants were right-handed by self-report (4 with at least one left-handed immediate family member) and as assessed with the Edinburgh Handedness Inventory (Oldfield, 1971), with mean handedness quotient of 0.73. Participants were remunerated with course credit for their time. All volunteers provided written informed consent before participating in the experiment and all protocols were reviewed and approved by the University of Illinois Institutional Review Board.

2.2 Materials

The stimulus set was identical to that used in several prior published studies (Federmeier & Kutas, 1999a,b, 2002). In brief, 33 two-sentence mini-scenarios were created such that the context (‘They wanted to make the hotel look like a tropical resort. So, along the driveway, they planted rows of …’) constrained for a particular imageable word (‘palms’) from a common semantic category (e.g., trees). For each of these stimuli, a second two-sentence scenario was created that constrained for a word from the same semantic category as the first stimulus (‘The air smelled like a Christmas wreath and the ground was littered with needles. The land in this part of the country was just covered with … ‘pines’). The ‘within-category violation’ condition was formed by swapping the expected words from these two scenarios. Next, for each of these sets of stimuli, two more scenarios were created that each constrained for a word from a semantic category (e.g., flowers) that shared coarse-grained features with the initial category pair (‘The gardener really impressed his wife on Valentine’s Day. To surprise her, he had secretly grown some… ‘roses’ and ‘The tourist in Holland stared in awe at the rows and rows of color. She wished she lived in a place where they grew … ‘tulips’). The expected words from these scenarios were swapped with the expected words from the initial pair to create the ‘between-category’ violation condition.

Mean constraint of the contexts (cloze probability for expected words) was 0.74 (range 0.17 to 1.0). Cloze probability for both violation conditions was always near 0.

These 33 sets of 4 sentence contexts were randomly assigned to three groups of 11 sets each. These groups were combined into lists so that all 132 scenarios appeared in each list. The critical words appeared only once within each list, but in all three conditions across the lists. Thus, each list contained 44 items in each of the three conditions. To balance the number of "expected" and "violating" sentence completions in the experiment, 44 two-sentence scenarios that were constructed in the same way as the other stimuli were completed with expected endings and added to each of the lists. Table 1 presents several more examples of the scenarios. See the prior published studies for further details on how stimuli were constructed and controlled.

2.3. Procedure

Participants were seated 100 cm in front of a 21″ CRT monitor in a darkened room. All stimuli were presented in black Arial font on a white background. The first sentence of every mini-scenario was presented in its entirety. This portion of the trial was self-paced. Participants advanced the trial with a button press. The screen was cleared and a warning sign was presented that consisted of several pluses in the center of the screen displayed for 500 ms, with a variable inter-stimulus interval (ISI) that ranged from 500 to 1200 ms in order to reduce brain potentials associated with anticipation of the upcoming stimuli. The second sentence of the scenario was presented word- by-word in the center of the screen with a fixed SOA that was manipulated within-subjects in a blocked design. In one block, each word was presented for 200 ms with an ISI of 300 ms (500 ms SOA). This is a direct replication of prior published studies. In the other block, words were presented for 200 ms with a 50 ms ISI (250 ms SOA). After a 3 second pause, the next trial was initiated automatically.

Stimuli were randomly ordered and then divided into two halves ("A" and "B"), such that an equal number of trials from each experimental condition appeared in each subset. The order of SOA block and order of stimulus subset was fully counterbalanced across participants, along with experimental list. Thus, half of the participants experienced the 500 ms SOA and then the 250 ms SOA, and, of these, half of the participants read set A in the 500 ms SOA and set B in the 250 ms SOA, with each experimental list represented an equal number of times in each counterbalancing combination.

Participants were instructed on the trial procedure; they were asked to read each two-sentence scenario and to 'try to understand what the sentences are saying in order to answer questions about the sentences at the end of the experiment'. They were asked to minimize muscle activity, eye movements, and blinking while reading the word-by-word sentences and during the blank screen that concluded each trial.

A short set of practice scenarios was presented to acclimate the participants to the experimental procedure. The session paused after approximately every 17 trials to give participants a short rest and a chance to communicate with the experimenter if necessary. At the end of the first SOA block, the experimenter stopped the session and gave participants a longer break. Participants were told that the second half of the experiment would continue in exactly the same way, except that they would notice a change in the pace of the word-by-word sentences. Before beginning the second experimental block, participants read an additional set of practice scenarios with sentences presented at the new SOA.

At the conclusion of the second block, participants completed a recognition memory test consisting of 50 two-sentence mini-scenarios. Three versions of the test were created such that for each experimental list, 20 of the scenarios were identical to stimuli in the experiment (10 with expected endings, 5 with within-category violations, and 5 with between-category violations), 20 of the scenarios were modified from the experimental stimuli such that the sentence-final critical word was changed (10 violations changed to expected words and 10 expected words changed to violations), and 10 scenarios were not seen in the experiment. Participants were asked to indicate for each item whether the scenario was “old”, “similar”, or “new”. For the scenarios marked as “similar”, they were asked to attempt to produce the word that was actually seen in the context during the experiment.

2.4. EEG recording and processing

EEG was recorded from 26 evenly spaced silver-silver chloride electrodes embedded within an Electrocap (the montage is illustrated in the schematic head diagram in Figure 1), referenced online to the left mastoid. Horizontal and vertical electrooculogram channels were also recorded to monitor eye movements. Recording sites were prepared such that electrode impedances were kept below 4 kΩ. All signals were digitized with Sensorium amplifiers using a 250 Hz sampling rate and analog filtering at a bandpass of 0.02 to 100 Hz.

EEG epochs time-locked to critical words (spanning 100 ms pre-stimulus onset through 920 ms post-stimulus onset) were screened for artifacts using semi-automatic detection procedures with thresholds individually adjusted for each participant. Eye blinks were corrected with a spatial filter as described in Dale (1994), except for 3 participants with very few epochs containing blinks. All other epochs that exceeded rejection thresholds were removed from further analysis. Overall trial rejection rate was 6.3%. ERPs were averaged according to ending type and SOA condition. All averages contained at least 16 trials for all participants (mean number of trials per bin across participants averaged between 20 and 21 trials for each ending type in the two SOA conditions). The averaged waveforms were re-referenced offline to the algebraic mean of the left and right mastoids and baseline corrected using the 100 ms pre-stimulus interval. Mean amplitudes were measured after applying a 0.2–20 Hz bandpass filter. Peak measurements were obtained after applying a 0.2–8 Hz bandpass filter in order to reduce spurious peak measurements due to higher frequency noise. All peak measurements were verified with visual inspection on individual subject ERPs.

Except where noted, analyses were performed with repeated-measures ANOVA and planned comparisons were conducted based on the results from past experiments and the hypotheses of the current study. For tests with greater than 1 degree of freedom in the numerator, results are reported with the Greenhouse-Geisser correction for sphericity applied to p-values, along with the epsilon value and the original degrees of freedom. For the main experimental contrasts of interest, 95% confidence intervals on the mean difference were constructed using the MATLAB bootci function with one million bootstrap samples and the widely recommended bias corrected and accelerated percentile (BCa) procedure (DiCiccio & Efron, 1996).

3. Results

3.1. Recognition test

On average, participants correctly endorsed as "old" 17.1 of the 20 (85.6%) recognition test items that were identical to experimental stimuli and correctly classified as "new" 9.5 of the 10 (95%) items not seen during the experimental session. Participants correctly recognized 13.9 of the 20 (69.6%) "similar" items that were modified from the experimental session, and were able to recall the sentence-final word that was actually presented in the session for 11.9 of those items on average.

For incorrectly classified items, participants were most likely to mistake modified sentences for items that were read during the experiment ("similar" items marked as "old", average 4.4 items). Participants were somewhat less likely to incorrectly report that items identical to experimental stimuli were modified ("old" marked as "similar", average 1.5), or to fail to recognize the identical ("old" marked as "new", average 1.4) or modified ("similar" marked as "new", average 1.7) items. Only a few participants incorrectly endorsed any of the items that were not seen during the experimental session as identical ("new" marked as "old", average 0.3) or modified ("new" marked as "similar", average 0.2) from the experimental session.

These results are in agreement with the past studies using this paradigm and confirm that participants were attending to the experimental material during EEG recording.

3.2 ERPs

Grand average ERPs for the two SOA conditions are presented in Figure 1. Presentation rate affects overall ERP morphology due to the differential component overlap in the two SOA conditions. With a 250 ms SOA, the ERP to the sentence-final critical word is superimposed on the visual sensory potentials elicited by the penultimate word. In both SOA conditions, the N400 is observed as a broadly distributed negative-going potential peaking around 400 ms post-stimulus onset that varies in amplitude by sentence ending type.

3.2.1. N400 latency—Before examining patterns of N400 amplitude as a function of SOA condition, peak latency of the N400 component was analyzed to determine whether presentation rate had any measureable effect on the timing of the component peak.

Negative peak latency between 250 and 550 ms post-stimulus onset was measured at the six medial central-parietal electrode sites for all expected sentence final words (including fillers) and all contextual violations (collapsed across category type). A repeated measures ANOVA did not uncover any effects of SOA condition or sentence ending type ($Fs<1$). Overall, the N400 component peaked at 366.5 ms in the 500 ms SOA condition and at 367.5 ms in the 250 ms SOA condition.

3.2.2 N400 amplitude—N400 amplitude was quantified for each sentence ending type (expected, within-category violation, or between-category violation) in both the 500 and 250 ms SOA conditions. Mean amplitudes from 300–500 ms post-stimulus onset were computed at all 26 electrode sites. An omnibus repeated-measures ANOVA revealed main effects of SOA condition [$F(1,23)=37.75$, $p<.0001$] and Ending type [$F(2,46)=30.45$, $p<.0001$, $\varepsilon=0.9481$], and an interaction of SOA and Ending type [$F(2,46)=4.58$, $p=0.017$, $\varepsilon=0.8335$]. Additionally, there were main effects of Electrode [$F(25,575)=6.75$, $p<0.001$, $\varepsilon=0.1569$] and interactions of SOA×Electrode [$F(25,575)=8.71$, $p<0.001$, $\varepsilon=0.1747$] and Ending type×Electrode [$F(50,1150)=8.00$, $p<0.001$, $\varepsilon=0.1148$], but no significant three-way interaction of SOA×Ending type×Electrode [$F(50,1150)=1.49$, $p=0.1734$, $\varepsilon=0.1358$].

3.2.3 N400 effects—To examine the significant interaction between SOA condition and Ending type on patterns of N400 amplitudes, ERP effects are examined with a point-by-point subtraction (difference wave) for contrasts of interest, compared across the two SOA conditions. The N400 expectancy effect is defined as the subtraction of the ERP for expected endings from the ERP for between-category violations. The N400 semantic similarity effect is formed by subtracting the ERP for the within-category violations from the ERP for the between-category violations. These subtractions remove overall ERP differences due to SOA and isolate the effect of message-level congruity (expectancy) and semantic feature overlap with predictable words (semantic similarity), both relative to message-level violations without a categorical relationship to expected items. Mean amplitudes for N400 effects were computed from 300–500 ms post-stimulus onset at all electrode sites. Figure 2 shows topographic voltage maps for the expectancy effect and the similarity effect in both SOA conditions during the N400 time window.

For the expectancy effect, there was not evidence for a modulation by SOA condition [$F(1,23)=1.59$, $p=0.219$; no interaction with electrode, $F(25,575)=1.38$, $p=0.26$, $\varepsilon=0.1376$]. Pairwise comparisons on unsubtracted waveform amplitudes confirmed that N400s to between-category violations were more negative than N400s to expected words for both the 500 ms SOA [$F(1,23)=15.00$, $p<0.001$] and the 250 ms SOA [$F(1,23)=40.00$, $p<0.001$].

There was, however, an effect of SOA on the size of the semantic similarity effect, with a significantly smaller effect for the 250 ms SOA ($F(1,23)=5.29$, $p=0.031$; no interaction with Electrode, $F(25,575)=1.76$, $p=0.16$, $\varepsilon=0.1337$). In line with this result, the unsubtracted waveform pairwise comparisons revealed that N400s to between-category violations were more negative than N400s to within-category violations for the 500 ms SOA [$F(1,23)=16.63$, $p<0.001$), but there was not evidence for this difference for the 250 ms SOA [$F(1,23)=2.68$, $p=0.115$].

These contrasts comprise the primary effects of interest for this study. Therefore, Table 2 presents the 95% confidence intervals for the mean difference in each contrast for both SOA conditions. All of the intervals exclude 0 except for the similarity effect in the 250 ms SOA. This interval indicates the maximum plausible mean difference for the similarity effect at the 250 ms SOA is −1.5 μV. In line with the significant interaction between SOA and the similarity effect, the confidence interval for the similarity effect in the 500 ms SOA indicates a plausible mean difference as large as −2.5 μV but no smaller than −0.9 μV.

Peak latencies of the N400 effects were also measured. A repeated measures ANOVA revealed no significant effects for SOA condition or N400 effect type on peak latency of the difference waves measured between 250 and 550 ms at the six medial central-parietal channels. Overall effects peaked at 394 ms (500 SOA-expectancy: 383.9 ms; 500 SOA-semantic similarity: 394.7 ms; 250 SOA-expectancy, 388 ms; 250 SOA-semantic similarity: 409 ms)[3]. Thus, as for peak latency of the N400 component, we did not find evidence that the SOA manipulation affected the timing of the effects on the N400.

3.2.4 Exploratory analysis of SOA block order—An initial exploratory ANOVA with a factor of block order did not reveal an interaction of block order with sentence ending type and SOA [F(1,22)=2.16, p=0.1557]. However, inspection of ERPs for the two groups of subjects revealed a strikingly different pattern of effects as a function of block order. Thus, we analyzed N400 effects for the two groups separately. For those subjects who received the 250 ms then the 500 ms SOA block, the results mirrored the overall pattern, with main effects of SOA [F(1,11)=9.47, p=0.012], Ending type [F(2,22)=15.19, p<0.001, ε=1.000], and a SOA×Ending type interaction [F(2,22)=5.05, p=0.016, ε=0.8966]. For those who received the 500 ms and then the 250 ms SOA, there was a main effect of SOA [F(1,11)=48.31, p<0.011] and Ending type [F(2,22)=15.51, p<0.001, ε=0.9589], but no interaction of SOA×Ending type [F(2,22)=0.74, p=0.49, ε=0.7659].

To specifically investigate the effect of SOA order on the prediction-related semantic similarity effect, difference waves for this effect were once again analyzed across SOA conditions for the two groups. The SOA effect for group who received the 250 ms SOA before the 500 ms SOA approached significance [F(1,11)=4.30, p=0.06, no interaction with electrode], but there was no evidence of an effect of SOA on the semantic similarity effect for participants who experienced the 500 ms SOA before the 250 ms SOA [F(1,11)=1.15, p=0.31, no interaction with electrode]. No effects of block order were observed for the expectancy effects (all p's>0.2).

Figure 3 shows the size of the N400 semantic similarity effect in both SOA conditions as a function of order of SOA block, in addition to ERPs for all three ending types in each of these conditions. The diminished semantic similarity effect for the 250 ms SOA seems to be driven by the group who received this faster-paced block in the first half of the experiment. Participants who first experienced the 500 ms SOA showed some evidence of a semantic similarity effect in the 250 ms SOA. Therefore, post-hoc pairwise comparisons were performed for the similarity effect in the 250 ms SOA condition only. This effect was significant for the group who received the 250 ms SOA after the 500 ms SOA [F(1,11)=4.58, p=0.05] but not for the group who received the 250 ms SOA in the first half of the experiment [F(1,11)=0.02, p=0.893].

Table 3 contains the 95% confidence intervals for the N400 effects of interest, separately for the two block orders. For the group who received the 250 ms SOA first, the confidence interval is centered around 0 and indicates that the largest plausible value for the effect is

3As there is little evidence of a semantic similarity effect in the 250 ms SOA condition, measurement of peak latency is less informative. Nevertheless, the analysis did not reveal an effect of SOA block on peak latency of this effect.

−1.1 μV, which is smaller than any of the other observed mean differences in the experiment. For the group who received the 250 ms SOA after the 500 ms SOA, the confidence interval does not include 0 and the upper limit on the size of the N400 effect is −2.4 μV, similar to the size of the intervals for the similarity effect observed under the slower presentation rate.

4. Discussion

The predictive nature of language comprehension is well documented. The brain routinely exploits contextual cues to anticipate likely upcoming information at various grains and levels of processing. However, prediction is not obligatorily engaged to the same extent in all comprehension circumstances. We have argued that predictive mechanisms are flexibly implemented depending on factors such as availability of processing resources, comprehension goals or task set, and the validity of contextual cues in a particular situational environment. Here we examined the impact of timing on predictive comprehension mechanisms. The results demonstrate that timing can affect predictive comprehension, but that prior experience with prediction in the experimental environment may modulate the effect of timing.

We focused on prediction of semantic features via contextual information in two-sentence mini-scenarios. This paradigm has been shown to robustly elicit evidence of pre-activation of semantic features in young adults, as reflected in the N400 component of the ERP. That is, a word that violates message-level expectations but that shares semantic features with a word that is expected in the context elicits reduced N400 amplitude compared to violations with less semantic overlap of predicted features. In this study, we found that doubling the presentation rate of the sentence from 2 to 4 words per second (500 ms SOA vs. 250 ms SOA) diminished this prediction-related semantic facilitation effect.

Prior investigations of the impact of speeded presentation on comprehension generally show either normal patterns or quantitative effects on processing, such as slowed response times, up to a rate at which language becomes incomprehensible. Explanations for these results suggest that working memory resources act as a “buffer” for the incoming language stream when the rate of input outpaces comprehension mechanisms. Context effects may be delayed as a result of buffering, but are supposed to act similarly when operating on the buffered material (Vagharchakian et al., 2012; Poldrack et al., 2001). Thus, the idea is that comprehension is generally unaltered unless the capacity of the buffer is exceeded and comprehension breaks down completely. Other work has shown that comprehenders may form expectations about timing itself, such that changes in meter or rhythm in language can interact with syntactic and semantic processing (Schmidt-Kassow et al., 2009; Rothermich, et al., 2012).

However, these paradigms typically examine responses to basic comprehension questions or overall congruency effects. Here, we did not find evidence that the overall N400 expectancy effect differed across the SOA conditions. Additionally, we obtained no evidence suggesting that semantic processing as indexed by the N400 was delayed as a result of the speeded presentation. Thus, the SOA manipulation in this study did not globally alter basic context effects. Other ERP studies have also shown qualitatively similar N400 effects at even faster serial visual presentation (SVP) rates, although N400 effects were delayed at presentation rates of 10 words per second (Kutas, 1987).

Despite the similarity of the overall context effect across the two SOA conditions, the speeded presentation rate diminished the effect of semantic similarity on message-level violations during online comprehension. The N400 reduction for within-category violations (compared to between-category violations) is interpreted as reflecting the pre-activation of semantic features of predictable words. We take this pattern of results as evidence that qualitatively different processing patterns can be obtained as a function of timing parameters. That is, speeded presentation rates can result in a shift to a non-predictive mode of comprehension. Our within-subjects manipulation allowed us to show that subjects who fail to elicit evidence of contextual pre-activation at 250 ms SOA do show such effects at 500 ms SOA, which replicates past studies. These findings add to the evidence suggesting that predictive comprehension mechanisms are malleable.

Some aspects of the paradigm allow us to constrain the role of timing in affecting contextual pre-activation of semantic features. For example, the initial context sentence of every mini-scenario was crucial in setting up expectations; any of the three types of target words could plausibly complete the second sentence on its own. As in all past studies, participants had as much time as they wanted to read the context sentence because this part of every trial was self-paced. Therefore, this contextual information should have been equally available across the two SOA conditions. Thus, it is unlikely that the pattern of effects observed here could be explained by decay in semantic activation based on simple priming or spreading activation. Such an account would predict a larger semantic similarity effect in the 250 ms SOA, as the overall duration from the offset of the context sentence to the sentence-final critical word was reduced by half compared to the 500 ms SOA condition. Other studies have also ruled out such "passive" mechanisms as explanations for effects attributed to prediction (e.g., Otten & Van Berkum, 2008).

Rather, we associate predictive mechanisms with building up message-level representations and continual top-down contextual influences on comprehension. As context builds, all available cues in the ongoing language stream are used to generate predictions at various levels of processing as incoming words are encountered. Our findings indicate that pre-activation of semantic features based on these cues is sensitive to timing during online comprehension. As such, it is possible that a fast presentation rate does not allow the appropriate representations to be activated in enough time to affect semantic processing of upcoming words. Alternatively, speeded presentation may increase comprehension difficulty such that resources allocated to predictive mechanisms are diminished.

Before further discussing those possibilities, it is important to note that a rate of 4 words/second is not especially fast compared to typical eye-movement rates across text during natural reading, and 2 words/second is rather slow. However, the SVP procedure used in ERP studies is dissimilar to natural reading in important ways. For example, in natural reading, the rate is under control of the comprehender and can be varied. Additionally, readers can skip words, regress to prior words, and gain preview information before fixating words. In contrast, the reader has no control over the input in SVP. As such, direct comparisons to rates of natural reading may be uninformative in terms of consequences for comprehension processes.

Reading in an SVP environment with a 250 ms SOA is subjectively difficult according to debriefing of experimental participants. The self-reports of participants in this study parallel data from an experiment in which ERPs were recorded during word-by-word sentence reading, with the duration of each word controlled by participants rather than fixed by the experimenter (Ditman, Holcomb, & Kuperberg, 2007). Those participants reported that self-control of presentation rate felt more comfortable than a fixed SVP rate. When given control, participants' word reading times, while variable across people, averaged between 400–500 ms per word. Thus, when readers exert control over presentation rate in an SVP environment, their speeds are much closer to the rate of 2 words/second typical of SVP presentation in many ERP sentence processing studies compared to the 4 words/second that constitutes the faster rate in this study. Thus, ERP results obtained with presentation rates faster than 3 words per second may be less indicative of "normal" comprehension processes than the more typical rates of presentation in ERP studies.

It is worth noting that ERP results from Ditman et al. were essentially identical to those obtained with a fixed SOA of 400 ms, even with analysis procedures that attempted to compensate for the technical difficulties of signal averaging with non-constant stimulus durations. Additionally, ERP patterns obtained under typical word-byword reading conditions are often replicated using auditory presentation at normal speech rates. Critically, for example, Federmeier et al. (2002) observed evidence for contextual pre-activation during natural connected speech using the same categorical manipulation of message-level violations (and the same stimuli) as we used here. These results show unequivocally that N400 effects associated with predictive processing are not an artifact of the somewhat artificial SVP reading environment used in ERP studies.

On the other hand, we observed that a fast presentation rate during visual reading does not necessarily preclude predictive comprehension in an absolute way. Importantly, we counterbalanced order of the SOA blocks between subjects. Examination of N400 patterns as a function of block order provides the potential for further insight into the effect of timing on predictive comprehension mechanisms. N400 patterns for the group of participants who first received the 250 ms SOA block mirrored the results for the group analysis. That is, there was evidence of a semantic similarity effect in the 500 ms SOA condition but not in the 250 ms SOA condition, as well as a statistically significant interaction between SOA and ending type. This shows that the participants who first experienced speeded presentation failed to show evidence for pre-activation at the faster rate, although they then did so with slower presentation in the second half of the experiment. However, analysis of the group who experienced the 250 ms SOA after the 500 ms SOA showed some evidence for the semantic similarity effect in both SOA conditions. That is, participants who received the speeded presentation rate after experiencing the slower rate continued to show evidence for contextual pre-activation of semantic features even under speeded conditions. These analyses were exploratory, as the analysis of SOA block order was based on the striking differences observed in the semantic similarity effect across the two groups. Thus, although future work must substantiate these findings, the results suggest that timing may be a critical factor in determining the degree of engagement of predictive comprehension mechanisms, but that it is not the case that prediction is inherently too slow to affect ongoing reading comprehension at presentation rates up to 4 words/second, even in the SVP environment.

The effect of SOA block order is broadly consistent with studies suggesting that predictive comprehension mechanisms can be flexibly implemented. For example, a recent study of associative semantic priming found that manipulating the ratio of related to unrelated prime-target pairs affected semantic facilitation observed on the N400. Larger N400 effects (greater facilitation) were observed when 50% of targets were related to primes, compared to blocks in which 10% of pairs were related (Lau et al., 2013). This enhancement of the N400 effect was attributed to the increased predictability of the target based on the prime in the higher relatedness proportion blocks. In the current study, participants who first experienced experimental conditions in which they successfully engaged predictive mechanisms were less affected by speeded presentation. One explanation of this pattern is that once a predictive comprehension mode was engaged during the session, resources were allocated to predictive mechanisms even under difficult processing conditions in the 250 ms SOA block. Another possibility is that general experience with the SVP environment rendered the faster presentation rate less difficult overall. In either case, the mechanism underlying the flexibility of predictive comprehension remains to be uncovered. For example, the degree to which predictive comprehension may be under strategic control is unknown. However, these results do show that the comprehension mechanisms that are engaged in a particular situational environment can depend on recent experience (cf. Fine, et al., 2013).

The emergence of distinct modes of comprehension even in the same individuals under different processing circumstances is also compatible with other lines of work. We have suggested that the brain may implement multiple modes of comprehension in parallel, and, in particular, that these mechanisms are distributed across the two cerebral hemispheres. Patterns associated with predictive comprehension, such as the semantic similarity effect in this study, are observed only with LH-biased processing, whereas RH-based processing patterns align instead with overall message-level plausibility (Federmeier & Kutas, 1999a). Older adults as a group also tend to show non-predictive comprehension patterns.

Processing speed has been invoked as an explanation for both hemispheric differences and age-related changes in comprehension. Generalized slowing has been hypothesized to account for aging effects across domains including language comprehension (Salthouse, 1996, 2000). RH processing has been associated with overall slower semantic activation compared to the LH (Koivisto, 1997). Given the association of both aging and RH processing with non-predictive comprehension, these explanations for such patterns imply that prediction may be strongly constrained by timing. However, several studies show that speed alone is not able to fully account for either age-related or hemispheric effects. For example, overall context effects are similar in onset and peak time across the two hemispheres (Federmeier, Mai, & Kutas, 2005), suggesting that RH processing is not simply delayed relative to the LH. Additionally, older adults fail to show evidence for pre-activation of a specific word given a contextual cue, even with cue intervals that are longer than the time in which the same participants were able to overtly produce the target word in a separate task (Federmeier, Schul, & Kutas, 2010). This study is in agreement with the possibility that predictive mechanisms are sensitive to timing, but also that processing speed cannot be the only factor that determines whether predictive comprehension mechanisms can be successfully engaged. Taken with prior findings, it appears instead that resources available for robust top-down contextual processing may be the critical requirement for pre-activation of likely upcoming information.

In conclusion, predictive processing is an important component of normal language comprehension, but prediction is not ubiquitous. This study demonstrates that timing is one factor that can decrease the likelihood that predictive processing will affect ongoing comprehension. However, we found some evidence that prediction can be successfully engaged even under speeded conditions, perhaps especially when predictive mechanisms have already been implemented during recent experience. These findings add to the growing literature demonstrating the ability of the brain to adapt as a function of the availability of processing resources in a particular situational environment.

Acknowledgments

This research was supported by the McDonnell Foundation and NIH grant AG026308 to Kara Federmeier, and NIH training grant T32-MH019990 at the University of Illinois. Sagar Shah, Clarissa Coyle, Jaimi Gollinger, Alexander Kurdi, and Derek Hashimoto provided assistance with data collection and processing.

References

Adank P, Devlin JT. On-line plasticity in spoken sentence comprehension: Adapting to time-compressed speech. Neuroimage. 2010; 49(1):1124–1132.10.1016/j.neuroimage.2009.07.032 [PubMed: 19632341]

Aydelott J, Baer-Henney D, Trzaskowski M, Leech R, Dick F. Sentence comprehension in competing speech: Dichotic sentence-word priming reveals hemispheric differences in auditory semantic processing. Language and Cognitive Processes. 2012; 27(7–8):1108–1144.10.1080/01690965.2011.589735

Banich, MT. The divided visual field technique in laterality and interhemispheric integration. In: Hugdahl, K., editor. Experimental methods in neuropsychology. Boston: Kluwer; 2002. p. 47-64.

Bar, M. Predictions in the brain: Using our past to generate a future. New York: Oxford University Press; 2011.

Catani M, Allin MP, Husain M, Pugliese L, Mesulam MM, Murray RM, Jones DK. Symmetries in human brain language pathways correlate with verbal recall. Proceedings of the National Academy of Sciences of the United States of America. 2007; 104(43):17163–17168.10.1073/pnas.0702116104 [PubMed: 17939998]

Dale, AM. Source localization and spatial discriminant analysis of event-related potentials: Linear approaches. University of California; San Diego, La Jolla, CA: 1994. Unpublished

DeLong KA, Urbach TP, Kutas M. Probabilistic word pre-activation during language comprehension inferred from electrical brain activity. Nature Neuroscience. 2005; 8(8):1117–1121.10.1038/nn1504 [PubMed: 16007080]

DiCiccio T, Efron B. Bootstrap confidence intervals. Statistical Science. 1996; 11(3):189–228.

Ditman T, Holcomb PJ, Kuperberg GR. An investigation of concurrent ERP and self-paced reading methodologies. Psychophysiology. 2007; 44(6):927–935.10.1111/j.1469-8986.2007.00593.x [PubMed: 17850242]

Federmeier KD. Thinking ahead: The role and roots of prediction in language comprehension. Psychophysiology. 2007; 44(4):491–505.10.1111/j.1469-8986.2007.00531.x [PubMed: 17521377]

Federmeier KD, Kutas M. Right words and left words: Electrophysiological evidence for hemispheric differences in meaning processing. Cognitive Brain Research. 1999; 8(3):373–392.10.1016/S0926-6410(99)00036-1 [PubMed: 10556614]

Federmeier KD, Kutas M. A rose by any other name: Long-term memory structure and sentence processing. Journal of Memory and Language. 1999; 41(4):469–495.10.1006/jmla.1999.2660

Federmeier KD, Kutas M, Schul R. Age-related and individual differences in the use of prediction during language comprehension. Brain and Language. 2010; 115(3):149–161.10.1016/j.bandl.2010.07.006 [PubMed: 20728207]

Federmeier, KD.; Laszlo, S. The psychology of learning and motivation. Vol. 51. San Diego, CA, US: Elsevier Academic Press; 2009. Time for meaning: Electrophysiology provides insights into the dynamics of representation and processing in semantic memory; p. 1-44.p. 51001-8.

Federmeier KD, McLennan DB, De Ochoa E, Kutas M. The impact of semantic memory organization and sentence context information on spoken language processing by younger and older adults: An ERP study. Psychophysiology. 2002; 39(2):133–146.10.1017/S0048577202001373 [PubMed: 12212662]

Federmeier KD, Wlotko EW, Meyer AM. What's "right" in language comprehension: ERPs reveal right hemisphere language capabilities. Language and Linguistics Compass. 2008; 2(1):1–17.10.1111/j.1749-818X.2007.00042.x [PubMed: 19777128]

Fine AB, Jaeger TF, Farmer TA, Qian T. Rapid expectation adaptation during syntactic comprehension. PloS One. 2013; 8(10):e77661.10.1371/journal.pone.0077661 [PubMed: 24204909]

Foucart A, Martin CD, Moreno EM, Costa A. Can bilinguals see it coming? Word anticipation in L2 sentence reading. Journal of Experimental Psychology. Learning, Memory, and Cognition. 2014; 40(5):1461–1469.10.1037/a0036756

Glasser MF, Rilling JK. DTI tractography of the human brain's language pathways. Cerebral Cortex (New York, NY 1991). 2008; 18(11):2471–2482.10.1093/cercor/bhn011

Kaan E. Predictive sentence processing in L2 and L1: What is different? Linguistic Approaches to Bilingualism. 2014; 4(2):257–282.10.1075/lab.4.2.05kaa

Kamide Y, Altmann GTM, Haywood SL. The time-course of prediction in incremental sentence processing: Evidence from anticipatory eye movements. Journal of Memory and Language. 2003; 49(1):133–156.10.1016/S0749-596X(03)00023-8

Koivisto M. Time course of semantic activation in the cerebral hemispheres. Neuropsychologia. 1997; 35(4):497–504.10.1016/S0028-3932(96)00100-5 [PubMed: 9106278]

Kuperberg, GR. The proactive comprehender: What event-related potentials tell us about the dynamics of reading comprehension. In: Miller, B.; Cutting, L.; McCardle, P., editors. Unraveling reading comprehension: Behavioral, neurobiological, and genetic components. Baltimore: Paul: Brookes Publishing; 2013. p. 176-192.

Kutas M. Event-related brain potentials (ERPs) elicited during rapid serial visual presentation of congruous and incongruous sentences. Electroencephalography and Clinical Neurophysiology. 1987; 40:406–411. Supplement.

Kutas, M.; DeLong, KA.; Smith, NJ. A look around at what lies ahead: Prediction and predictability in language processing. In: M, Bar, editor. Predictions in the brain: Using our past to generate a future. New York, NY: Oxford University Press; 2011. p. 190-207.

Laszlo S, Federmeier KD. A beautiful day in the neighborhood: An event-related potential study of lexical relationships and prediction in context. Journal of Memory and Language. 2009; 61(3):326–338.10.1016/j.jml.2009.06.004 [PubMed: 20161064]

Lau EF, Holcomb PJ, Kuperberg GR. Dissociating N400 effects of prediction from association in single-word contexts. Journal of Cognitive Neuroscience. 2013; 25(3):484–502.10.1162/jocn_a_00328 [PubMed: 23163410]

Lee C, Federmeier KD. Differential age effects on lexical ambiguity resolution mechanisms. Psychophysiology. 2011; 48(7):960–972.10.1111/j.1469-8986.2010.01158.x [PubMed: 21175671]

MacDonald MC. How language production shapes language form and comprehension. Frontiers in Psychology. 2013; 4:226.10.3389/fpsyg.2013.00226 [PubMed: 23637689]

Oldfield RC. The assessment and analysis of handedness: The Edinburgh inventory. Neuropsychologia. 1971; 9(1):97–113.10.1016/0028-3932(71)90067-4 [PubMed: 5146491]

Otten M, Van Berkum JJA. Discourse-based word anticipation during language processing: Prediction or priming? Discourse Processes. 2008; 45(6):464–496.10.1080/01638530802356463

Pickering MJ, Garrod S. An integrated theory of language production and comprehension. The Behavioral and Brain Sciences. 2013; 36(4):329–347.10.1017/S0140525X12001495 [PubMed: 23789620]

Poldrack RA, Temple E, Protopapas A, Nagarajan S, Tallal P, Merzenich M, Gabrieli JD. Relations between the neural bases of dynamic auditory processing and phonological processing: Evidence from fMRI. Journal of Cognitive Neuroscience. 2001; 13(5):687–697.10.1162/089892901750363235 [PubMed: 11506664]

Rothermich K, Schmidt-Kassow M, Kotz SA. Rhythm's gonna get you: Regular meter facilitates semantic sentence processing. Neuropsychologia. 2012; 50(2):232–244.10.1016/j.neuropsychologia.2011.10.025 [PubMed: 22178743]

Salthouse TA. The processing-speed theory of adult age differences in cognition. Psychological Review. 1996; 103(3):403–428.10.1037/0033-295X.103.3.403 [PubMed: 8759042]

Salthouse TA. Aging and measures of processing speed. Biological Psychology. 2000; 54(1–3):35–54.10.1016/S0301-0511(00)00052-1 [PubMed: 11035219]

Schmidt-Kassow M, Kotz SA. Event-related brain potentials suggest a late interaction of meter and syntax in the P600. Journal of Cognitive Neuroscience. 2009; 21(9):1693–1708.10.1162/jocn.2008.21153 [PubMed: 18855546]

Schwanenflugel PJ, LaCount KL. Semantic relatedness and the scope of facilitation for upcoming words in sentences. Journal of Experimental Psychology: Learning, Memory, and Cognition. 1988; 14(2):344–354.10.1037/0278-7393.14.2.344

Taylor WL. Cloze procedure: A new tool for measuring readability. Journalism and Mass Communication Quarterly. 1953; 30(4):415–433.

Vagharchakian L, Dehaene-Lambertz G, Pallier C, Dehaene S. A temporal bottleneck in the language comprehension network. The Journal of Neuroscience: The Official Journal of the Society for Neuroscience. 2012; 32(26):9089–9102.10.1523/JNEUROSCI.5685-11.2012 [PubMed: 22745508]

Van Berkum JJA, Brown CM, Zwitserlood P, Kooijman V, Hagoort P. Anticipating upcoming words in discourse: Evidence from ERPs and reading times. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2005; 31(3):443–467.10.1037/0278-7393.31.3.443

Van Petten C, Luka BJ. Prediction during language comprehension: Benefits, costs, and ERP components. International Journal of Psychophysiology. 2012; 83(2):176–190.10.1016/j.ijpsycho.2011.09.015 [PubMed: 22019481]

Wicha NYY, Moreno EM, Kutas M. Anticipating words and their gender: An event-related brain potential study of semantic integration, gender expectancy, and gender agreement in Spanish sentence reading. Journal of Cognitive Neuroscience. 2004; 16(7):1272–1288.10.1162/0898929041920487 [PubMed: 15453979]

Wlotko EW, Federmeier KD. Two sides of meaning: The scalp-recorded N400 reflects distinct contributions from the cerebral hemispheres. Frontiers in Psychology. 2013; 4:181.10.3389/fpsyg.2013.00181 [PubMed: 23630506]

Wlotko EW, Federmeier KD, Kutas M. To predict or not to predict: Age-related differences in the use of sentential context. Psychology and Aging. 2012; 27(4):975–988.10.1037/a0029206 [PubMed: 22775363]

Wlotko EW, Federmeier KD. Finding the right word: Hemispheric asymmetries in the use of sentence context information. Neuropsychologia. 2007; 45(13):3001–3014.10.1016/j.neuropsychologia.2007.05.013 [PubMed: 17659309]

Wlotko EW, Federmeier KD. Flexible implementation of anticipatory language comprehension mechanisms [Abstract]. Journal of Cognitive Neuroscience. 2011; 23(Supplement 1):233. (Supplement 1).

Wlotko EW, Federmeier KD. Age-related changes in the impact of contextual strength on multiple aspects of sentence comprehension. Psychophysiology. 2012; 49(6):770–785.10.1111/j.1469-8986.2012.01366.x [PubMed: 22469362]

Wlotko EW, Lee C, Federmeier KD. Language of the aging brain: Event-related potential studies of comprehension in older adults. Language and Linguistics Compass. 2010; 4(8):623–638.10.1111/j.1749-818X.2010.00224.x [PubMed: 20823949]

Predictive sentence processing mechanisms are sensitive to timing

N400 effects associated with predictive processing are diminished with fast presentation

The effect of timing on prediction depends on recent experience

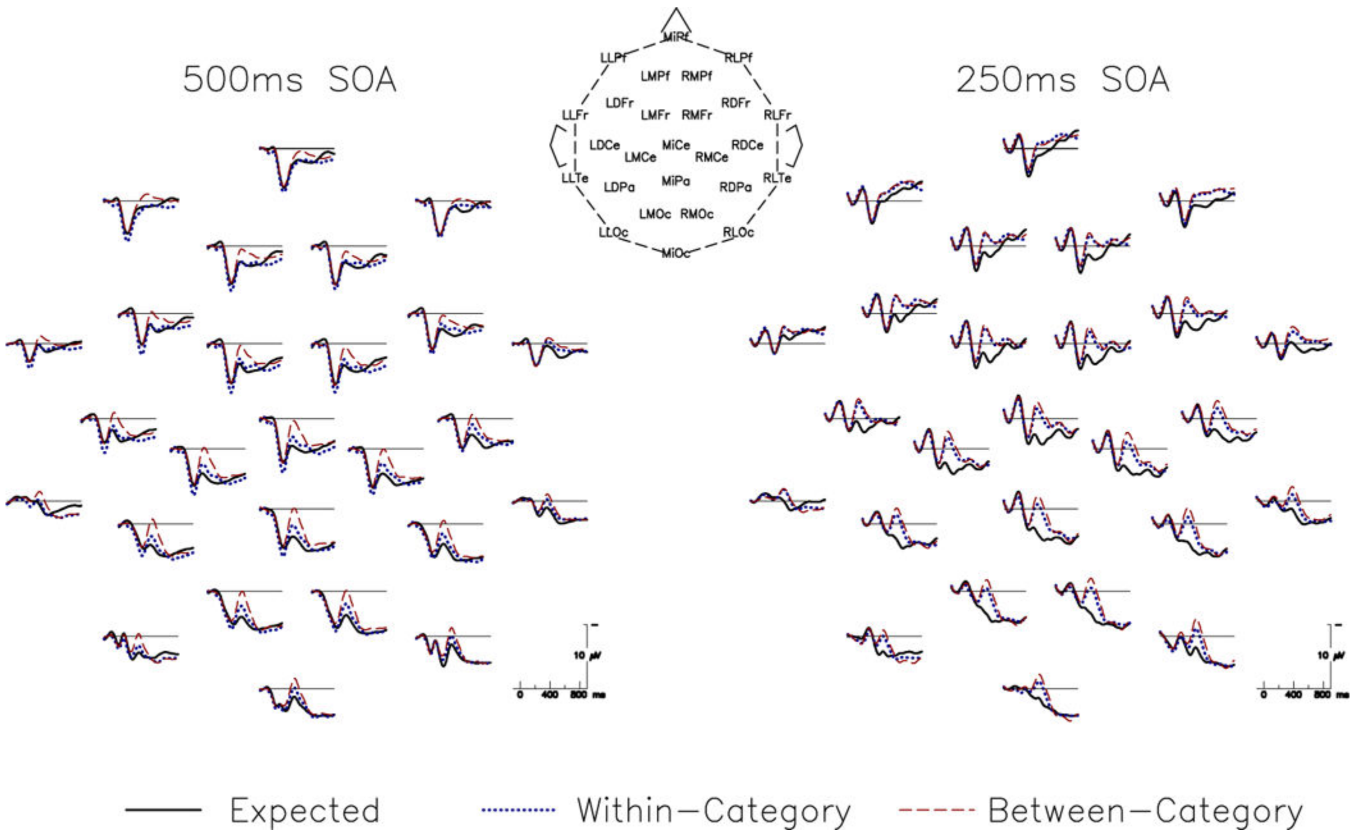

Figure 1.

Grand average ERPs for the three sentence ending types in the 500 ms and 250 ms SOA conditions, shown for the 26 scalp recording sites. Negative is plotted up. The schematic head (nose at top) shows the arrangement. The N400 effect of expectancy (between-category vs. expected) is similar for the both SOA conditions, but the N400 effect of semantic similarity (between-category vs. within-category violation) is apparent for the 500 ms SOA and not the 250 ms SOA. (Electrode site abbreviations: Midline Prefrontal (MiPf), Left and Right Medial Prefrontal (LMPf and RMPf), Lateral Prefrontal (LLPf and RLPf), Medial Frontal (LMFr and RMFr), Mediolateral Frontal (LDFr RDFr), Lateral Frontal (LLFr and RLFr), Midline Central (MiCe), Medial Central (LMCe and RMCe), Mediolateral Central (LDCe and RDCe), Midline Parietal (MiPa), Mediolateral Parietal (LDPa and RDPa), Lateral Temporal (LLTe and RLTe), Midline Occipital (MiOc), Medial Occipital (LMOc and RMOc), and Lateral Occipital (LLOc and RLOc))

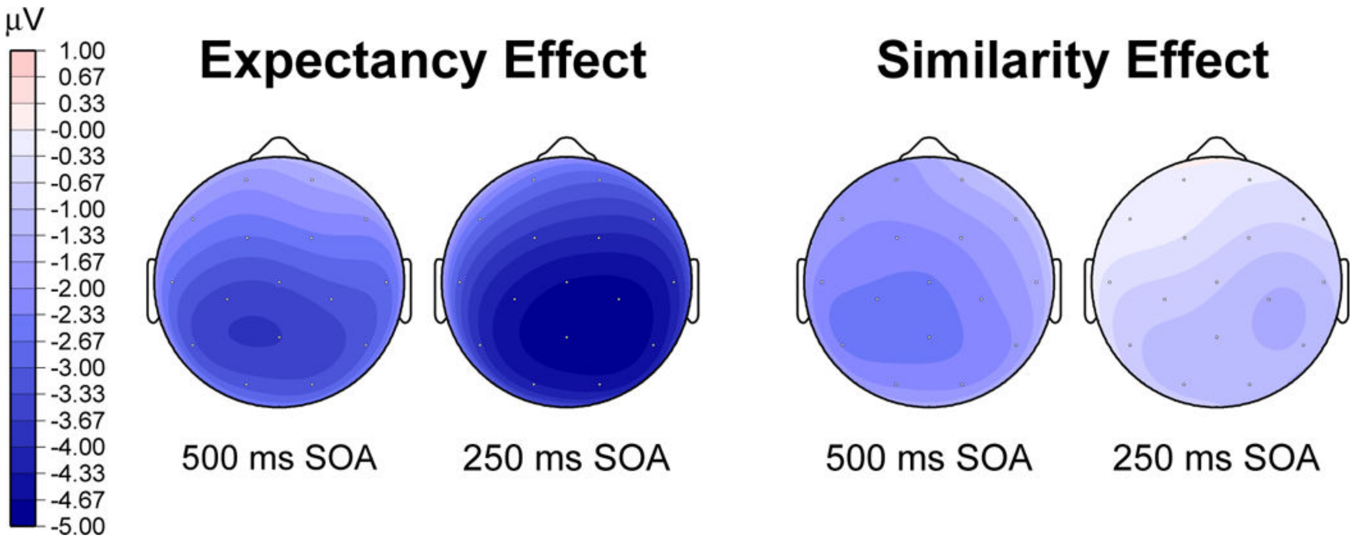

Figure 2.

Topographic maps (based on spherical spline interpolation) of the expectancy effect and the similarity effect in each SOA condition show a medial central-parietal distribution typical of the N400.

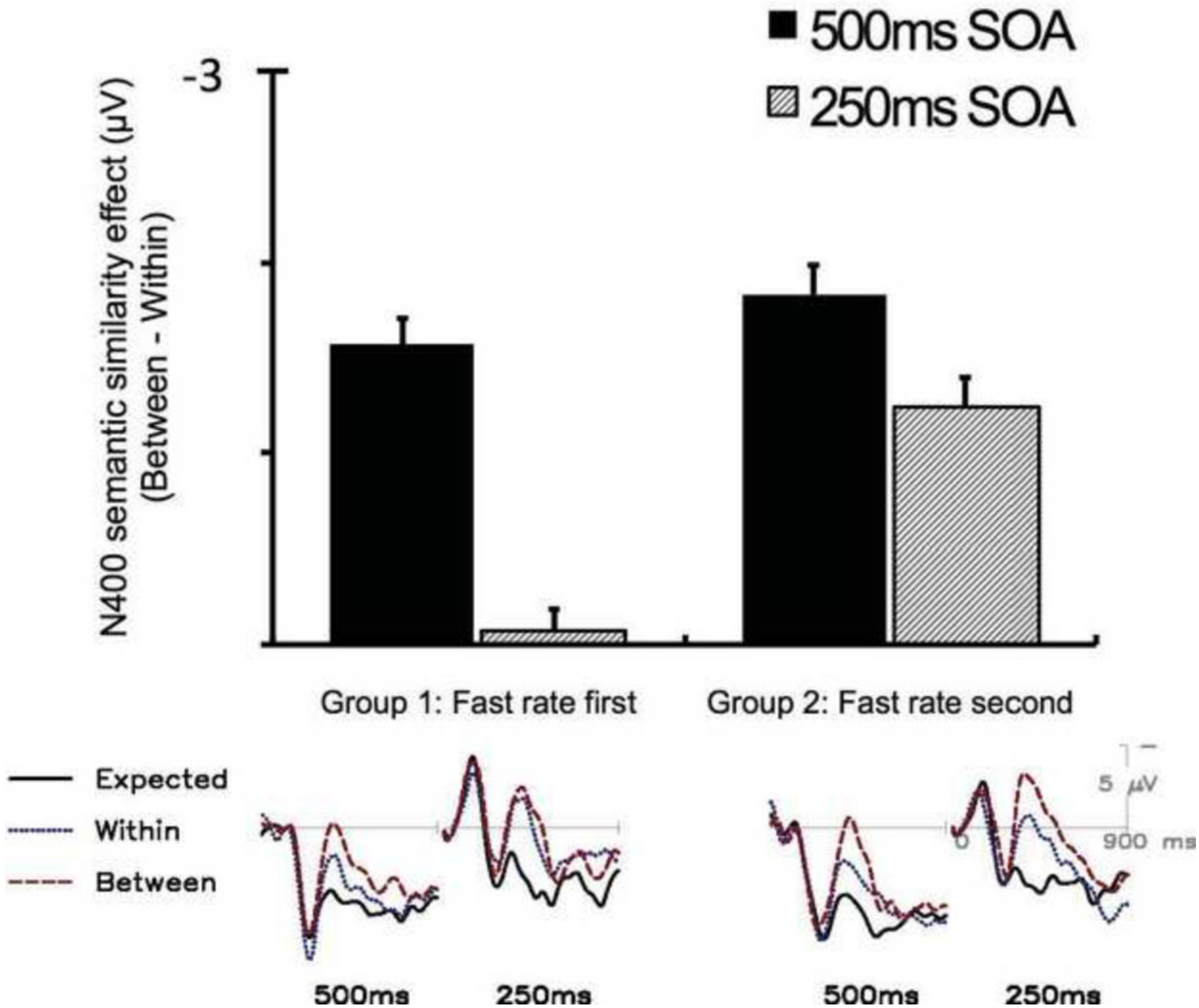

Figure 3.

Mean N400 amplitudes for the semantic similarity effect difference wave (Between category minus Within-category) in the 300–500 ms window post-stimulus onset, for the 250 ms SOA and the 500 ms SOA as a function of SOA block order. ERPs from the right mediolateral parietal site are shown below the bar graph for the two groups in both SOA conditions. Whereas both groups show the semantic similarity effect for the 500 ms SOA, only the group of participants who received the 250 ms SOA block after the 500 ms SOA shows evidence of a semantic similarity effect at the faster presentation rate. Negative is plotted up. Error bars represent standard error of the grand mean.

Table 1

Examples of stimulus sets for the three types of sentence endings in the mini-scenarios.

Set	Context Sentence	Sentence Frame	Expected Word	Within-category violation	Between-category violation
1	Getting both himself and his car to work on the neighboring island was time-consuming.	Every morning he drove for a few minutes and then boarded the	ferry	gondola	plane
1	She felt that she couldn’t leave Venice without the experience.	It might be a touristy thing to do, but she wanted to ride in a	gondola	ferry	helicopter
1	Amy was very anxious about traveling abroad for the first time.	She felt surprisingly better, however, when she actually boarded the	plane	helicopter	gondola
1	The patient was in critical condition and the ambulance wouldn’t be fast enough.	They decided they would have to use the	helicopter	plane	ferry
2	I guess his girlfriend really encouraged him to get it pierced.	But his father sure blew up when he came home wearing that	earring	necklace	lipstick
2	She keeps twirling it around and around under her collar.	Stephanie seems really happy that Dan gave her that	necklace	earring	mascara
2	She wanted to make her eyelashes look really black and thick.	So she asked to borrow her older friend’s	mascara	lipstick	necklace
2	He complained that after she kissed him, he couldn’t get the red color off his face.	He finally just asked her to stop wearing that	lipstick	mascara	earring

Table 2

95% Confidence Intervals for main contrasts of interest

		95% Confidence Interval	
Contrast	**Mean difference**	**Upper Limit**	**Lower Limit**
Expectancy Effect (Between – Expected)			
500 ms SOA	−2.33	−1.3	−3.7
250 ms SOA	−3.27	−2.3	−4.3
Similarity Effect (Between – Within)			
500 ms SOA	−1.70	−0.9	−2.5
250 ms SOA	−0.66	0.1	−1.5

Table 3

95% Confidence Intervals for main contrasts of interest for both SOA block orders

		95% Confidence Interval	
Contrast	**Mean difference**	**Upper Limit**	**Lower Limit**
250 ms SOA first			
Expectancy Effect (Between – Expected)			
500 ms SOA	−1.70	−0.7	−3.2
250 ms SOA	−2.97	−1.6	−4.2
Similarity Effect (Between – Within)			
500 ms SOA	−1.57	−0.5	−2.5
250 ms SOA	−0.07	0.9	−1.1
250 ms SOA second			
Expectancy Effect (Between – Expected)			
500 ms SOA	−2.95	−1.3	−5.1
250 ms SOA	−3.56	−2.2	−5.1
Similarity Effect (Between – Within)			
500 ms SOA	−1.83	−0.7	−3.1
250 ms SOA	−1.25	−0.2	−2.4