

Alpha power decreases associated with prediction in written and spoken sentence comprehension

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ABSTRACT

Alpha and beta power decreases have been associated with prediction in a variety of cognitive domains. Recent studies in sentence comprehension have also reported alpha and/or beta power decreases preceding contextually predictable words, albeit with remarkable spatiotemporal variability across reports. To contribute to the understanding of the mechanisms underlying this phenomenon, and the sources of variability, the present study explored to what extent these prediction-related alpha and beta power decreases might be common across different modalities of comprehension. To address this, we re-analysed the data of two EEG experiments that employed the same materials in written and in spoken comprehension. Sentence contexts were weakly or strongly constraining about a sentence-final word, which was presented after a 1 s delay, either matching or mismatching the expectation. In written comprehension, alpha power (8–12 Hz) decreased before final words appearing in strongly (relative to weakly) constraining contexts, in line with previous reports. Furthermore, a similar oscillatory phenomenon was evidenced in spoken comprehension, although with relevant spatiotemporal differences. Altogether, the findings agree with the involvement of both modality-specific and general-domain mechanisms in the elicitation of prediction-related alpha power decreases in sentence comprehension. Specifically, we propose that this phenomenon might partly reflect richer and more precise information representation when linguistic contexts afford prediction.

1. Introduction

Prediction is thought to have an important role in achieving fast and efficient comprehension (Kuperberg et al., 2020; Kuperberg and Jaeger, 2016), a notion that is grounded in abundant evidence showing that readers and listeners can pre-activate different aspects of the incoming linguistic input during language comprehension, including semantic (Federmeier and Kutas, 1999), grammatical (van Berkum et al., 2005; Wicha et al., 2004) or phonological features of words (DeLong et al., 2005; but see Nieuwland, 2018). Yet, the neural mechanisms that underlie predictive language processing remain unclear.

Neural oscillations – patterns of synchronization and desynchronization of neural activity captured in the EEG and MEG signal as power increases and decreases – have been associated with predictive language

processing in the past (Lewis and Bastiaansen, 2015; Meyer, 2018). A common strategy to study prediction in language comprehension is to manipulate the degree to which semantic contexts are constraining about a specific word, such that they are strongly predictive, or not (high constraint contexts, HC or low constraint contexts, LC; for examples, see Table 1). Using this approach, oscillations in the theta (4–7 Hz) and gamma (>40 Hz) bands have been attributed to the match and mismatch of lexical and semantic predictions of critical words after they are perceived (Bastiaansen and Hagoort, 2015; Hald et al., 2006; Wang et al., 2017). By contrast, prediction implies that processing differs *before* the critical input is encountered. Accordingly, an MEG study reported theta (4–8 Hz) power increases before words (e.g., ‘apple’) that could be unequivocally predicted from a preceding HC pictorial context (a picture of an apple), relative to LC pictorial contexts (a picture of a

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Table 1
Example sentences of each condition (original sentences in Spanish in brackets).

Condition	Sentence context	Congruent	Incongruent
HC	The goalkeeper managed to catch the (El portero fue capaz de atrapar la)	ball (pelota)	shore (orilla)
LC	As a present she gave her son a (Le ha regalado a su hijo una)	ball (pelota)	shore (orilla)

grocery bag), an effect that was localized at left mid-temporal and visual cortex, suggesting pre-activation of lexical and visual form representations (Dikker and Pylykänen, 2013). More recently, M/EEG studies employing written sentential contexts have observed alpha (8–12 Hz) and/or beta (~13–25 Hz) power decreases prior to critical words in HC relative to LC contexts (Rommers et al., 2017; Li et al., 2017; Wang et al., 2017; Terporten et al., 2019). The alpha and beta power effects in these studies broadly overlap at left frontal sites. For instance, Wang and colleagues (2018) localized their effect in a left-lateralized top-down network involving left inferior frontal gyrus and mid-temporal areas, as well as visual regions, suggesting lexical and/or semantic prediction. However, the available data in written comprehension is still somewhat scarce, and the experimental settings diverge considerably across studies, thus hindering the functional interpretation of these alpha and beta power decreases in regard to predictive language processing (see for reviews, Molinaro et al., 2016; Prystauka and Lewis, 2019) and justifying the need for further research.

Furthermore, a question that remains unclear is to what extent these pre-word alpha and beta power decreases may be common across different modalities of comprehension, which can provide important information about the cognitive mechanisms underlying their elicitation. On the one hand, pre-stimulus alpha and beta power decreases have been previously associated with processes that are sensitive to input modality, including sensory gating of relevant input (Jensen et al., 2012) or the sensory prediction of upcoming input (Arnal and Giraud, 2012). Consistent with these views, in perceptual tasks, alpha power decreases emerge at posterior-occipital sites prior to an imperative visual stimulus (Thut et al., 2006; Worden et al., 2000; Foxe et al., 1998), or at temporal sites when the imperative stimulus is auditory (for a review, see Weisz et al., 2011). On the other hand, other accounts propose that pre-stimulus alpha and beta power decreases reflect operations that enable and support information processing beyond sensory and perceptual aspects (Hanslmayr et al., 2012; Van Ede, 2018; Griffiths et al., 2019). Specifically, it has been suggested that alpha and beta power decreases provide an optimal brain state for information processing (Hanslmayr et al., 2012), which can account for their correlations with successful memory encoding in a variety of tasks (Klimesch, 1997; Khader and Rösler, 2011; Hanslmayr et al., 2011). Also, alpha and beta power decreases have been associated with lexico-semantic retrieval before naming a picture that is preceded by an HC context in both visual and auditory modalities (for a review, see Piai and Zheng, 2019).

Given this background, we aimed to further characterize alpha and beta power decreases associated with prediction in sentence comprehension, and to explore to what extent these neural signatures might be common across modalities of comprehension. To this end, we performed time-resolved power analyses in the pre-existing datasets of two separate EEG studies using the same materials in written (León-Cabrera et al., 2019) and in spoken comprehension (León-Cabrera et al., 2017). In these studies, participants either read or listened to HC and LC sentences with a 1-s delay before the presentation of the final word (see Table 1). The actual word could match or mismatch the most likely word given the previous context. For each dataset (written and spoken), we assessed power changes in the 1-s interval prior to the sentence-final words. First, we performed the analyses in the written comprehension task, in which we expected to find alpha and beta power decreases for HC compared to LC based on previous studies using similar tasks and the

same modality of comprehension (Rommers et al., 2017; Li et al., 2017; Wang et al., 2017; Terporten et al., 2019; see for reviews, Molinaro et al., 2016; Prystauka and Lewis, 2019). Then, we explored to what extent there were similar power changes in the spoken comprehension task.

2. Methods

2.1. Written comprehension task

2.1.1. Participants

Twenty-four young adults (12 females) voluntarily participated in the experiment in exchange for monetary compensation. The data of two participants was removed due to excessive blinking and movement artefacts, resulting in a final dataset of 22 participants (12 females; $M = 23.3$ years [$SD = 4.4$]). All participants were native Spanish speakers, right-handed, with normal or corrected-to-normal vision and no history of neurological problems. The study was approved by the Ethics Committee of Hospital Universitari de Bellvitge.

2.1.2. Materials

A total of 176 high constraint (HC) and 176 low constraint (LC) sentence contexts were employed (created and categorized by Mestres-Missé et al., 2006) (see Table 1 for sentence examples). The sentence contexts were originally designed to have the same final word (best completion) in both conditions. For example, the LC sentence “The dot in the sky must be a *plane*” shared the final word with the HC sentence “I have never flown on a *plane*”. For every participant, a set of 80 HC sentences and 80 LC sentences were pseudo-randomly selected from the list with the condition that none shared the final word. As a result, each final word was encountered only once during the experiment while their constraint status was counterbalanced across participants. Half of the sentences in each constraint condition ended with a congruent word (the best completion) and half with an incongruent and implausible word. The mean cloze probability of the final words was 6.1% ($SD \pm 10.3\%$) in the LC condition and 76% ($SD \pm 17.7\%$) in the HC condition. Incongruent endings were selected from the ESPAL database (Duchon et al., 2013) so that they matched the congruent endings in mean word length, mean number of syllables, word frequency, familiarity, imaginability and concreteness. Finally, a non-semantic condition (NS) served as a control condition in which no meaning could be derived from the sentence contexts (further specifications about this condition can be found in the original papers, León-Cabrera et al., 2017, 2019). We note, however, that this condition will not be analysed in the present study.

2.1.3. Procedure

Participants were comfortably seated approximately 70 cm away from the computer screen. The EEG cap was set up and the state of each electrode was checked. Before the experiment started, participants were briefed on the importance of minimizing movement and were instructed to synchronize their blinks to the blinking signal and to prevent them at other times. Participants were told to attentively read the sentences and that they would have to complete a short recognition test of the final words at the end of every block of sentences.

Following the instructions, the experiment started. The experiment consisted of 10 blocks of 20 trials (4 HC congruent, 4 HC incongruent, 4 LC congruent, 4 LC incongruent and 4 NS). The order of the sentences within each block was random. Words were black on white background (font type: Courier New; font size: 36 points). On each trial, a fixation point (a cross) appeared at the centre of the screen for a variable interval (between 1.35 and 1.75 s in a uniform distribution with a 50 ms step). Then, a sentence was presented word-by-word (200 ms per word, followed by a 300 ms blank screen). Between the penultimate and the final word, the blank screen remained for a period of 1 s (pre-word interval). After the final word (200 ms duration), a blank screen was presented (800 ms) before the blinking signal (2 s; depiction of an eye at the centre of the screen). The next trial began after the offset of the blinking signal.

To ensure that participants remained engaged during the task, a recognition test followed each block, in which they were presented with 5 old and 5 new words, one at a time, and had to indicate whether each word had appeared in the previous block or not. The next block started immediately after the test except for even-numbered blocks, which were followed by a resting period that could be resumed anytime by the participant.

2.1.4. Data acquisition

Electrophysiological data (EEG; sampling rate = 500 Hz; on-line bandpass filter = .015–250 Hz [half amplitude cut offs]) was recorded from 31 tin scalp electrodes at standard 10/20 system positions (electrode positions: FPz, FP1/2, Fz, F3/4, F7/8, FCz, FC3/4, Cz, C3/4, CPz, CP3/4, Pz, P3/4, TP7/8, T3/4, T5/6, Oz, O1/2, left and right mastoids). Vertical and horizontal electro-oculograms (outer canthus and infraorbital ridge of the right eye) were recorded to monitor eye blinks and movement. All electrode impedances were kept below 5 k Ω . The EEG was amplified with a BrainAmp Standard amplifier and recorded with Brainvision Recorder V 1.20.05.

2.1.5. EEG pre-processing

EEG analyses were performed using FieldTrip version 20181231 (Oostenveld et al., 2011) in MATLAB R2019b. First, data were notch-filtered at 50 Hz to attenuate electrical line noise and re-referenced offline to the average of the mastoid electrodes. The continuous data were segmented into epochs of 3 s relative to the onset of interval prior to the sentence-final word: 1 s before and 2 s after the onset of the anticipatory interval. Then, Independent Component Analysis (ICA) (as implemented in FieldTrip) was applied to remove eye movement artefacts. Between 1 and 3 components per participant were removed. Additionally, any remaining epochs with artefacts (eye blinks, eye movements, electrode drifting or muscle activity) were rejected through visual inspection before trials were split by condition. After artefact rejection, the percentage of valid trials was 90.2% in the HC condition (mean = 72 trials; std = 6.28 trials), and 89.65% in the LC condition (mean = 71 trials; std = 5.26 trials).

2.1.6. Time-resolved power analyses

Time-frequency (TF) representations of power were computed on the segmented epochs and from 2 to 30 Hz in the spectral domain (Rommers et al., 2017). To obtain the TF representations, a moving window, short-time Fast Fourier Transform (FFT) approach was used. A sliding window of three cycles was advanced in steps of 20 ms and 1 Hz. Thus, the window length varied across frequencies, such that the temporal resolution improved at higher frequencies – i.e., it had a length of 375 ms at 8 Hz (lower alpha), and of 200 ms at 15 Hz (upper alpha/lower beta). Then, the data in each window was multiplied with a Hanning taper and Fourier-transformed. The resulting spectrograms were averaged over trials for each participant and condition. For visualization and statistical analysis of the contrasts between conditions, each condition was normalized by the average across conditions (i.e., for every participant, the power spectrum of each condition was divided, element by element, by the averaged power spectrum of the two conditions) (for other studies using a similar approach, see Piai et al., 2014; Rommers et al., 2017). We used this approach because it allows to assess relative power changes without pre-stimulus baseline correction, which was appropriate in this case given that differences between the conditions were expected to be present before the anticipatory interval due to the processing of sentence contexts (León-Cabrera et al., 2019). For visual inspection of power changes in individual conditions in the anticipatory interval, power was computed relative to a baseline from –500 ms to –150 ms time-locked to the onset of the anticipatory interval.

We tested for effects of contextual constraint in the whole 1 s anticipatory interval using a non-parametric cluster-based permutation test (Maris and Oostenveld, 2007), as implemented in FieldTrip. Importantly, this statistical approach successfully controls the

family-wise error rate (FWER) in the set of multiple comparisons. We restricted the analysis to the 8–20 Hz frequency range, based on previous evidence showing effects of contextual constraint in the alpha (8–12 Hz) and lower beta (15–20 Hz) bands (Rommers et al., 2017; Li et al., 2017; Wang et al., 2017). Within this spectral range, all time points and electrodes were blindly scanned for adjacent frequencies, time points and electrodes with a similar difference across conditions. Every sample (frequency \times time \times channel) was compared between the two conditions (HC vs. LC) by means of a paired-samples *t*-statistic. Channels were set to have an average of 6.1 neighbours. Then, adjacent time-frequency-channel samples were clustered based on a *t*-value threshold of ± 2.07 (for an alpha level of 0.05 with 21 degrees of freedom). The permutation *p*-value was computed using the Monte Carlo method involving 5000 random permutations. Only effects with a permutation *p*-value below 5% (two-tailed testing) were considered significant.

2.2. Spoken comprehension task

2.2.1. Participants

Twenty-two young adults (12 females; $M = 21.1$ years [$SD = 1.8$]) voluntarily participated in the experiment in exchange of monetary compensation. All participants had normal hearing, were native Spanish speakers, right-handed, with normal or corrected-to-normal vision and no history of neurological problems. The study was approved by the Ethics Committee of Hospital Universitari de Bellvitge.

2.2.2. Materials

The materials were the same as the in the written comprehension task (see Section 2.1.2). For auditory presentation, all the linguistic stimuli were transformed to audio using a voice-synthesizer software (Loquendo TTS Director, 2005). This software creates natural-sounding audio, very close to natural speech, while allowing precise control of the speech rate, the amplitude and the prosody of the speech (for a sample sentence of each condition, see the supplementary materials of León-Cabrera et al., 2017). After audio conversion, sentence contexts had a mean duration of 1966 ms ($SD = 288$ ms) (HC = 2000 ms, LC = 1925 ms and NS = 1992 ms). Final words had a mean duration of 490 ms ($SD = 122$ ms) (Congruent words = 485 ms; Incongruent words = 494 ms; Neutral words = 495 ms).

2.2.3. Procedure

The procedure followed was the same as in the written comprehension task (see Section 2.1.3), but the task was adapted for auditory presentation. Trials proceeded as follows. A fixation point (a black cross on white background) appeared and remained at the centre of the screen throughout the trial. Participants were instructed to fixate their gaze on it. Two seconds after the presentation of the fixation point, the sentence was auditorily presented with a silent interval of 1 s between the penultimate and the final word. One second after the offset of the final word the blinking signal was presented (a depiction of an eye at the centre of the screen). The blinking signal remained for 2 s before the next trial began.

2.2.4. Data acquisition

The only differences compared to the description of the written comprehension task (Section 2.1.4) were the sampling rate, which was 1000 Hz (band-pass filtering of 0.015–500 Hz [half amplitude cut off]) and the montage, which also included 31 tin scalp electrodes at standard 10/20 system positions, but with a different configuration (electrode positions: Fp1/2, Fz, F3/4, F7/8, FCz, FC1/2, FC5/6, Cz, C3/4, T3/4, T5/6, CP1/2, CP5/6, Pz, P3/4, PO1/2, Oz, left and right mastoids). The EEG was amplified with a BrainAmp Standard amplifier and recorded with Brainvision Recorder V 1.20.0601.

A) Written comprehension

B) Spoken comprehension

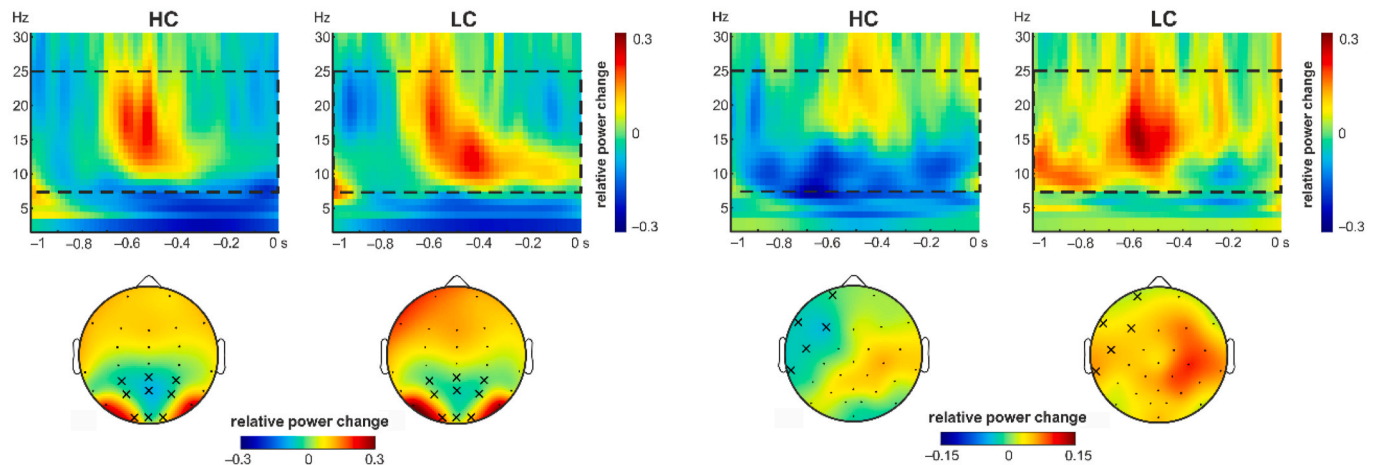


Fig. 1. Grand-averaged TF representations and topographical maps of the individual conditions (HC and LC) for the two tasks. In all plots, the color scale indicates the proportion of power change relative to a baseline of -500 to -150 ms time-locked to the onset of the anticipatory interval. The final word appeared at 0 s. A) Written comprehension. Top: TFRs of the individual conditions at the subset of channels highlighted in the scalp maps (CP3/4, CPz, P3/4, Pz, O1/2, Oz). The discontinuous line indicates the alpha and beta ranges (8–25 Hz). Bottom: corresponding scalp maps of averaged power in the alpha and beta bands (8–25 Hz). B) Spoken comprehension. Top: TFRs of the individual conditions at a subset of representative channels highlighted in the scalp maps at the bottom (FP1, F3, F7, C3, T3). Bottom: corresponding scalp maps of the averaged power in the alpha and beta bands (8–25 Hz). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2.2.5. EEG pre-processing

The pre-processing settings and criteria were the same as in the written comprehension task (see Section 2.1.5). After artefact rejection, a total of 91.3% valid trials were retained in the HC condition (mean = 73 trials; std = 6.55 trials) and of 93% in the LC condition (mean = 74 trials; std = 5.43 trials).

2.2.6. Time-resolved power analyses

The parameters for this analysis were selected based on the findings in the written comprehension task, as the purpose was to determine to what extent power decreases were common in the two modalities of comprehension. Of note, the decision to start with the written comprehension task was motivated by the fact that there were already several available studies showing constraint-related alpha-beta power decreases in that modality (Li et al., 2017; Rommers et al., 2017; Terporten et al., 2019; Wang et al., 2017), which allowed us to first attempt to replicate this finding, and then proceed to extend the prediction to the spoken comprehension modality in a hypothesis-driven manner. Therefore, as the power decreases in the written comprehension were most prominent in the alpha and lower beta band (see Section 3.1.), the time-resolved power analyses in the spoken comprehension task were constrained to this spectral range. Time-resolved representations of alpha power were computed on the 3-s-long epochs (1 s before and 2 s after the onset of the anticipatory interval), applying a FFT with discrete prolate spheroidal sequences (DPSS) tapers to the data. The frequency of interest was set to 12 Hz with a spectral smoothing of 4 Hz. The window length was 3 cycles (i.e., 250 ms) and slid in steps of 20 ms. The obtained time series of estimated power were averaged over the 8–16 Hz range and over trials for each participant and condition. Following the same procedure as in the written comprehension task, data were normalized by the average across conditions before visualization and statistical analysis (see Section 2.1.6. for more details about the normalization procedure).

For statistical analysis, a non-parametric cluster-based permutation test (Maris and Oostenveld, 2007) was performed on the averaged frequencies, thus reducing the dimensionality of the data to the temporal and spatial domain. The 1-s anticipatory interval was blindly scanned for adjacent time points and electrodes with a similar difference across the two conditions. Every sample (time x channel) was compared

between the two conditions (HC vs. LC) by means of a paired-samples t -statistic. Channels were set to have an average of 6.1 neighbours. Then, adjacent spatio-temporal samples were clustered based on a t -value threshold of ± 2.07 (for an alpha level of 0.05 with 21 degrees of freedom). The permutation p -value was computed using the Monte Carlo method involving 5000 random permutations. Only effects with a permutation p -value below 5% (two-tailed testing) were considered significant.

3. Results

To visualize the power changes for the individual conditions (see Fig. 1), we computed power changes relative to the baseline from -500 to -150 ms time-locked to the onset of the anticipatory interval. Because the baseline contains activity of the processing of the penultimate word, no baseline normalization was performed for contrasts between conditions (read Section 2.1.6 for details). Therefore, the spectrograms of the contrasts (Fig. 2 and Fig. 3) do not derive directly from those of the individual conditions (Fig. 1).

3.1. Written comprehension

Visual inspection of the relative power changes as a function of contextual constraint revealed a transient decrease in power in the alpha band for HC relative to LC (Fig. 2). The relative difference in power was supported by the finding of a significant difference ($p = 0.0378$), detected in the 8–12 Hz alpha band. This result is displayed in Fig. 2, which shows the relative power decrease for the HC compared to the LC condition at two representative electrodes (top left and top right), with the cluster with the most extreme cluster statistic of the contrast bordered in white. Although the scalp distribution of the cluster was widespread, the effect was most prominent over frontal and parieto-occipital sites. The effect had a mainly frontocentral distribution from -600 to -400 ms, and later, from -400 to -200 ms, it was more constricted to parieto-occipital sites.

Written comprehension

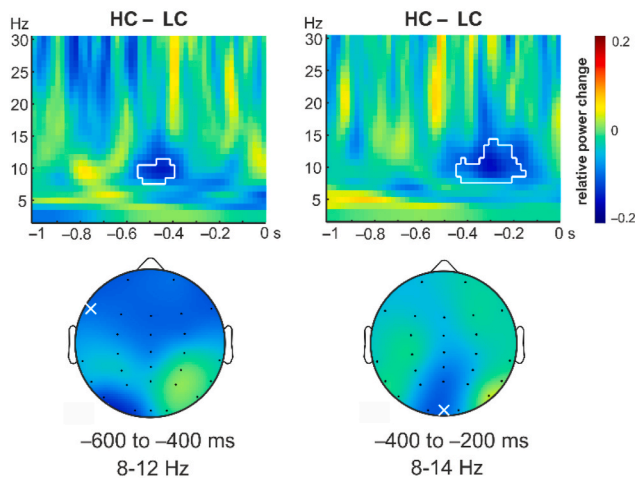


Fig. 2. Main results of the time-resolved power analyses in the written comprehension task. Grand-averaged TF of the constraint effect (HC minus LC) in the anticipatory interval, showing the cluster with the most extreme cluster statistic of the contrast (bordered in white) at the F7 (left) and Oz (right) electrodes, which are highlighted in the scalp maps below (white crosses). The scalp maps were computed in the time interval and frequency range that were most representative of the observed cluster. The data were normalized by the average of the two conditions. The final word appeared at 0 s.

Spoken comprehension

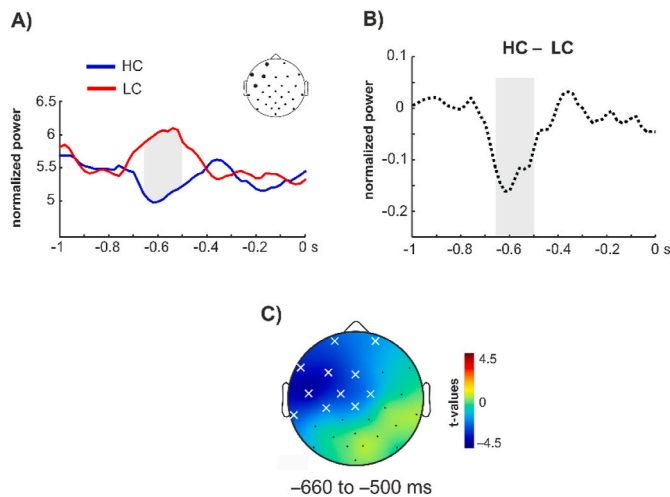


Fig. 3. Main results of the time-resolved power analyses in the spoken comprehension task. Time-resolved power was computed using 12 Hz as centre frequency with a ± 4 Hz smoothing to focus selectively on the alpha band. A) Normalized power changes for HC (in blue) and LC (in red) averaging a set of left frontal electrodes for display purposes (Fp1, F7, F3, and FC3). The grey shadowed area indicates the most prominent time interval of the cluster. B) Difference waveform (HC minus LC) of normalized power, again highlighting the time window of the effect. C) Scalp map of the mean power differences from -660 to -500 ms (time-locked to the onset of the sentence-final word), which is the most prominent time interval associated with the cluster with the most extreme cluster-statistic of the constraint effect in the alpha band. The electrodes with the most extreme cluster-statistic are highlighted in the scalp map (white crosses). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.2. Spoken comprehension

Following the findings in the written comprehension task, we tested to what extent the observed power decreases were common across modalities of comprehension. To this end, in the spoken comprehension task, the analysis was constrained in the spectral domain to the alpha band, where the constraint effect was observed in the written comprehension task (with the frequency of interest set to 12 Hz and a smoothing of 4 Hz). The contrast between HC and LC revealed a negative cluster ($p = 0.032$). As can be seen in Fig. 3, the most prominent time interval of the cluster was from -660 to -550 ms before the presentation of the final word, in which alpha power was decreased in HC compared to LC. In terms of spatial distribution, electrodes at left fronto-central positions were most associated with the cluster.

To improve between-experiment comparability, we conducted an additional analysis on the spoken comprehension dataset, applying the same parameters as those used in the written comprehension task (see Section 2.1.6). Grand-averaged time-frequency plots and scalp maps of both tasks are displayed together in Fig. 4. In this case, however, the contrast yielded no significant clusters in the spoken comprehension dataset. This suggests that the effect in the spoken comprehension task was weaker than in the written comprehension modality, as it did not survive when the analysis was not constrained in the power domain a priori. Nevertheless, there are several reasons that may account for a weaker effect in the auditory modality. For example, spoken sentences have variable durations, unlike sentences presented in written format, which all had the same duration. As a result, there may be a higher inter-trial variability in the timing of underlying neural processes, which, in turn, would lead to smaller effects in the averaged signal. Lastly, the method chosen for statistical testing may have been too conservative in this specific situation. Although the cluster-based permutation approach is appropriate for multidimensional data, it may become too conservative to detect small but meaningful effects (Groppe et al., 2011; Huang and Zhang, 2017).

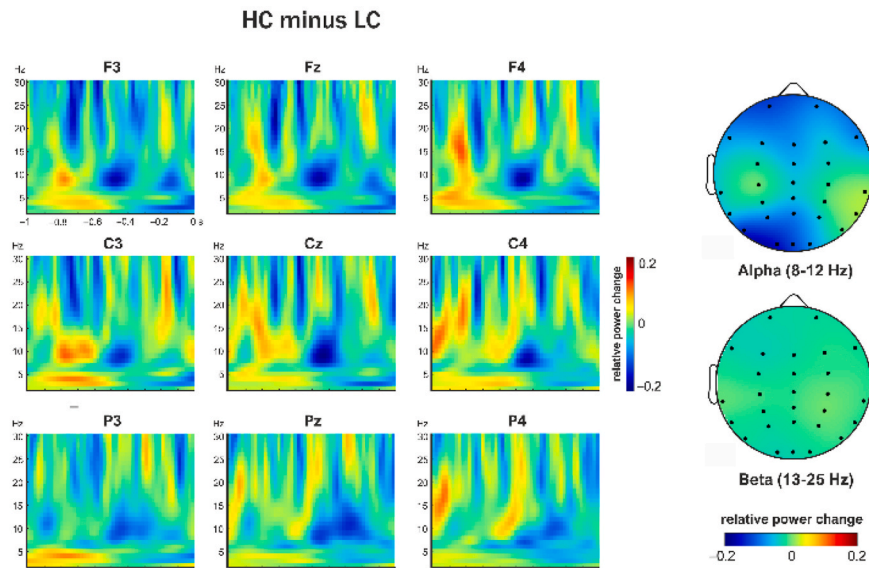
3.3. Group-level power spectra in spoken and written comprehension

To provide complementary information, we additionally inspected the group-level power spectra as a function of contextual constraint over separate subsets of electrodes (frontocentral, left frontocentral, right frontocentral, centroparietal and parieto-occipital) in each task. We plotted frequencies from 7 to 25 Hz to capture the alpha and beta range, where the effects were expected given previous literature (e.g., Rommers et al., 2017; Li et al., 2017; Wang et al., 2017; Terporten et al., 2019). As can be seen in Fig. 5, and in line with the time-resolved power analyses, spectral power was restricted to the lower alpha band (8–12 Hz) in both tasks, and absolute power was visibly reduced for HC compared to LC. In the spoken comprehension task, however, this pattern of differences was inverted in the parieto-occipital subset, in which absolute power was greater for HC than for LC.

4. Discussion

This study investigated alpha and beta power decreases associated with prediction in sentence comprehension, and their generality across different modalities of comprehension. To test this, the datasets from two EEG studies using the same materials in written and spoken comprehension were re-analysed. Participants either read or listened to HC and LC sentence contexts, which respectively established strong or weak semantic expectations about a sentence-final word that was presented after a 1-s delay. The sentence-final word could match or mismatch the contextual expectation. In written comprehension, alpha power (8–12 Hz) decreased in HC relative to LC in the interval prior to the critical word, as we had hypothesized based on previous reports (Li et al., 2017; Rommers et al., 2017; Terporten et al., 2019; Wang et al., 2017). In addition, a similar oscillatory phenomenon was evidenced in

A) Written comprehension



B) Spoken comprehension

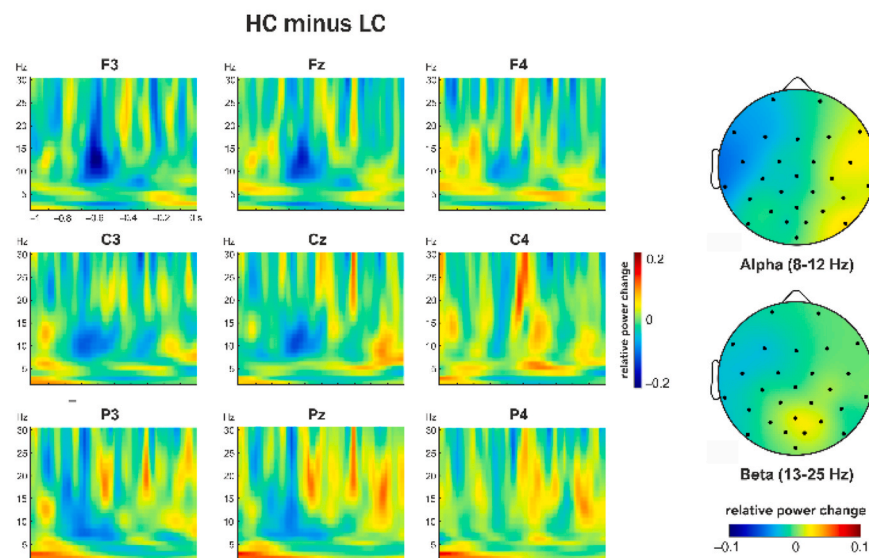


Fig. 4. Grand-averaged TFRs and topographical maps for qualitative comparison of effects between comprehension modalities. Scalp maps of the averaged power in the anticipatory interval in alpha (8–12 Hz) and beta (13–25 Hz) bands.

spoken comprehension, although with relevant spatiotemporal differences.

The current results agree with the involvement of both general domain and modality-specific processes in the elicitation of constraint-related alpha power decreases in sentence comprehension. Overall, both comprehension modalities exhibited an alpha power decrease in the pre-word interval when final words were more predictable (HC relative to LC), and the effects coarsely overlapped at left frontal electrodes. While these similarities suggest the engagement of a common, domain general cognitive process, there is also considerable variability in the spatial distribution and the duration of the two effects, pointing to the intervention of modality-specific mechanisms. Specifically, in the written comprehension task, the scalp distribution of the alpha power decrease was variable within the pre-word interval, with an initially widespread distribution (about –600 to –400 ms) and a later more constrained parieto-occipital distribution (about –400 to –200 ms).

This pattern is similar to that reported by Rommers et al. (2017), who observed successive short-lived alpha power decreases at fronto-central electrodes and then at posterior-occipital electrodes, in the 200 msec immediately preceding constrained sentence-final words. This posterior-occipital alpha power decrease might be associated with sensory-specific anticipation given that, in other cognitive domains, pre-stimulus alpha power decreases over posterior-occipital regions are reliably found when anticipating an imperative visual stimulus (Bidet-Caulet et al., 2012; Thut et al., 2006; Worden et al., 2000) and in some cases correlate with improved visual perception (Jensen and Mazaheri, 2010; Jensen et al., 2012; Mathewson et al., 2014; van Dijk, Schoffelen, Oostenveld & Jensen, 2008).

In the spoken comprehension task, the alpha power decrease was comparatively more restricted to left frontal electrodes, began earlier and was shorter-lived. Of note, in this modality, differences were significant only in the planned analysis, when the statistical analysis was

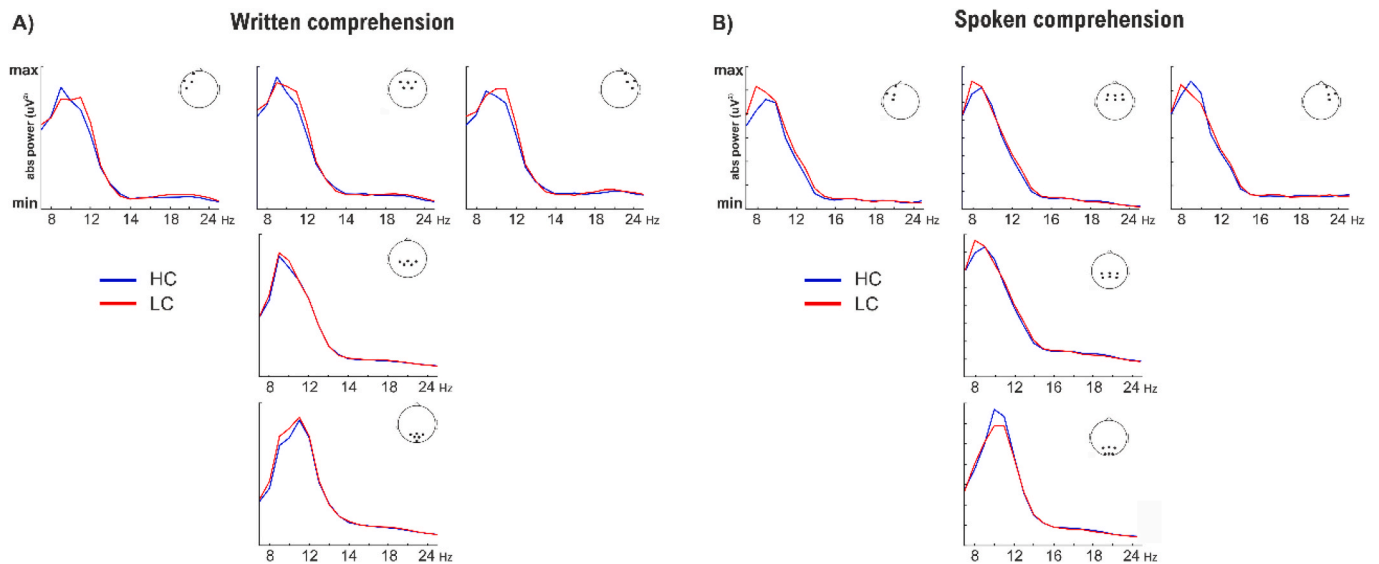


Fig. 5. Time-averaged power spectra for HC (in blue) and LC (in red) in the (A) written and in the (B) spoken comprehension task, averaged over five sets of electrodes that are highlighted next to each spectrum. Note that the electrodes included in each set differ between the two tasks, as different EEG montages were employed. The power axis (y-axis) is scaled to span from 0 to maximum power for each spectrum individually. The frequency axis (x-axis) ranges from 7 to 25 Hz. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

restricted to the alpha band (8–12 Hz) in a hypothesis-driven manner based on the results from the written comprehension task (see Section 2.2.6). When the test was spectrally uninformed, the alpha power decrease did not reach statistical significance, suggesting that the effect was weaker in the spoken comprehension task. Given the importance of methodological choices in the detection of this phenomenon (and the variability in the field, as discussed below), we recommend future studies to pre-register their analyses. Although the finding in the spoken comprehension task requires further replication, we deem it unlikely that it is spurious, considering its similarities with the effects in the current and in previous written comprehension tasks (Li et al., 2017; Rommers et al., 2017; Terporten et al., 2019; Wang et al., 2017). In fact, during the process of publishing this work, another study also reported similar alpha and beta power decreases in spoken comprehension (Gastaldon et al., 2020), further corroborating the reliability of the observed effect. Alternatively, a weaker effect in the spoken comprehension task could also be explained by task-related factors. In written comprehension studies, sentences are typically presented one word at a time at a uniform and relatively slow pace (minimum of 200 msec of word presentation and of 300 of inter-word delay, in some cases up to 800 msec [Terporten et al., 2019; Wang et al., 2017]), whereas in the spoken comprehension task the duration of the sentences –and consequently the onset of the sentence-final word– is more variable. As a result, in written comprehension studies, individuals have more time to predict sentence-final words, an aspect that is known to boost prediction-related phenomena (Huettig and Guerra, 2019; Wlotko and Federmeier, 2015). However, critically, this factor was kept constant between experimental conditions (HC and LC), and thus cannot fully account for the nature of the effect.

On a broader scope, the current findings add up to the pre-existing variability in the field, which is noteworthy given the scarcity of the available data about this phenomenon in sentence comprehension (reviewed in Molinaro et al., 2016; Prystauka and Lewis, 2019). For example, the spectral range of the effect sometimes only encompasses the alpha band (8–12 Hz) (current study; Rommers et al., 2017; Terporten et al., 2019), the beta band (16–25 Hz) (Li et al., 2017; Molinaro et al., 2016), and sometimes both bands (Gastaldon et al., 2020; Wang et al., 2017). With respect to its timing, the onset and duration of the effect is variable but tends to be short-lived and largest within the 500 ms preceding the target word (Gastaldon et al., 2020; Li et al., 2017;

Rommers et al., 2017; Terporten et al., 2019; Wang et al., 2017), as in the current study. Finally, the spatial distribution is probably the most inconsistent feature of this phenomenon. Identified sources of the effect in written and spoken comprehension include prefrontal locations (Gastaldon et al., 2020; Wang et al., 2017) and right (Terporten et al., 2019) and left posterior-temporal locations (Gastaldon et al., 2020; Wang et al., 2017). Here, the effects in written comprehension and spoken comprehension coarsely overlapped at left frontocentral electrodes, although their exact sources remain unknown. It is altogether difficult to establish the origin of this variability given differences in the technique (i.e., EEG or MEG), the methods (e.g., the spectral decomposition approach and statistical approach), or the materials employed (e.g., all or only half of words are expected) in the available studies.

Overall, what seems to tie the different available studies together, including the current one, is the notion that alpha and/or beta is lower about 500 msec prior to contextually more predictable words, notwithstanding relevant differences in the exact spectral range, timing, and spatial distribution of the effects. What mechanism could account for this commonality? Pre-stimulus alpha-beta power decreases have been associated with encoding and retrieval of information (Hanslmayr et al., 2012). Specifically, they have been recently linked to richness of information represented in the system (Griffiths et al., 2019). Accordingly, HC contexts (compared to LC), would lead to richer and more precise lexical and/or semantic representations (for similar notions, see Graesser et al., 1994; Singer et al., 1994). Furthermore, some of these pre-stimulus alpha/beta power decreases in other cognitive domains have been localized to sources in the left inferior prefrontal cortex, suggesting a link to language-related mechanisms (Hanslmayr et al., 2011; Kieler et al., 2015; Meeuwissen et al., 2011). Here, we observed a certain spatio-temporal overlap of the effects in the two modalities at left-fronto central sites, which is also reminiscent of other fronto-central left-lateralized constraint-related power decreases in the alpha band (Gastaldon et al., 2020; Wang et al., 2017). For example, Wang et al. (2017) source-localized their constraint-related alpha power decrease to a left-lateralized brain network involved in language processing. Altogether, the alpha and/or beta constraint-related decrease consistent across studies might reflect greater and more precise representation of linguistic information in HC (compared to LC) contexts. The greater amount of information being represented within the system in HC might be associated with the construction of a richer context representation,

from which the comprehender might then derive predictions of features at lower representational levels (Ferreira and Chantavarin, 2018). More broadly, this interpretation is also compatible with a more general view of alpha power decreases as reflecting functional disinhibition of task-relevant regions to boost information processing (Jensen and Mazaheri, 2010; Klimesch, 2012).

Finally, caution must be taken when attempting to generalize the current findings to more naturalistic settings. Task dispositions, such as the introduction of an artificial delay or a silent gap before the sentence-final word, might lead to task-related strategic processing. Yet, the effects resemble those of prior studies introducing less salient delays (Li et al., 2017; Rommers et al., 2017), suggesting that they might not be entirely dependent on that manipulation. To elucidate this, future studies could combine delays with different durations. Another limitation of the current study is that we could not perform direct quantitative comparisons between the effects observed in the two tasks, as they were conducted using different participants and with different electrode montages. Future studies could adopt a more appropriate within-subjects approach. For example, Gastaldon et al. (2020) recently adopted a within-subject design to uncover similar and correlated alpha-beta constraint-related power decreases in comprehension and production. In production tasks, alpha-beta (8–25 Hz) power decreases have been consistently found at left inferior parietal and temporal (and frontal) areas before naming a picture in HC contexts (e.g., Piai et al., 2015; Piai et al., 2018; Hustá et al., 2021; Roos and Piai, 2020), which is taken as a fingerprint of lexical and semantic retrieval (see for a review Piai and Zheng, 2019). However, in Gastaldon et al. (2020), the effects were shorter-lived and weaker in the comprehension than in the production task. This fact, along with the variability that we have highlighted, calls for further examination of the constraint-related alpha-beta power decreases in language comprehension.

5. Conclusions

The current findings add up to the general observation that, in written comprehension, alpha power decreases immediately prior to strongly contextually constrained words (relative to unconstrained ones). In addition, our findings contribute by describing this phenomenon in spoken comprehension, although evidencing a weaker effect in this modality. Our results are compatible with the involvement of both sensory-related and domain general mechanisms in the elicitation of the effect. We propose that constrained-related alpha power decreases might reflect richer and more precise information representation in contexts that afford strong lexical and/or semantic predictions. Yet, considering the remarkable variability in the field, this phenomenon merits further investigation.

Credit author statement

PLC: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing - Original draft, and Writing - Review & Editing; VP: Methodology, Formal analysis, Writing - Review & Editing; JM: Conceptualization, Methodology, Writing - Review & Editing; ARF: Conceptualization, Methodology, Writing - Review & editing.

Declaration of competing interest

The authors declare no disclosure of financial interests and potential conflict of interest.

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