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Predictability's aftermath: Downstream consequences of word predictability as revealed by repetition effects

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Abstract

Stimulus processing in language and beyond is shaped by context, with predictability having a particularly well-attested influence on the rapid processes that unfold during the presentation of a word. But does predictability also have downstream consequences for the quality of the constructed representations? On the one hand, the ease of processing predictable words might free up time or cognitive resources, allowing for relatively thorough processing of the input. On the other hand, predictability might allow the system to run in a top-down "verification mode", at the expense of thorough stimulus processing. This EEG study manipulated word predictability, which reduced N400 amplitude and inter-trial phase clustering (ITPC), and then probed the fate of the (un)predictable words in memory by presenting them again. More thorough processing of predictable words should increase repetition effects, whereas less thorough processing should decrease them. Repetition was reflected in N400 decreases, late positive complex (LPC) enhancements, and late alpha/beta band power decreases. Critically, prior predictability tended to reduce the repetition effect on the N400, suggesting less priming, and eliminated the repetition effect on the LPC, suggesting a lack of episodic recollection. These findings converge on a top-down verification account, on which the brain processes more predictable input less thoroughly. More generally, the results demonstrate that predictability has multifaceted downstream consequences beyond processing in the moment.

keywords: *word predictability; repetition; alpha power; sentence comprehension*

Introduction

Language input is to some extent predictable. Highly predictable words are easier to process than less predictable words, which is reflected in shorter fixation durations during natural reading and reduced lexical decision and pronunciation latencies (Ehrlich & Rayner, 1981; Fischler & Bloom, 1979; Kleiman, 1980; Stanovich & West, 1979). Studies on how and when effects of context manifest have led to a consensus that the available context can very rapidly influence incremental language processing (e.g., Altmann & Steedman, 1988; Hagoort & van Berkum, 2007; Kutas & Federmeier, 2000; Tanenhaus & Trueswell, 1995). In event-related brain potentials (ERPs), predictability attenuates the N400, a centroparietally distributed negativity that peaks around 400 ms after the onset of a potentially meaningful stimulus and is a sensitive index of semantic processing (Kutas & Hillyard, 1980; for review, see Kutas & Federmeier, 2011). N400 amplitude is strongly negatively correlated with the cloze probability of a word in a sentence (Kutas & Hillyard, 1984), which is the proportion of an independent group of participants who complete the sentence fragment with that word in an off-line task. Later studies have also shown post-N400 effects related to different aspects of predictability, suggesting that frontally distributed effects are elicited when predictions are disconfirmed (Federmeier, Wlotko, De Ochoa-Dewald, & Kutas, 2007; van Petten & Luka, 2012) or when situations arise in which the context needs to be reconsidered (Wlotko & Federmeier, 2012). However, it is unclear whether predictability only influences the rapid processes that unfold during the presentation of a word or also the resulting representations that comprehenders are left with. The present study sought to probe these representations in order to characterize the downstream consequences of word predictability.

In particular, this study examined the representations that are formed when processing predictable and unpredictable words, to gain insights into how thoroughly such words are processed. On the one hand, the fact that predictable words are easier to process might mean that time or cognitive resources are freed up, allowing for additional processing of the input. Further enhancement of the representations of predictable words in memory might come from the fact that, on top of stimulus-driven processing, aspects of predictable words can also become activated through sentence context in a top-down fashion (for reviews, see Altmann & Mirković, 2009; Federmeier, 2007; Kamide, 2008; Kutas, DeLong, & Smith, 2011). However, on the other hand, a sentence context that is strongly predictive of a particular word leads to a low likelihood of gaining new information, which might instead encourage the system to run in a top-down "verification mode" (e.g., van Berkum, 2010). This would come at the expense of thoroughly processing the bottom-up input, such that predictability would decrease the quality of word representations in memory.

Previous studies, which differed in many ways and were not always explicitly designed to investigate these issues, have reported recall or recognition memory performance for some of the conditions of interest. Some of these data show better memory for predictable words (those with greater conditional probability or cloze probability) than for less predictable words (Miller & Selfridge, 1950; Riggs, Wingfield, & Tun, 1993), but other studies suggest that memory is poorer for predictable than unpredictable words (Cairns, Cowart, & Jablon, 1981; Corley, MacGregor, & Donaldson, 2007; Federmeier et al., 2007; O'Brien & Myers, 1985; Perry & Wingfield, 1994). Importantly, end state measures such as recall or recognition summate across the temporally extended perceptual and memory access processes that predictability may influence. To better examine the unfolding processing of predictable and unpredictable words upon first encounter and then downstream, this study recorded continuous EEG signals while manipulating the predictability of words in sentences and then probing their fate in memory by presenting the words again a few sentences later. Analyses focused on the repetition effect, a multifaceted but well-documented phenomenon (with possible explanations including facilitation, fatigue, and sharpening; Grill-Spector, Henson, & Martin, 2006).

Compared with words presented for the first time in an experiment, repeated words are processed faster and more accurately in lexical decision and naming tasks (Feustel, Shiffrin, & Salasoo, 1983; Scarborough, Cortese, & Scarborough, 1977). In the ERP signal, repeated words elicit a reduced N400 in word lists (e.g., Rugg, 1985) as well as in sentences (van Petten et al., 1991). This is followed by a late positive complex (LPC), which is typically more positive at second presentation than initial presentation (Besson & Kutas, 1993; Besson, Kutas, & Van Petten, 1992; Rugg, 1985; Rugg et al., 1998; but see Van Petten et al., 1991). Across intervening trials, the N400 repetition effect seems to be shorter-lasting than the LPC effect, dissipating at or before a lag of 15-20 minutes in word lists (Rugg, 1990), although when words are repeated in identical sentence contexts the N400 repetition effect can survive a lag of 45 minutes (Besson, Kutas, & van Petten, 1992). When memory judgments are made in response to repeated ("old") and unrepeated ("new") items, similar N400 and LPC effects obtain. The two components show distinct relationships to memory performance, suggestive of a time course in which later conscious recollection follows earlier more implicit memory processes (or familiarity; Rugg & Curran, 2007). For example, the LPC is more positive in response to old words that are explicitly recognized as old (hits) than old words that are not recognized (misses) or new words (Van Petten & Senkfor, 1996), whereas N400 decreases relative to new words can occur regardless of recognition accuracy (Rugg et al., 1998). Furthermore, 'deep' encoding tasks that lead to high rates of recognition are associated with enhanced LPCs at retrieval, whereas N400 decreases can occur regardless of the depth of processing at encoding (Paller & Kutas, 1992; Paller, Kutas, & McIsaac, 1995; Rugg et al., 1998). LPC enhancements have also been associated with accurate memory for episodic details about encoding modality or source (Wilding, Doyle, & Rugg, 1995; Wilding & Rugg, 1996), and with subjective judgments of "remembering" a previous occurrence of a stimulus beyond just "knowing" that it had previously been studied (Smith, 1993; but see Voss & Paller, 2009). Finally, in patients with amnesia, who have impaired explicit (declarative) memory abilities but relatively spared implicit (procedural) memory, the N400 repetition effect is preserved but the LPC repetition effect is not (Olichney et al., 2000). In sum, repetition effects in ERPs may speak to the nature of the stimulus representations that are formed and retrieved.

The present study evaluated repetition effects in response to words as a function of their prior predictability. Participants read words like "car" presented as either the most expected ending of a strongly constraining sentence frame ("Alfonso has started biking to work instead of driving his car") or presented as an unpredictable but plausible ending in a weakly constraining sentence frame ("Jason tried to make space for others by moving his car"). Constraint was operationalized as the cloze probability of the most frequently given response in an off-line sentence completion task. A few sentences later, the previously predictable or previously unpredictable word was presented again in a different weakly constraining sentence, and repetition effects were evaluated relative to a control condition in which the word in question had not previously been presented (a design that has the advantage of keeping constant across conditions the sentence context in which the critical word occurred). An example is shown in Table 1. We hypothesized that, if predictable words are processed more thoroughly than unpredictable words, they should elicit larger repetition effects upon second presentation. Alternatively, if predictable words are processed less thoroughly than unpredictable words, making them more similar to unseen words, they should elicit smaller repetition effects. The nature of the repetition effects (N400, LPC) should be informative of the levels at which more or less thorough processing occurred.

Besides examining N400 and LPC amplitude, time-frequency analyses of power (amplitude squared) were also performed to gain further insights into possible consequences of predictability. Although ERPs have been more precisely characterized and linked to cognitive processes, they are unlikely to capture signals that are not phase-locked to stimuli (or responses), because peaks that are not aligned in time across trials tend to cancel each other when averaging in the time domain (e.g., Tallon-Baudry and Bertrand, 1999). Time-frequency analyses do capture non-phase-locked signals, by decomposing the EEG into different frequencies and extracting their power over time prior to averaging. Various frequency bands have been distinguished, including theta (4-7 Hz), alpha (8-12 Hz), beta (13-30 Hz) and gamma (>30 Hz). In word (pair) lists, repetition has been associated with theta power increases and alpha power decreases (Burgess & Gruzelier, 2000; Klimesch, Doppelmayr, Schimke, & Ripper, 1997; van Strien, Verkoeijen, van der Meer, & Franken, 2007). Here, we aimed to establish the frequencies that are sensitive to repetition in sentence contexts, and to investigate whether any repetition effects depended on the prior predictability of the repeated words. Finally, at initial presentation, we characterized effects of predictability beyond the established ERP effects. Relative to predictable words, previous studies have observed theta band increases in response to unexpected words or semantic anomalies in medium to strongly constraining contexts (Bastiaansen & Hagoort, 2015; Hald, Bastiaansen, & Hagoort, 2006; Rommers et al., 2017; Wang, Zhu, & Bastiaansen, 2012). To our knowledge, spectro-temporal responses to predictable words have not previously been compared with a baseline of unpredictable but plausible words in weakly constraining contexts, as we do here.

Methods

Participants

Thirty native speakers of American English (18 women and 12 men; average age 20 years, range 18-29 years) participated in exchange for course credit or cash. All were right-handed; 13 reported having left-handed family members. All had normal or corrected-to-normal vision and none reported a history of neurological or psychiatric disorders.

Materials and design

The stimuli consisted of 123 sentence triplets. In each triplet, one sentence frame was a strongly constraining item from Federmeier et al. (2007) and two sentence frames were weakly constraining (as confirmed in a norming study, described below); all three ended in the same word, used in the same sense, which was the most expected word in the strongly constraining sentence frame.

One of the weakly constraining sentences from each triplet served as the critical sentence, with the critical word as its sentence-final completion (future studies could investigate any role of sentence-final wrap-up effects in the resultant patterns). There were three conditions, which featured the same critical sentence but differed in terms of the sentences preceding it. In the Previously Predictable condition, the critical word had been presented previously in a strongly constraining context. In the Previously Unpredictable condition, the critical word had been presented previously in a weakly constraining context (different from the critical sentence). In the Not Previously Seen condition, the critical word had not previously been presented. Table 1 shows examples, including two intervening filler sentences between the first and second presentation. Further examples are listed in the Appendix.

Table 1

Examples of the stimuli

	Previously Predictable
First presentation	Alfonso has started biking to work instead of driving his car.
Filler	The mother of the tall guard had the same accent.
Filler	The lawyer feared that his client was guilty.
Critical sentence	It had been several years since they last cleaned the car.
	Previously Unpredictable
First presentation	Jason tried to make space for others by moving his car.
Filler	The mother of the tall guard had the same accent.
Filler	The lawyer feared that his client was guilty.
Critical sentence	It had been several years since they last cleaned the car.
	Not Previously Seen
Filler	The final score of the game was tied.
Filler	The mother of the tall guard had the same accent.
Filler	The lawyer feared that his client was guilty.
Critical sentence	It had been several years since they last cleaned the car.

Note. Critical words are underlined. The critical sentence was always weakly constraining, but the conditions differed in terms of what participants had previously seen. If the critical word had previously been seen, it had been predictable or unpredictable (average cloze probability 0.86 or 0.01, respectively).

The sentences were selected from a larger set of 400 sentences based on cloze probability norms. Consistent with norms in the literature, the cloze probability of a word in a sentence frame was defined as the proportion of participants that completed the sentence frame with that word in a sentence completion task, and the degree of constraint of a sentence frame was operationalized as the cloze probability of its most frequently provided completion. The cloze probabilities were obtained online through Mechanical Turk (www.mturk.com). The cloze probability norming participants were 160 native speakers of English with a location in the United States (86 women and 74 men, age (mean ± SD) 26 ± 5.5 years) whose input had been approved in 100% of the other Mechanical Turk tasks they had done in the past. The sentences were divided up into eight lists in which maximally one sentence from a given triplet appeared. Each participant read one list of about fifty sentence frames and completed each frame using "the word they would generally expect to find completing the sentence fragment". Each sentence was completed by twenty participants. Based on the results, fifty sentences were re-written and twenty additional participants completed the re-written sentence frames (4 women and 16 men, age 28 ± 6 years).

In the sentences used for the first presentation (in the Previously Unpredictable or Previously Predictable conditions), the cloze probability of Predictable words was higher (0.86 ± 0.13, range 0.45-1.00) than that of Unpredictable words (0.01 ± 0.04, range 0-0.25). The cloze probability of the most frequent completion in (i.e., the constraint of) the sentence frames of the Unpredictable condition was 0.19 ± 0.08 (range 0.05-0.35). Sentence length was matched (Predictable: 10.02 ± 3.96 words, range 4-21; Unpredictable: 10.02 ± 3.95 words, range 4-21). In the critical weakly constraining sentences, the final word had a cloze probability of 0.01 ± 0.05 (range 0-0.30) and the cloze probability of the most frequent completion was 0.18 ± 0.08 (range 0.05-0.35). The average length of the critical sentences was 8.08 ± 2.23 words (range 4-17 words). Critical words were rotated across conditions, so visual input and all lexical variables were matched.

The sentences from each triplet were divided across three counterbalanced lists such that participants would see each critical word in only one condition. Eighty-two filler sentences were added to each list, which ensured that over 70% of the sentence endings in a list did not constitute a repetition. The cloze probability of the sentence endings in fillers was 0.41 on average (range 0.24-0.68). The 287 sentences on each list were distributed across 13 blocks of 21 sentences and one block of 14 sentences. Critical word repetitions only occurred within a block. Lists were pseudo-randomized individually for each participant. In the Previously Predictable and Previously Unpredictable conditions, two sentences intervened between initial presentation and the critical sentence. The intervening sentences comprised fillers as well as first presentation sentences or critical sentences belonging to different triplets.

Procedure

Participants were tested individually, seated at a distance of approximately 100 cm from a screen. They were instructed to read the sentences attentively and silently for comprehension while avoiding blinks, muscle movements and eye movements. Stimuli were presented in a white Arial font, size 20, on a black background. Each trial started with a central fixation cross which remained on the screen for 650 ms, followed by a 350 ms blank screen. Then each word was presented for 200 ms in the center of the screen, with an interstimulus interval of 300 ms. After the final word of each sentence and an interstimulus interval of 1300 ms, three asterisks (* * *) appeared for 2 seconds, indicating that participants were free to blink. Participants took a short break between blocks.

After reading the sentences, participants took an untimed paper-and-pencil word recognition test, enabling us to quantify to what extent they had been paying attention to the sentences. They read a list containing the 123 critical words along with 123 unseen words (similar in frequency and length) in alphabetical order, and circled all words they remembered seeing during the experiment. Finally, they took a verbal fluency test, which involved producing as many words as they could within one minute. These data were collected to extend previous reports of correlations between effects of predictability and verbal fluency (e.g., Federmeier et al., 2002), which are of interest with respect to the link between prediction and production (Dell & Chang, 2014; Federmeier, 2007; Pickering & Garrod, 2007), albeit not the focus of this study. In six versions of the task, participants produced words beginning with a specific letter ("F", "A", or "S") or belonging to a certain semantic category ("animals", "fruits and vegetables", "first names"). Participants' responses were recorded and tallied on-line.

EEG recording and analysis

During the sentence reading part of the study, EEG was recorded from 26 evenly spaced Ag/AgCl electrodes mounted in a cap, referenced online to the left mastoid (see Figure 1). Additional electrodes were placed on the right mastoid, on the outer canthus of each eye to monitor eye movements, and on the left infraorbital ridge to monitor blinks. Electrode impedances were kept below 5 kΩ. The signals were amplified using BrainAmp amplifiers with a bandpass filter of 0.016-250 Hz and digitized on-line at a sampling frequency of 1000 Hz.

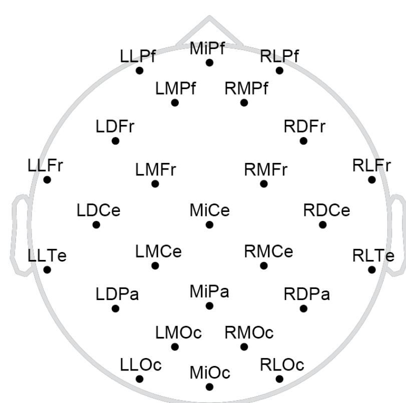

Figure 1. Schematic of the electrode montage with labels.

Analyses were performed using EEGlab, ERPlab, and Fieldtrip (Delorme & Makeig, 2004; Lopez-Calderon & Luck, 2014; Oostenveld, Fries, Maris, & Schoffelen, 2011). The following pre-processing steps were common to all subsequent analyses. The data were re-referenced offline to the average of the left and right mastoids, and horizontal and vertical bipolar electrooculogram (EOG) derivations were created. The continuous EEG was filtered with a 0.1 Hz high-pass filter (two-pass Butterworth with a 12 dB/oct roll-off) and then segmented into epochs encompassing the signal from -750 to 1250 ms relative to the onset of the final word of each sentence. A 200 ms pre-stimulus baseline was subtracted. In the data of seven participants that exhibited many blink artifacts (>30% of trials, leaving fewer than 30 trials), trials with blinks (which primarily occurred during the blank screen after presentation of the critical word) were corrected using Adaptive Mixture Independent Component Analysis (AMICA; Palmer, Kreutz-Delgado, & Makeig, 2011). To this end, ICA components that correlated with the bipolar vertical EOG at Pearson $r > .60$ were removed (one or two components per participant) and the corrected trials added back into the EEG record. In three participants, one particularly noisy channel was spline-interpolated (channel RLPf, LLPf or LLFr). Remaining trials containing blinks, drifts, eye movements, or excessive muscle activity were removed in a semi-automatic fashion using participant-specific thresholds. In total, 15.1% of the trials were removed, with similar trial numbers remaining across conditions: Predictable 35 ± 3 (mean ± SD), Unpredictable 33 ± 4, Previously Predictable 36 ± 2, Previously Unpredictable 35 ± 3, Not Previously Seen 35 ± 3.

Event-related potentials. Trials were averaged in the time domain for each condition and each participant, forming ERPs. A 20 Hz low-pass filter was applied (two-pass Butterworth with a 24 dB/oct roll-off). To quantify the N400, mean amplitude measures were taken in an a priori determined time window of 300-500 ms, averaged across six centroparietal channels where N400 amplitude is usually maximal (LMCe, RMCe, MiCe, MiPa, LDPa, RDPa; following Wlotko, Federmeier, & Kutas, 2012). At initial presentation of the words, post-N400 mean amplitude was measured in a (a priori determined) 500-800 ms window across 11 frontal channels (MiPf, LLPf, RLPf, LMPf, RMPf, LDFr, RDFr, LMFr, RMFr, LLFr, RLFr) to capture the effect observed in Wlotko and Federmeier (2012). In the repetition conditions, the late positive complex (LPC) mean amplitude was measured in that same 500-800 ms window across the previously mentioned six centroparietal channels (e.g., Rugg et al., 1998).

In alignment with most of the literature, ANOVAs are reported, supplemented with confidence intervals and effect sizes (Cohen's d_z for within-subject designs). In addition, we planned to explore whether activity at second presentation could be predicted from the size of specific predictability-related (N400 or post-N400) responses at initial presentation, which would begin to link these responses to the subsequent accessibility of words in memory. To enable these trial-level analyses, mixed-effects models were used that simultaneously take into account participants and items as random effects (Baayen, Davidson, & Bates, 2008).

Time-frequency analysis of power. Power was calculated using a moving window short-time Fast Fourier Transform (FFT) approach. A 500 ms window was moved along the time axis in 10 ms steps (this was based on a previous study using a 400 ms window, in which sentential constraint and word expectancy were associated with effects in the alpha and theta bands, thus supporting the utility of increasing frequency precision and improving power estimates at low frequencies; Rommers et al., 2017). Each instance of a window was multiplied with a Hanning taper and Fourier transformed, extracting power from 4 to 30 Hz in 1 Hz steps (i.e., applying some interpolation). The resulting spectrograms were averaged across trials within each participant and condition, and then normalized by dividing (element-wise) by the average spectrogram across all conditions (rather than baseline correction, to avoid effects driven by pre-stimulus condition differences). In the absence of a priori hypotheses about the spatio-spectro-temporal signatures of the effects of interest, power during the 1 second after critical word onset was compared between pairs of conditions across all time points, frequencies and channels, using cluster-based permutation tests to control the false alarm rate in the face of the multiple comparisons problem (Maris & Oostenveld, 2007). Clusters of data points showing a significant difference were formed across neighboring time points, frequencies, and channels (a triangulation approach resulted in an average of 6.2 neighbors per channel). P values were computed by comparing the cluster with the largest summed t value against a reference distribution based on 1000 permutations in which participant averages were randomly assigned to one of the conditions.

Results

Behavioral memory performance

The percentage of words that participants correctly recognized (43.0%) was larger by 30.2% (95% CI [26.1, 34.2], $d_z = 2.78$) than the percentage of false alarms to unseen words (12.8%). This difference was present in all participants and led to an average d' of 1.082 (95% CI [0.908, 1.255]). The fact that participants were able to distinguish between seen and unseen words suggests that they had been paying attention.

Among the words that had been presented in the sentences, all had appeared as an unpredictable word in a weakly constraining critical sentence, whereas some had also appeared as a predictable or unpredictable word prior to the critical sentence, resulting in three levels of the factor Prior Presentation in the recognition test: Unpredictable, Unpredictable+Unpredictable and Predictable+Unpredictable. The responses at the trial level (1 = judged seen, 0 = judged not seen) were analyzed using a logistic mixed-effects regression model (Baayen, Davidson, & Bates, 2008; Jaeger, 2008). Along with the fixed effect of Prior Presentation, by-item and by-participant random intercepts and by-item random slopes for Prior Presentation were entered as predictors (the model failed to converge when by-participant random slopes were included, which would have been the maximal random effect structure warranted by the design; Barr, Levy, Scheepers, & Tily, 2013; this also held for a model with by-participant random slopes instead of by-item random slopes). There was an effect of Prior Presentation, as revealed by a likelihood ratio test of the model relative to an otherwise identical model without the fixed effect of Prior Presentation, χ^2 (2) = 33.316, $p < .0001$. Compared with the Unpredictable words (35.5%), Predictable+Unpredictable words (46.5%) were recognized more often by 11.0% (95% CI [6.9, 15.1], $d_z = 1.00$), $\beta = 0.501$, $SE = 0.101$, $z = 4.940$, $p < .0001$. Unpredictable+Unpredictable words (46.8%) were also recognized more often than Unpredictable words, by 11.3% (95% CI [7.8, 14.8], $d_z = 1.19$), $\beta = 0.531$, $SE = 0.097$, $z = 5.474$, $p < .0001$. There was no evidence for a difference between the Predictable+Unpredictable and Unpredictable+Unpredictable conditions (0.3% difference, 95% CI [-3.7, 4.3], $d_z = 0.03$), $\beta = 0.030$, $SE = 0.102$, $z = 0.294$, $p = 0.769$. Thus, repetition enhanced performance, but differences in the predictability of the words upon the first of the two presentations did not measurably affect participants' recognition memory performance at the end of the experiment.

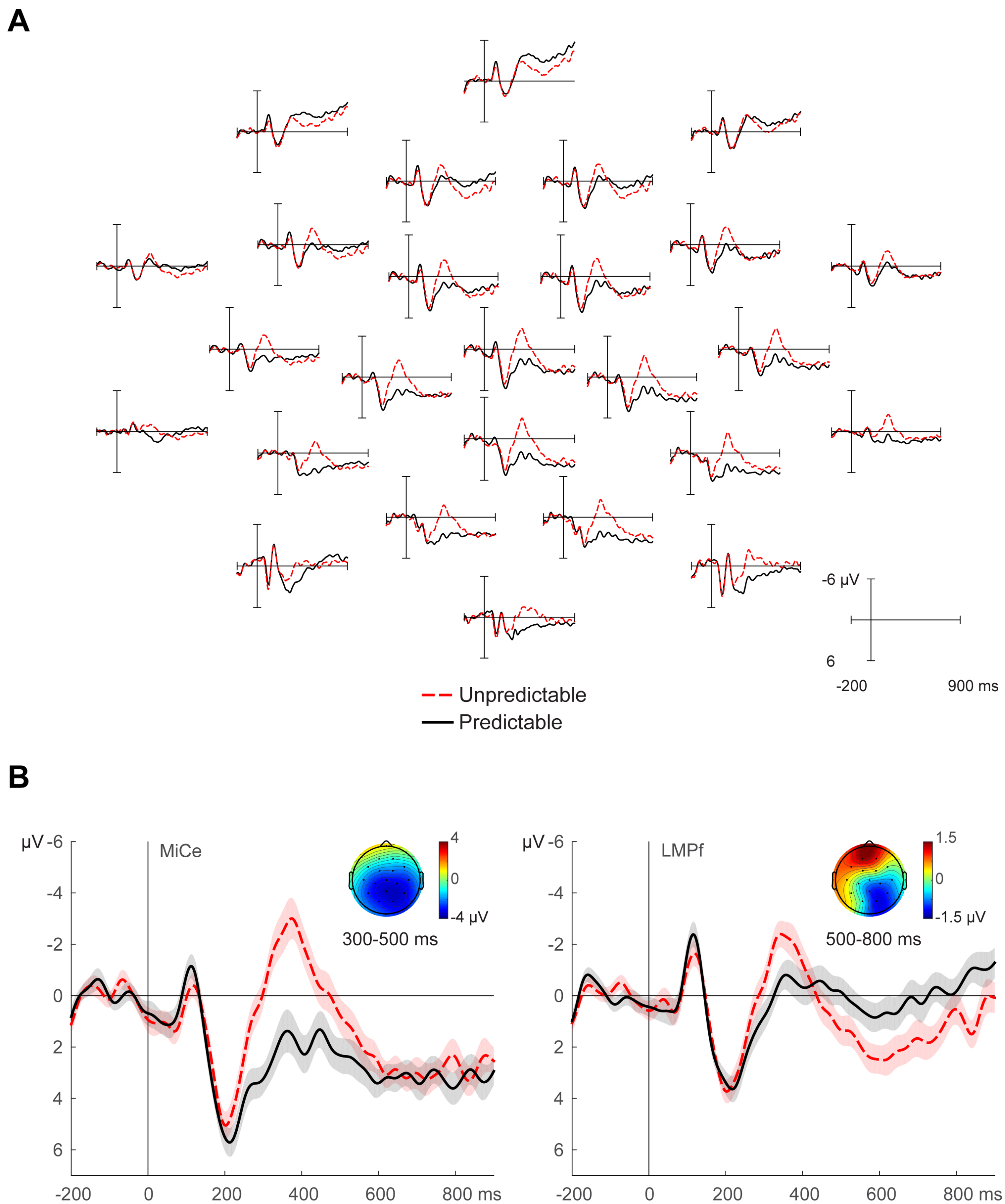

Figure 2. Grand-average ERPs time-locked to words upon initial presentation. Words were predictable (presented in strongly constraining sentence contexts) or unpredictable (presented in weakly constraining sentence contexts). Negative is plotted up in all ERP figures. A) All scalp electrode sites; the position of the channels in the figure approximates the position on the head, with the nose at the top. B) Close-ups of a central channel (MiCe) showing the N400, and of a frontal channel (LMPf) showing the post-N400 effect. Shading reflects unbiased within-subjects

SEM (Cousineau, 2005; Morey, 2008). Insets show scalp topographies of the difference (Unpredictable - Predictable).

Event-related potentials

Figure 2 shows the ERPs time-locked to the first presentation of the critical words. After a visual P1, N1 and P2, a clear N400 was elicited, followed by a late positive-going wave. Confirming numerous previous studies, the amplitude of the N400 in response to predictable words was attenuated by 3.34 μV (95% CI [2.12, 4.56], $d_z = 1.03$) compared with the N400 to unpredictable words, F (1,29) = 31.560, $p < .0001$. Consistent with previous studies, there was a post-N400 difference over frontal channels as well, with more negative-going waveforms by 0.78 μV (95% CI [0.01, 1.55], $d_z = 0.38$) in response to predictable words compared with unpredictable words, F (1,29) = 4.341, $p = 0.046$.

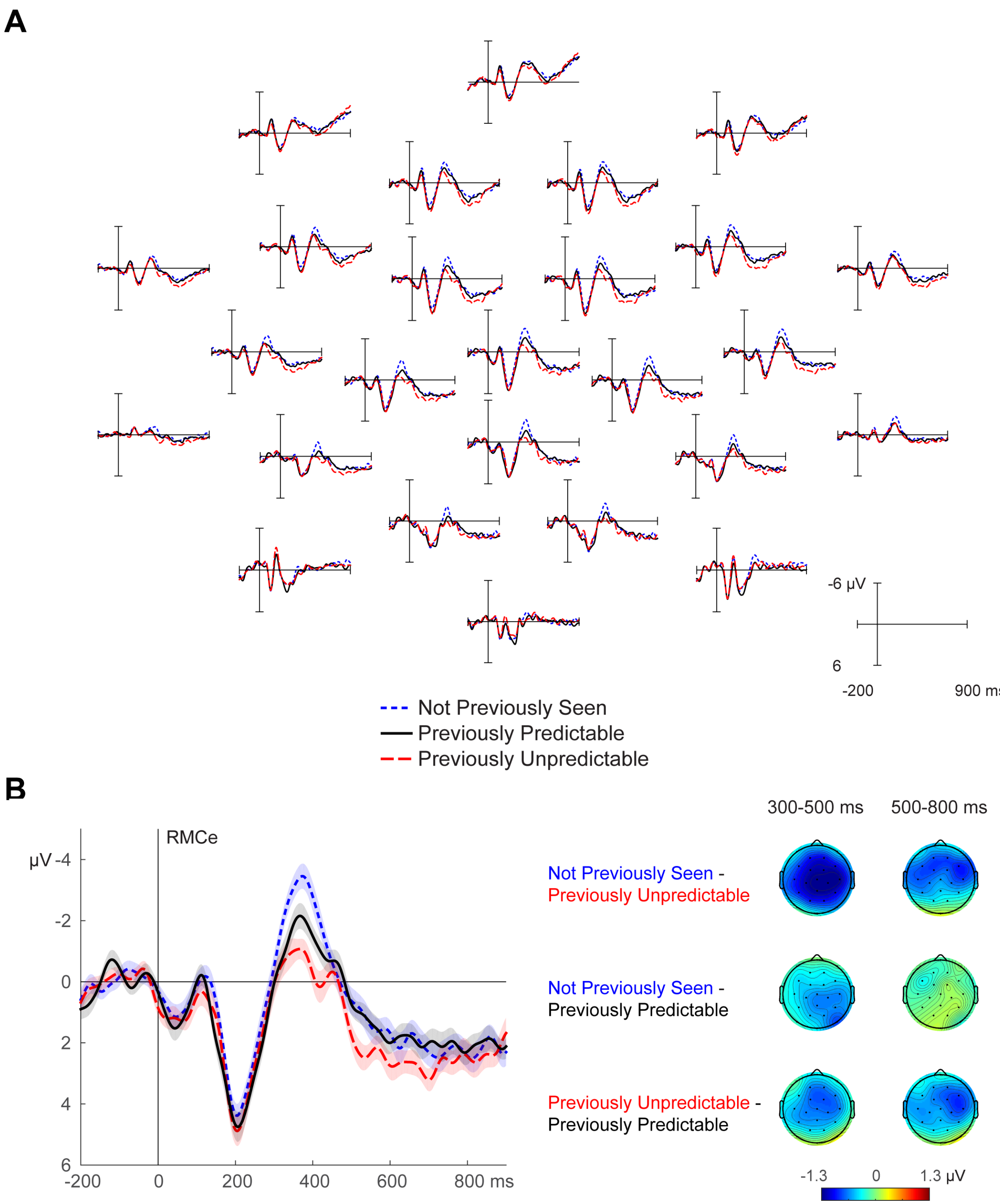

Figure 3. Grand-average ERPs time-locked to sentence-final words in the critical weakly constraining sentences. The words were either repetitions (Previously Predictable, Previously Unpredictable) or unseen words presented in the same sentence contexts (Not Previously Seen). A) All scalp electrode sites. B) Close-up of a right medial channel (RMCe) showing the N400

and LPC. Shading reflects unbiased within-subjects SEM (Cousineau, 2005; Morey, 2008). Scalp topographies show the repetition effect for previously unpredictable words, the repetition effect for previously predictable words, and the effect of prior predictability.

Figure 3 shows the ERPs elicited by the critical words in the critical sentences. N400 amplitude differed between the three conditions, F (2,58) = 7.314, p = 0.002 (Greenhouse-Geisser corrected; ε = 0.984). Relative to the Not Previously Seen words, which elicited the largest N400, the N400 in response to Previously Unpredictable words was attenuated by 1.27 µV (95% CI [0.60, 1.95], d_z = 0.70), F (1,29) = 14.751, p = 0.0006. The N400 in response to Previously Predictable words was attenuated by 0.62 µV (95% CI [-0.03, 1.26], d_z = 0.36), F (1,29) = 3.864, p = 0.059. Thus, both predictable and unpredictable words elicited repetition effects on the N400 when presented again. However, the repetition effect for Previously Predictable words was about half the size of that for Previously Unpredictable words – different by 0.65 µV (95% CI [-0.06, 1.37], d_z = 0.34), F (1,29) = 3.465, p = 0.0728. [1] In sum, prior predictability tended to reduce the repetition effect on the N400.

Thus, while predictable words initially elicited a reduced N400 relative to unpredictable words, the effect of initial predictability was reversed when the words were presented again. A combined analysis (leaving out the Not Previously Seen words) emphasized this cross-over interaction of Initial Predictability (Predictable, Unpredictable) and Presentation (First, Second), 3.99 µV (95% CI [2.73, 5.26], d_z = 1.18), F (1,29) = 41.740, p < .0001.

Replicating prior word repetition effects, an LPC effect was also apparent, with a widespread though relatively anterior distribution (but see Allan & Rugg, 1997; Mecklinger,

[1] Note that these analyses reach conventional levels of significance in a narrower window around the peak of the N400 (350-450 ms; Rugg, 1985; Schendan, Ganis, & Kutas, 1998): repetition effect for Previously Predictable words 0.91 µV (95% CI [0.23, 1.59], d_z = 0.50), F (1,29) = 7.542, p = 0.010; effect of Prior Predictability 0.88 µV (95% CI [0.15, 1.62], d_z = 0.45), F (1,29) = 6.050, p = 0.020. See also the trial-level analyses for converging statistical support for the effect of Prior Predictability.

1998). Overall, LPC amplitudes tended to differ between conditions, F (2,58) = 2.611, p = 0.084 (Greenhouse-Geisser corrected, ε = 0.974). Relative to the Not Previously Seen words, LPC amplitude in response to Previously Unpredictable words was more positive by 0.62 µV (95% CI [-0.03, 1.27], d_z = 0.35), F (1,29) = 3.755, p = 0.062. Such a repetition effect was not observed in response to Previously Predictable words, which elicited an LPC of essentially identical magnitude to the Not Previously Seen words (0.004 µV difference, 95% CI [-0.68, 0.67], d_z = 0.002), F (1,29) = 1.840, p = 0.989. The LPC to Previously Unpredictable words was more positive by 0.62 µV (95% CI [0.03, 1.21], d_z = 0.39) compared with the Previously Predictable words, F (1,29) = 4.676, p = 0.039. In sum, prior predictability eliminated the repetition effect on the LPC.

Further analyses explored whether, and if so, how, the downstream repetition effects were related to the specific effects observed at initial presentation, beyond their more general link with predictability. The N400, post-N400 frontal effect and LPC were each averaged across the relevant channels and time-points mentioned previously, but at the trial level (in the subset of trials for which both presentations of a given word had passed artifact rejection; trial numbers mean ± SD: Previously Predictable 31 ± 4, Previously Unpredictable 29 ± 4). In separate mixed-effects models of N400 amplitude and LPC amplitude at second presentation, the following fixed effects served as predictors: the condition effect of Prior Predictability (deviation-coded; Previously Unpredictable 0.5, Previously Predictable -0.5), Prior N400 amplitude, Prior post-N400 frontal amplitude (both z-scored relative to each participant's condition average in order to separate them from the effect of Prior Predictability), and the Prior Predictability × Prior N400 and Prior Predictability × Prior Post-N400 interactions (the three-way interaction could not be fit and would be difficult to interpret). By-participant and by-item random intercepts and random slopes for all fixed effects were included, but random correlations were excluded to aid convergence (Barr, Levy, Scheepers, & Tily, 2013). Confirming the earlier analyses, N400 amplitude was greater for Previously Predictable words than for Previously Unpredictable words, $\beta = 0.846$, $SE = 0.404$, $t = 2.092$, χ^2 (1) = 4.180, $p = 0.041$. However, there were no main effects of Prior N400 or Prior Post-N400 frontal amplitude, and no interactions of these factors with Prior Predictability, all $|t| < 1.000$, $\chi^2 < 1.010$, $p > 0.315$. Also confirming the earlier analyses, LPC amplitude was greater in response to Previously Unpredictable words than Previously Predictable words, $\beta = 0.824$, $SE = 0.425$, $t = 1.939$, χ^2 (1) = 3.736, $p = 0.053$. This effect of Prior Predictability showed a tendency to interact with Prior N400 amplitude, $\beta = -0.769$, $SE = 0.456$, $t = -1.688$, χ^2 (1) = 2.853, $p = 0.091$. Looking within each condition suggested that there was a negative relationship between Prior N400 and LPC in the Previously Unpredictable condition, and if anything, numerically a smaller, opposite effect in the Previously Predictable condition. Given the opposite polarity of the N400 and LPC, the negative beta estimate suggests that a greater N400 in response to unpredictable words was associated with a greater LPC effect at second presentation. In summary, the ERPs showed effects of predictability at initial presentation, and repetition effects at second presentation, which were decreased or even eliminated when words had previously been predictable. Trial-level analyses confirmed these effects and revealed a limited relationship between the specific ERP effects observed at initial and second presentation.[2]

[2] Confirming previous studies, participants with better semantic verbal fluency (average of the animals, first names, and fruits and vegetables categories) showed a somewhat larger N400 effect at initial presentation, $r = 0.343$, $p = 0.064$. Verbal fluency was not strongly correlated with the post-N400 effect at initial presentation or with the N400 or LPC effects at second presentation, rs < 0.242, ps > 0.197.

Time-frequency analysis

Power changes at initial presentation are shown in Figure 4A. Sentence endings in all conditions elicited an early broadband power increase with an occipital maximum, followed by an alpha/beta decrease with occipital and anterior maxima, and a late, broadly distributed alpha/beta increase and occipital theta decrease. No effect of predictability on power after word onset was detected, *p*s > 0.377. In an additional analysis of the 500 ms prior to word onset, there were also no apparent effects of constraint, $p = 0.1998$. A previous study had detected such an effect prior to word onset using different weakly constraining sentences, more items per condition (~70) and longer epochs (Rommers et al., 2017; see also Piai, Roelofs, Rommers, & Maris, 2015).

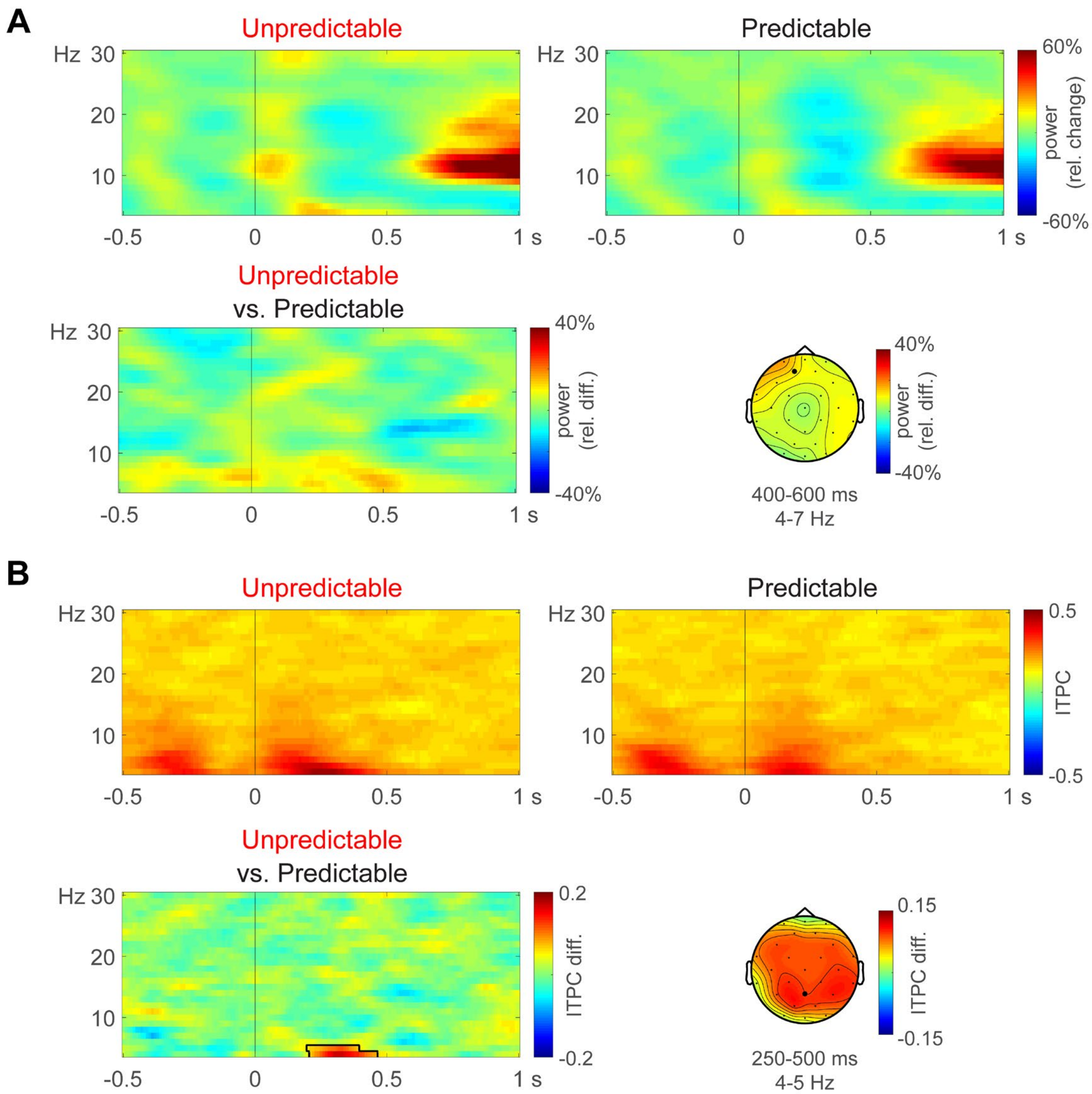

Figure 4. Grand-average time-frequency representations of power and inter-trial phase clustering (ITPC) time-locked to word onset at initial presentation. Spectrograms of individual conditions and their difference are shown along with the scalp topography of the difference. A) Power changes relative to a -500 to -150 ms baseline at a frontal channel (LMFr; indicated with a black dot in the scalp map). Power was similar for Predictable and Unpredictable words, as shown in the bottom panel (difference relative to the average across all conditions). B) Inter-trial phase clustering at a parietal channel (MiPa; indicated with a black dot in the scalp map). The contour line in the spectrogram indicates cluster extent in permutation tests of the difference.

In the presence of strong predictability effects in the ERPs, which primarily capture signals time- and phase-locked to stimulus onset, one might have expected to see a predictability effect on power, which captures non-phase-locked activity in addition to phase-locked activity.

Some possible reasons for this pattern of results are that the difference in the ERPs may have been swamped by larger non-phase-locked signals in the time-frequency analyses; that the ERP effects would be represented at frequencies below 4 Hz (the lowest frequency at which power was analyzed); or that the ERP effects were mainly a result of differences in terms of phase-locking rather than power. We therefore explored a different measure, inter-trial phase clustering (ITPC; also known as inter-trial phase coherence or phase-locking value; Lachaux, Rodriguez, Martinerie, & Varela, 1999), which represents the non-uniformity of the distribution of phase angles across trials (0 = random phases, 1 = perfect phase clustering) independently of power. The same Fourier spectrograms from which power was extracted were normalized by their amplitude and the length of the average vector across trials was computed. The conditions were compared in the same manner as for power, except that no baseline correction or normalization was applied (because ITPC is not affected by $1/f$ scaling; e.g., Cohen, 2014). As shown in Figure 4B, the presentation of the final words elicited a low frequency ITPC increase, as did the directly preceding words. Relative to predictable words, ITPC was greater in response to unpredictable words between approximately 250 and 500 ms. A cluster was detected with a broad scalp distribution (not unlike the N400), mostly limited to the frequencies 4 and 5 Hz, $p = 0.0380$. Thus, although ERP-related power effects may be present at lower frequencies, one explanation for the clear N400 effects in the absence of effects on power seems to be that predictability affected the phase consistency across trials. The absence of a clear accompanying power difference suggests that the predictability effect was specific to phase, highlighting the independence of these two aspects of the signal (e.g., Cohen, 2014).

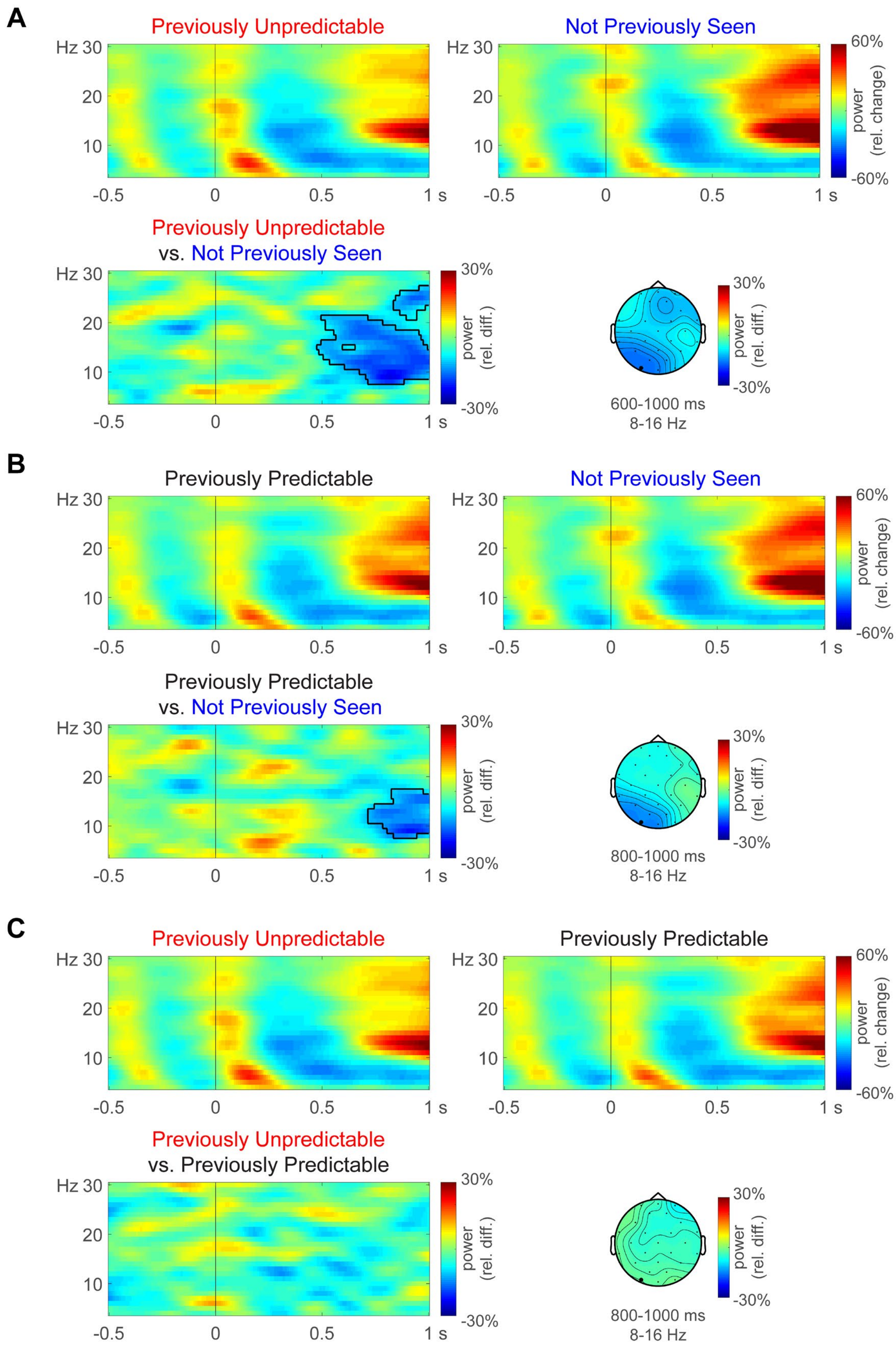
A
Previously Unpredictable
Not Previously Seen
Hz 30
20
10
-0.5
0
0.5
1 s
60%
power
(rel. change)
-60%
Previously Unpredictable
vs. Not Previously Seen
30%
power
(rel. diff.)
-30%
600-1000 ms
8-16 Hz
B
Previously Predictable
Not Previously Seen
Previously Predictable
vs. Not Previously Seen
800-1000 ms
8-16 Hz
C
Previously Unpredictable
Previously Predictable
Previously Unpredictable
vs. Previously Predictable
800-1000 ms
8-16 Hz

Figure 5. Grand-average time frequency representations of power time-locked to final words in the critical sentences, at an occipital channel (LLOc; indicated with a black dot in the scalp maps). The top panels show power changes relative to a -500 to -150 ms baseline within each condition. The bottom panels show power differences (relative to the average across all conditions) and their scalp topography. Contour lines indicate cluster extent in permutation tests. A) Repetition effect for previously unpredictable words. B) Repetition effect for previously predictable words. C) Numerical effect of prior predictability.

Power changes in response to words in the critical sentences are shown in Figure 5. Relative to unseen words, Previously Unpredictable words elicited a clear late alpha/beta power decrease with an occipital and frontal distribution (a repetition effect). This was reflected in a cluster, $p = 0.002$. Words that were Previously Predictable also showed a repetition effect, which also manifested as a late alpha/beta band decrease and was detected as a cluster, $p = 0.0739$. Compared with the repetition effect for previously unpredictable words, the repetition effect for previously predictable words seemed to begin somewhat later in time and was more restricted to posterior channels, but the cluster-based permutation test did not detect a difference between Previously Unpredictable and Previously Predictable words, $p = 0.1958$. For illustration only, we inspected the size of the repetition effects roughly where they were observed (that is, not in a data-independent fashion), averaged across six (left) posterior channels (LLOc, RLOc, MiOc, LMOc, LDPa, LLTe), the frequencies 8-16 Hz, and the time window 600-1000 ms. The repetition effect for Previously Unpredictable words was -14.7% (95% CI [-10.1, -19.2], d_z = 1.20), the repetition effect for Previously Predictable words was -10.3% (95% CI [-4.7, -15.8], d_z = 0.69), and the effect of Prior Predictability was -4.4% (95% CI [1.4, -10.2], d_z = 0.28). In sum, late alpha/beta band power showed repetition effects for previously unpredictable words and for previously predictable words, but there was no strong evidence for an effect of prior predictability on power.

Discussion

Previous work on predictability has focused on how it affects rapid identification and integration processes during word processing, leaving open the question of whether predictability ultimately affects the quality of the constructed representations. This study manipulated the predictability of words in sentences and, to characterize the downstream consequences, presented the words again to probe their fate in memory.

At initial presentation, clear effects of predictability were observed in the form of an attenuated N400 and a frontal post-N400 negativity in response to predictable relative to unpredictable words, consistent with past work (Kutas & Hillyard, 1984; Wlotko & Federmeier, 2012). This frontal post-N400 effect has previously been linked to the need to reconsider aspects of the sentence context, for instance because a different interpretation was initially considered by a subset of the participants (Wlotko & Federmeier, 2012).[3] Interestingly, no effect of predictability was detected on power, despite earlier reports of theta increases in response to unexpected words and semantic anomalies (relative to predictable words) in strongly constraining sentences (Bastiaansen & Hagoort, 2015; Hald, Bastiaansen, & Hagoort, 2006; Rommers et al., 2017; Wang, Zhu, & Bastiaansen, 2012). However, this is compatible with the hypothesis that theta power increases can reflect a processing consequence of disconfirmed predictions (Rommers et al., 2017), because the unpredictable words in the present study were presented in *weakly* constraining sentences, where they are unlikely to disconfirm predictions. In addition, and perhaps explaining the absence of effects on power in the presence of a substantial N400 effect, inter-trial phase clustering revealed that phase angles in the lower theta band were more consistent across trials in response to unpredictable words than predictable words (for

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[3] Based on the difference in eliciting conditions, combined with differences in scalp distribution, we assume that this post-N400 effect is different from the LPC linked to recollection.

essentially the same result in the auditory modality, see a supplemental analysis of Strauss, Kotz, and Obleser, 2013, in Strauss, 2015; see also Roehm, Bornkessel-Schlesewsky, & Schlesewsky, 2007). We can speculate that this might reflect a relative reduction in stimulus-driven processing of predictable words (perhaps mediated by decreased attention, which can decrease ITPC; e.g., Kim et al, 2007).

Our main interest was in repetition effects at second presentation. As expected, previously unpredictable words elicited a strong N400 decrease relative to unseen words, as well as an enhanced LPC, suggesting consequences for both implicit and explicit aspects of processing. An N400 decrease was also observed in response to previously predictable words, but critically, this repetition effect was of smaller magnitude, revealing less facilitation at the semantic level from prior presentation. In addition, the previously predictable words did not elicit a repetition effect on the LPC, suggesting that prior predictability eliminated recollection of a prior episode of having seen the word. Thus, this pattern would suggest that unpredictable words led to priming and recollection, whereas predictable words led only to (some) priming. Across presentations, the N400 pattern consisted of a reduction in response to predictable words on initial presentation, but this effect of initial predictability was reversed when the words were presented again. This is suggestive of a trade-off: predictability facilitated semantic processing on-line, but seemed to come with the consequence of reduced accessibility further downstream.

It should be noted that the effects at second presentation seemed relatively small compared with the strong effect of predictability at initial presentation. This is perhaps not surprising after two intervening sentences, and highlights that prior predictability is only one of many factors affecting the processing of repeated stimuli. Collectively however, the N400 and LPC patterns converge to reveal that, compared with previously unpredictable words, previously predictable words were processed more like unseen words, consistent with the idea that they had been processed less thoroughly.

A third repetition effect was observed in the form of late occipitally distributed alpha/beta power decreases after 500 ms post-stimulus. Despite a numerical difference in the same direction as the ERP effects, the power decreases in response to previously predictable and unpredictable words were statistically not distinguishable. Their timing and scalp distribution do accord well with results from a few previous studies investigating recognition memory for words in lists (Burgess & Gruzelier, 2000; Klimesch, Doppelmayr, Schimke, & Ripper, 1997; van Strien, Verkoeijen, van der Meer, & Franken, 2007). As such, the results help establish late alpha/beta decreases as a neural signature of repetition and extend it to incidental word repetitions in sentence contexts. As has been hypothesized for the word list results, this effect might reflect the reactivation of memory traces (Klimesch, Schack, & Sauseng, 2005). More generally, alpha oscillations are associated with inhibition of task-irrelevant brain areas (Jensen & Mazaheri, 2010; Klimesch et al., 1999). Conversely, alpha *decreases* would indicate a release from inhibition, resulting in active engagement. To the extent that memory-related areas underlie the observed effects, alpha decreases might enable these areas to re-activate memory traces upon repetition.

In a recognition test administered at the end of the experiment, participants demonstrated memory for the materials, and repeated words were more likely to be recognized than words presented only once, but there was no effect of the predictability of the initial presentation. These results cannot be linked directly to the first or the second presentation. However, it is conceivable that even the reduced processing of predictable words was enough to allow later recognition, or that in recognition rates the opposite effects of predictability on initial presentation and second presentation canceled each other.

A few alternative explanations of the observed effects of prior predictability are possible. First, one might argue that the constraining sentence contexts led to the activation of a somewhat more narrow sense of the critical words' meaning than did the weakly constraining contexts, and that this is what decreased the repetition effect upon second presentation (for instance, the example sentence about driving emphasized different aspects of the concept "car" than did the sentences about moving and cleaning). Indeed, Bainbridge, Lewandowski, and Kirsner (1993) showed that a change in sense can reduce repetition priming in a lexical decision task. However, Bainbridge et al.'s stimuli seem to contain rather strong changes in sense (compare "ticket" following "The policeman pulled him over and gave him a…" versus "At the door to the cinema she collected a…"), which were avoided in the present study. Moreover, repeated homographs have been observed to elicit indistinguishable N400s whether the sentence contexts on first and second presentation were biased towards the same or a different meaning (Besson & Kutas, 1993). Similarly, N400 reductions to repeated words have been observed to be insensitive to whether or not the first and second presentation referred to the same discourse entity (Anderson & Holcomb, 2005). Thus, it seems unlikely that sense differences explain the differential repetition effects observed. A related alternative interpretation is that the weakly constraining sentence contexts were more general in meaning than the strongly constraining sentence contexts, making them more likely to be compatible with the critical sentence as an ongoing story, generating contextual support and reducing the N400 if participants treated the sentences that way. However, this also seems unlikely because two unrelated sentences intervened between initial and second presentation, and the direction of the LPC effect patterned with results from word list studies rather than with results from connected text (Van Petten et al., 1991). Having evaluated these possibilities, the idea of less thorough processing of predictable words seems to be the most straightforward explanation of the fact that, compared with previously unpredictable words, the pattern of ERP results showed that the processing system treated the previously predictable words more like words that had not been seen before.

Regarding neural mechanisms, the way in which our sentences increased word predictability is reminiscent of manipulations outside the domain of sentence processing that reduce "expected uncertainty" (the predicted variability in observed outcomes; Yu & Dayan, 2005).[4] Consistent with our findings for predictable words, when expected uncertainty is low, the cholinergic system seems to down-regulate sensory processing and decrease learning (Avery et al., 2012; Yu & Dayan, 2005). In addition, some studies suggest that less information about the presented stimulus content is present in brain signals elicited by predictable compared with less predictable objects and spoken words (Blank & Davis, 2016; Kumar, Kaposvari, & Vogels, 2017; though for a comparison with prediction disconfirmations, see Kok, Jehee, & De Lange, 2012). Taken together, predictable stimuli would be less well encoded in memory, which should decrease downstream repetition effects.

Overall, the results are compatible with a top-down verification account, on which more predictable input is processed less thoroughly because it confirms what the context already supported. Predictability seemed to have downstream effects on both implicit and explicit aspects of processing, as reflected in the N400 and LPC. Furthermore, the N400 pattern suggested that predictability can result in a trade-off between on-line processing benefits and

[4] One could also view the results as consistent with predictive coding, an account on which the brain generally processes prediction error, the difference between expected and actual input (Friston, 2005; Rao & Ballard, 1999). The unpredictable words were not designed to disconfirm strong expectations, but would result in prediction error (and relatively more thorough processing) under the strong assumption that readers always make predictions, even in unconstraining sentences. This assumption would need independent validation.

reduced accessibility further downstream. More generally, these findings demonstrate that predictability does not only influence the rapid processes that unfold during the presentation of a word, but also has consequences for the resulting representations.

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References

Allan, K., & Rugg, M. D. (1997). An event-related potential study of explicit memory on tests of cued recall and recognition. *Neuropsychologia*, *35*(4), 387-397.

Altmann, G., & Mirković, J. (2009). Incrementality and prediction in human sentence processing. *Cognitive Science*, *33*(4), 583-609.

Altmann, G., & Steedman, M. (1988). Interaction with context during human sentence processing. *Cognition*, *30*(3), 191-238.

Anderson, J. E., & Holcomb, P. J. (2005). An electrophysiological investigation of the effects of coreference on word repetition and synonymy. *Brain and Language*, *94*(2), 200-216.

Avery, M. C., Nitz, D. A., Chiba, A. A., & Krichmar, J. L. (2012). Simulation of cholinergic and noradrenergic modulation of behavior in uncertain environments. *Frontiers in Computational Neuroscience*, *6*.

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language*, *59*(4), 390-412.

Bainbridge, J. V., Lewandowski, S., & Kirsner, K. (1993). Context effects in repetition priming are sense effects. *Memory & Cognition, 21(5),* 619-626.

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, *68*(3), 255-278.

Bastiaansen, M. C. M., & Hagoort, P. (2015). Frequency-based segregation of syntactic and semantic unification during online sentence level language comprehension. *Journal of Cognitive Neuroscience, 27(11),* 2095–2107.

Besson, M., & Kutas, M. (1993). The many facets of repetition: A cued-recall and event-related potential analysis of repeating words in same versus different sentence contexts. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *19*, 1115-1115.

Besson, M., Kutas, M., & Van Petten, C. (1992). An event-related potential (ERP) analysis of semantic congruity and repetition effects in sentences. *Journal of Cognitive Neuroscience*, *4*(2), 132-149.

Blank, H., & Davis, M. H. (2016). Prediction errors but not sharpened signals simulate multivoxel fMRI patterns during speech perception. *PLoS Biology*, *14*(11), e1002577.

Burgess, A. P., & Gruzelier, J. H. (2000). Short duration power changes in the EEG during recognition memory for words and faces. *Psychophysiology*, *37*(5), 596-606.

Cairns, H. S., Cowart, W., & Jablon, A. D. (1981). Effects of prior context upon the integration of lexical information during sentence processing. *Journal of Verbal Learning and Verbal Behavior*, *20*(4), 445-453.

Cohen, M. X. (2014). *Analyzing Neural Time Series Data: Theory and Practice*. Cambridge, MA, USA/London, UK: MIT Press.

Corley, M., MacGregor, L. J., & Donaldson, D. I. (2007). It's the way that you, er, say it: Hesitations in speech affect language comprehension. *Cognition*, *105*(3), 658-668.

Cousineau, D. (2005). Confidence intervals in within-subject designs: A simpler solution to Loftus and Masson's method. *Tutorials in Quantitative Methods for Psychology*, *1*(1), 42-45.

Dell, G. S., & Chang, F. (2014). The P-chain: relating sentence production and its disorders to comprehension and acquisition. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *369*(1634), 20120394.

Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics. *Journal of Neuroscience Methods, 134,* 9-21.

Ehrlich, S. F., & Rayner, K. (1981). Contextual effects on word perception and eye movements during reading. *Journal of Verbal Learning and Verbal Behavior*, *20*(6), 641-655.

Federmeier, K. D. (2007). Thinking ahead: The role and roots of prediction in language comprehension. *Psychophysiology*, *44*(4), 491-505.

Federmeier, K. D., McLennan, D. B., De Ochoa, E., & Kutas, M. (2002). The impact of semantic memory organization and sentence context information on spoken language processing by younger and older adults: An ERP study. *Psychophysiology*, *39*(2), 133-146.

Federmeier, K. D., Wlotko, E. W., De Ochoa-Dewald, E., & Kutas, M. (2007). Multiple effects of sentential constraint on word processing. *Brain Research*, *1146*, 75-84.

Feustel, T. C., Shiffrin, R. M., & Salasoo, A. (1983). Episodic and lexical contributions to the repetition effect in word identification. *Journal of Experimental Psychology: General*, *112*(3), 309.

Fischler, I., & Bloom, P. A. (1979). Automatic and attentional processes in the effects of sentence contexts on word recognition. *Journal of Verbal Learning and Verbal Behavior, 18,* 1-20.

Friston, K. (2005). A theory of cortical responses. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, *360*(1456), 815-836.

Grill-Spector, K., Henson, R., & Martin, A. (2006). Repetition and the brain: neural models of stimulus-specific effects. *Trends in Cognitive Sciences*, *10*(1), 14-23.

Hagoort, P., & Van Berkum, J. J. A. (2007). Beyond the sentence given. *Philosophical Transactions of the Royal Society. Series B: Biological Sciences, 362,* 801-811.

Hald, L. A., Bastiaansen, M. C., & Hagoort, P. (2006). EEG theta and gamma responses to semantic violations in online sentence processing. *Brain and Language*, *96*(1), 90-105.

Jaeger, T. F. (2008). Categorical data analysis: Away from ANOVAs (transformation or not) and towards logit mixed models. *Journal of Memory and Language*, *59*(4), 434-446.

Jensen, O., & Mazaheri, A. (2010). Shaping functional architecture by oscillatory alpha activity: gating by inhibition. *Frontiers in Human Neuroscience*, *4*.

Kamide, Y. (2008). Anticipatory processes in sentence processing. *Language and Linguistics Compass*, *2*(4), 647-670.

Kim, Y. J., Grabowecky, M., Paller, K. A., Muthu, K., & Suzuki, S. (2007). Attention induces synchronization-based response gain in steady-state visual evoked potentials. *Nature neuroscience*, *10*(1), 117-125.

Kleiman, G. M. (1980). Sentence frame contexts and lexical decisions: Sentence-acceptability and word-relatedness effects. *Memory & Cognition*, *8*(4), 336-344.

Klimesch, W., Doppelmayr, M., Schimke, H., & Ripper, B. (1997). Theta synchronization and alpha desynchronization in a memory task. *Psychophysiology*, *34*(2), 169-176.

Klimesch, W., Doppelmayr, M., Schwaiger, J., Auinger, P., & Winkler, T. (1999). Paradoxical alpha synchronization in a memory task. *Cognitive Brain Research*, *7*(4), 493-501.

Klimesch, W., Schack, B., & Sauseng, P. (2005). The functional significance of theta and upper alpha oscillations. *Experimental Psychology*, *52*(2), 99.

Kok, P., Jehee, J. F., & De Lange, F. P. (2012). Less is more: expectation sharpens representations in the primary visual cortex. *Neuron*, *75*(2), 265-270.

Kumar, S., Kaposvari, P., & Vogels, R. (2017). Encoding of predictable and unpredictable stimuli by inferior temporal cortical neurons. *Journal of Cognitive Neuroscience, 29(8),* 1445-1454.

Kutas, M., DeLong, K.A., Smith, N.J. (2011). A look around at what lies ahead: Prediction and predictability in language processing. In M. Bar (Ed.), *Predictions in the Brain: Using Our Past to Generate a Future*. Oxford University Press (pp. 190-207).

Kutas, M., & Federmeier, K. D. (2000). Electrophysiology reveals semantic memory use in language comprehension. *Trends in Cognitive Sciences*, *4*(12), 463-470.

Kutas, M., & Federmeier, K. D. (2011). Thirty years and counting: finding meaning in the N400 component of the event-related brain potential (ERP). *Annual Review of Psychology*, *62*, 621-647.

Kutas, M., & Hillyard, S. A. (1980). Reading senseless sentences: Brain potentials reflect semantic incongruity. *Science*, *207*(4427), 203-205.

Kutas, M., & Hillyard, S. A. (1984). Brain potentials during reading reflect word expectancy and semantic association. *Nature, 307,* 161-163.

Lachaux, J. P., Rodriguez, E., Martinerie, J., & Varela, F. J. (1999). Measuring phase synchrony in brain signals. *Human Brain Mapping*, *8*(4), 194-208.

Lopez-Calderon, J., & Luck, S. J. (2014). ERPLAB: an open-source toolbox for the analysis of event-related potentials. *Frontiers in Human Neuroscience*, *8*, 213.

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods*, *164*(1), 177-190.

Mecklinger, A. (1998). On the modularity of recognition memory for object form and spatial location: a topographic ERP analysis. *Neuropsychologia*, *36*(5), 441-460.

Miller, G. A., & Selfridge, J. A. (1950). Verbal context and the recall of meaningful material. *The American Journal of Psychology*, *63*(2), 176-185.

Morey, R.D. (2008). Confidence intervals from normalized data: a correction to Cousineau (2005). *Tutorials in Quantitative Methods for Psychology*, *4(2),* 61–64.

O'Brien, E. J., & Myers, J. L. (1985). When comprehension difficulty improves memory for text. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *11*(1), 12-21.

Olichney, J. M., Van Petten, C., Paller, K. A., Salmon, D. P., Iragui, V. J., & Kutas, M. (2000). Word repetition in amnesia. *Brain*, *123*(9), 1948-1963.

Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J. M. (2011). FieldTrip: Open Source Software for Advanced Analysis of MEG, EEG, and Invasive Electrophysiological Data. *Computational Intelligence and Neuroscience, 2011,* 156869.

Paller, K. A., & Kutas, M. (1992). Brain potentials during memory retrieval provide neurophysiological support for the distinction between conscious recollection and priming. *Journal of Cognitive Neuroscience*, *4*(4), 375-392.

Paller, K. A., Kutas, M., & McIsaac, H. K. (1995). Monitoring conscious recollection via the electrical activity of the brain. *Psychological Science*, *6*(2), 107-111.

Palmer, J. A., Kreutz-Delgado, K., & Makeig, S. (2011). AMICA: An adaptive mixture of independent component analyzers with shared components. Retrieved from https://sccn.ucsd.edu/~jason/amica_a.pdf.

Perry, A. R., & Wingfield, A. (1994). Contextual encoding by young and elderly adults as revealed by cued and free recall. *Aging and Cogntion*, *1*(2), 120-139.

Piai, V., Roelofs, A., Rommers, J., & Maris, E. (2015). Beta oscillations reflect memory and motor aspects of spoken word production. *Human Brain Mapping*, *36*(7), 2767-2780.

Pickering, M. J., & Garrod, S. (2007). Do people use language production to make predictions during comprehension? *Trends in Cognitive Sciences*, *11*(3), 105-110.

Rao, R. P., & Ballard, D. H. (1999). Predictive coding in the visual cortex: a functional interpretation of some extra-classical receptive-field effects. *Nature Neuroscience*, *2*(1). 79-87.

Riggs, K. M., Wingfield, A., & Tun, P. A. (1993). Passage difficulty, speech rate, and age differences in memory for spoken text: Speech recall and the complexity hypothesis. *Experimental Aging Research*, *19*(2), 111-128.

Roehm, D., Bornkessel-Schlesewsky, I., & Schlesewsky, I. (2007). The internal structure of the N400: Frequency characteristics of a language related ERP component. *Chaos and Complexity Letters, 2,* 365–395.

Rommers, J., Dickson, D. S., Norton, J. J. S., Wlotko, E. W., & Federmeier, K. D. (2017). Alpha and theta band dynamics related to sentential constraint and word expectancy. *Language, Cognition and Neuroscience, 32(5),* 576-589.

Rugg, M. D. (1985). The Effects of Semantic Priming and Word Repetition on Event-Related Potentials. *Psychophysiology*, *22*(6), 642-647.

Rugg, M. D. (1990). Event-related brain potentials dissociate repetition effects of high-and low-frequency words. *Memory & Cognition*, *18*(4), 367-379.

Rugg, M. D., & Curran, T. (2007). Event-related potentials and recognition memory. *Trends in Cognitive Sciences*, *11*(6), 251-257.

Rugg, M. D., Mark, R. E., Walla, P., Schloerscheidt, A. M., Birch, C. S., & Allan, K. (1998). Dissociation of the neural correlates of implicit and explicit memory. *Nature*, *392*(6676), 595-598.

Scarborough, D. L., Cortese, C., & Scarborough, H. S. (1977). Frequency and repetition effects in lexical memory. *Journal of Experimental Psychology: Human Perception and Performance*, *3*(1), 1.

Schendan, H. E., Ganis, G., & Kutas, M. (1998). Neurophysiological evidence for visual perceptual categorization of words and faces within 150 ms. *Psychophysiology*, *35*(3), 240-251.

Smith, M. E. (1993). Neurophysiological manifestations of recollective experience during recognition memory judgments. *Journal of Cognitive Neuroscience*, *5*(1), 1-13.

Strauß, A. (2015). *Neural oscillatory dynamics of spoken word recognition.* Leipzig: Max Planck Institute Series in Human Cognitive and Brain Sciences, 163.

Strauß, A., Kotz, S. A., & Obleser, J. (2013). Narrowed expectancies under degraded speech: revisiting the N400. *Journal of Cognitive Neuroscience*, *25*(8), 1383-1395.

Stanovich, K. E., & West, R. F. (1979). Mechanisms of sentence context effects in reading: Automatic activation and conscious attention. *Memory & Cognition*, *7*(2), 77-85.

Tallon-Baudry, C., & Bertrand, O. (1999). Oscillatory gamma activity in humans and its role in object representation. *Trends in Cognitive Sciences*, *3*(4), 151-162.

Tanenhaus, M.K. & Trueswell, J.C. (1995). Sentence Comprehension. In Eimas & Miller (Eds.) Handbook in Perception and Cognition, Volume 11: Speech Language and Communication. Academic Press, pp. 217-262.

Van Berkum, J. J. A. (2010). The brain is a prediction machine that cares about good and bad - Any implications for neuropragmatics? *Italian Journal of Linguistics, 22,* 181-208.

Van Petten, C., Kutas, M., Kluender, R., Mitchiner, M., & McIsaac, H. (1991). Fractionating the word repetition effect with event-related potentials. *Journal of Cognitive Neuroscience*, *3*(2), 131-150.

Van Petten, C., & Luka, B. J. (2012). Prediction during language comprehension: Benefits, costs, and ERP components. *International Journal of Psychophysiology*, *83*(2), 176-190.

Van Petten, C., & Senkfor, A. J. (1996). Memory for words and novel visual patterns: Repetition, recognition, and encoding effects in the event-related brain potential. *Psychophysiology*, *33*(5), 491-506.

Van Strien, J. W., Verkoeijen, P. P., Van der Meer, N., & Franken, I. H. (2007). Electrophysiological correlates of word repetition spacing: ERP and induced band power old/new effects with massed and spaced repetitions. *International Journal of Psychophysiology*, *66*(3), 205-214.

Voss, J. L., & Paller, K. A. (2009). Remembering and knowing: Electrophysiological distinctions at encoding but not retrieval. *Neuroimage*, *46*(1), 280-289.

Wang, L., Zhu, Z., & Bastiaansen, M. (2012). Integration or predictability? A further specification of the functional role of gamma oscillations in language comprehension. *Frontiers in psychology*, *3*, 187.

Wilding, E. L., Doyle, M. C., & Rugg, M. D. (1995). Recognition memory with and without retrieval of context: An event-related potential study. *Neuropsychologia*, *33*(6), 743-767.

Wilding, E. L., & Rugg, M. D. (1996). An event-related potential study of recognition memory with and without retrieval of source. *Brain*, *119*(3), 889-905.

Wlotko, E. W., & Federmeier, K. D. (2012). So that's what you meant! Event-related potentials reveal multiple aspects of context use during construction of message-level meaning. *NeuroImage*, *62*(1), 356-366.

Wlotko, E. W., Federmeier, K. D., & Kutas, M. (2012). To predict or not to predict: Age-related differences in the use of sentential context. *Psychology and aging*, *27*(4), 975.

Yu, A. J., & Dayan, P. (2005). Uncertainty, neuromodulation, and attention. *Neuron*, *46*(4), 681-692.

Appendix

Further examples of the materials appear below.

Triplet	Condition	Sentence Frame	Word
1	Predictable	The jeweler was asked if he would examine the ring's huge	diamond
	Unpredictable	The guy was still wondering if anyone had noticed the big	diamond
	Critical	He started looking for the	diamond
2	Predictable	She thought she had seen a	ghost
	Unpredictable	He read a novel about a	ghost
	Critical	They had heard about the	ghost
3	Predictable	When Drew arrived unexpectedly at the restaurant, Laurie got him a chair from the adjacent	table
	Unpredictable	While Katie spent the morning working in the garden, Dan went shopping for a new	table
	Critical	They were told there was a problem with the	table
4	Predictable	Sam could not believe her story was	true
	Unpredictable	Brian was under the impression it was	true
	Critical	She had seen that it was not	true
5	Predictable	Joe went to the hardware store and bought a replacement window at twice the original	price
	Unpredictable	Robert had been studying hard for his Chinese test, but couldn't remember the translation for	price
	Critical	It was only later that Barbara discovered the	price
6	Predictable	Their picnic was ruined by the	rain
	Unpredictable	The kangaroo was surprised by the	rain
	Critical	They first tried whether it would work in the	rain
7	Predictable	The exit was marked by a large	sign
	Unpredictable	He described all the details of the	sign
	Critical	He looked around and saw a	sign
8	Predictable	After realizing he forgot utensils for his salad, the doctor went back to get himself a	fork
	Unpredictable	Everybody was disappointed when all they dug up in the middle of the field was a	fork
	Critical	He wondered whether it would be worth bringing a	fork
9	Predictable	In caring for hospitalized patients, a doctor often needs the help of a	nurse
	Unpredictable	One of my friends talked to me while the other talked to the	nurse
	Critical	Linda was looking at the	nurse
10	Predictable	Nora couldn't take the message because she didn't have a pencil or a piece of	paper
	Unpredictable	The man who stuttered always got tripped up when he had to say the word	paper
	Critical	She idly wondered whether there was a different word for	paper