Speech-brain phase coupling is enhanced in low contextual semantic predictability conditions

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Abstract

Semantic prediction and cortical entrainment to the acoustic landmarks of the speech envelope are two fundamental yet qualitatively different mechanisms that facilitate speech comprehension. However, it is not clear how and to what extent those mechanisms interact with each other. On the one hand, richer semantic context could enhance the perceptual representation of a predictable stimulus, thus improving speech entrainment. On the other hand, pre-activating an upcoming item could inhibit further bottom-up analyses to minimize processing costs, thus weakening speech entrainment. To test these competing hypotheses, we recorded EEG activity from 27 participants while they listened to a 14-minute recording of text reading. The passage contained target words presented twice: once in a highly constraining and once in a minimally constraining context. First, we measured event related potentials on target words in the two conditions. In line with previous research, we showed that semantic predictability modulated the N400 amplitude: words in minimally constraining contexts elicited larger negative amplitudes than words in highly constraining contexts between 250 and 450 ms. Second, we evaluated speech entrainment effects by analyzing phase alignment between neural activity and the envelope of target words. Importantly, we found increased speech entrainment for words in minimally constraining compared to highly constraining contexts between 400 and 450 ms. Both effects were located in central electrodes and were significantly correlated. Our results indicate a trade-off between semantic pre-activation and cortical entrainment to speech and support the cost minimization hypothesis.

Keywords: Speech comprehension, Predictive processing, Speech entrainment, N400, Phase Locking Value

1. Introduction

Speech comprehension is an incredibly complex process that involves online parsing of information at different hierarchical levels, ranging from the acoustic properties of the speech stream to the computation of syntactic and semantic structures. All of this takes place within a few hundred milliseconds.

Semantic pre-activation has been identified as a key mechanism facilitating smooth, efficient language processing (DeLong, Urbach, & Kutas, 2005; Donhauser & Baillet, 2020; Federmeier & Kutas, 1999; Kalikow, Stevens, & Elliott, 1977, Van Berkum, Brown, Zwitserlood, Kooijman, & Hagoort, 2005). Semantically constraining contexts could pre-activate target word information and thus facilitate its recognition and integration. Convincing evidence for the influence of context on the early stages of language processing has been provided by classic ERP (event-related potential) studies (Kutas & Federmeier, 2011). These studies show that context modulates brain activity around 400 ms after target word onset; words that are more predictable due to constraining contexts show reduced N400 amplitudes (less negative polarity). Such effects appear to reflect reduced semantic processing costs for contextually predictable (semantically pre-activated: Federmeier & Kutas, 1999) words; less predictable words arguably require further analysis before they are recognized and integrated. However, it remains unclear if such pre-activation merely involves hypotheses about high-order semantic representations or also leads to low-level pre-activation of the predicted stimulus (Kuperberg & Jager 2016). Evidence for phonology-level pre-activation during sentence comprehension has been reported (DeLong et al., 2005). However, several attempts to replicate these results, including a large-scale study across nine laboratories (Nieuwland et al., 2018), did not provide systematic support for such effects (see however Urbach, DeLong, Chan & Kutas, 2020).

Here we take an alternative approach to studying how contextual predictability might influence low-level processing of the incoming stimulus, by focusing on cortical entrainment to speech. Auditory-related neural activity oscillates in synchrony with the rhythmic regularities of external sounds, a phenomenon hypothesized to be crucial for encoding the acoustic properties of speech (Obleser & Kayser, 2019). This mechanism ensures realignment of the phase of maximum neural excitability to match the temporal regularities of perceptual input (Ding et al., 2017). As a result, the acoustic representation of the stimulus that is tracked can be enhanced. This is particularly beneficial for speech comprehension, since the rate at which the input is presented and processed is determined by the speaker's production rate and cannot be adjusted by the listener (Giraud, 2020; Peelle & Davis, 2012). Speech entrainment would thus contribute to the initial acoustic encoding of speech input (Giraud & Poeppel, 2012; Hyafil et al., 2015), while remaining sensitive to top-down modulatory activity (for a review: Obleser & Kayser, 2019).

Donhauser and Baillet (2020) evaluated the role of semantic prediction in speech entrainment. After collecting MEG recordings of participants listening to TED talks, they modeled the neural data with semantic prediction measures (surprise and uncertainty). Their results pinpointed two different subregions involved in predictive speech comprehension that operated at different frequency bands and at different latencies. Theta activity (3-8 Hz), mainly evident in the primary auditory cortex, emerged at earlier processing stages (60-120 ms and 230 ms). Crucially, its amplitude changed as a function of uncertainty: when a word or phoneme was less predictable, the brain response in these sensory regions was enhanced. On the other hand, later responses were observed in the associative auditory cortex. Those responses had a slower time-course (delta band, < 3 Hz) and were mostly modulated as a function of surprise: when a prediction error occurred, activity in this area was enhanced at 80-160 ms, spreading to the primary auditory cortex at 230-420 ms and 550-700 ms. The authors compared this finding to the previously described N400 effect as well as to a later positivity that is usually observed when a prediction error occurs (i.e., the P600 effect; Kuperberg & Jager 2016; Van Petten & Luka, 2012). However, these authors did not directly test which of those ERP components was related to the observed oscillatory effects or the direction of the modulation (i.e., if larger ERP components related to more or less speech-brain coupling). Overall, the current literature suggests that speech entrainment reflects the temporal tuning of brain signals to relevant speech information (Zoefel & VanRullen, 2015). Top-down mechanisms including prediction (Donhauser & Baillet, 2020; Park et al., 2015) could determine which information in the input stream is preferentially parsed to support comprehension.

In the present study, we focused on the relation between high-level semantic prediction and low-level speech entrainment, thus bridging the two streams of research discussed above. Specifically, we evaluated whether the reported N400 effects had a time-simultaneous counterpart in terms of entrainment efficiency. Most studies investigating semantic predictability have used words or isolated sentences and involved the comparison of congruent targets and violations. Here, we studied these pre-activation effects by manipulating the cloze probability of target words embedded in a coherent story with no violations or overt task demands. This relatively natural context ensured processing was similar to that engaged by naturalistic speech.

We considered two possible scenarios based on previous findings. On the one hand, studies show increased speech entrainment (Luo & Poeppel, 2007) and top-down modulation from higher-order brain regions, such as the left inferior frontal cortex (Park et al., 2015), as speech intelligibility increases. Studies on audiovisual speech perception also show that adding visual to auditory information enhances speech tracking due to the predictive nature of lip cues (Golumbic et al., 2013). These findings suggest that greater semantic predictability enhances phase alignment of neural activity with an incoming speech signal, while semantically unexpected auditory stimuli might temporarily disrupt it. This would support the *perception facilitation view*, i.e., the view that semantic pre-activation triggers lower-level predictions, thus facilitating speech entrainment. On the other hand, Donhauser and Baillet's (2020) results suggest lower semantic predictability leads to increased speech entrainment (to ensure comprehension), while higher semantic pre-activation obviates the need for highly detailed temporal representations of speech input. This is the *cost minimization view*, which proposes that the brain invests more resources in lower-level envelope tracking when semantic information has not been preactivated. We tested these competing hypotheses by recording EEG activity during auditory discourse comprehension and comparing the phase-locking values of brain oscillations to the speech envelope (Gross et al., 2013).

2. Methods

2.1. Participants

Thirty-four Spanish speakers (17 females) took part in the study. They were all matched for socioeconomic status defined as their annual net income. We excluded participants based on the following criteria: neurological/psychiatric disorders, reported speech or hearing impairments, incomplete behavioral and/or electroencephalography (EEG) protocols or noisy EEG data (see the *EEG data and acquisition section* below). The final sample thus included 27 participants (14 females). Participants' ages ranged from 29 to 51 years (M = 40.81, SD = 4.7). The Basque center on Cognition Brain and Language (BCBL) ethical committee approved the experiment (following the principles of the Declaration of Helsinki) and all participants provided written informed consent.

2.2. Speech stimuli

We acquired a 14-minutes recording of a Spanish native male speaker reading a text, digitized at 44.1 kHz using a digital recorder (Marantz PMD670). Audio files (*.wav) were segmented using Praat (Boersma & Weenink, 2018). The reader was blind to the purpose of the experiment. An original text from a journalistic source was manipulated to contain 45 high frequency target words, which were presented twice: once in a highly constraining (cloze probability ≥ 0.50) and once in a minimally constraining (cloze probability < 0.50) context.

In order to obtain an objective measure of predictability, cloze probabilities for the target words were calculated based on the ratings of 20 native speakers of Spanish. The auditory stimuli were presented via earphones at 80 dB SPL using *Psychopy* (Peirce, 2009). Participants listened to 108 sentences containing 54 target items and were asked to complete each sentence with the first word that came to mind, typing this word on a computer keyboard so that responses could be digitally recorded. In order to maintain text coherence, we presented the sentences in their original order. The contexts in which the targets reached a cloze probability of ≥ 0.5 were classified as highly constraining, whereas the contexts for which this threshold was not reached were considered as minimally constraining. After the first cloze-probability rating, we identified 19 target pairs that did not fulfil both the high and minimal constraint requirements. These pairs were further manipulated and reinserted in the original text. This second version of the text was re-rated by another 20 native speakers of Spanish who had not taken part in the first rating. In this second round, 45 out of the original 54 targets were placed once in a highly constraining context (cloze probability of ≥ 0.5) and once in a minimally constraining context (cloze probability of < 0.5), therefore fulfilling the requirements for our manipulation. We discarded 9 targets to obtain the final text with a total of 45 targets. This provided a final text which contained a total of 45 targets appearing once in each of the two conditions (90 sentences in total). Finally, ten filler sentences were added to ensure discourse-level coherence, and the final version was recorded in a single go to avoid differences across recording sessions (Appendix A for the transcription of the final speech passage).

Additionally, in order to ensure that all of our target words were highly frequent words in Spanish, we calculated their log count values using *Espal* (Duchon et al., 2013). The log count was found to be high overall (range: 3.03 to 5.60; $M = 4.24$; $SD = 0.59$).

The mean cloze probability of the targets in the highly constraining condition was 0.74 (SD = 0.14; ranging from 0.50 to 1); targets in the minimally constraining condition had a mean cloze probability of 0.14 (SD = 0.14; ranging from 0 to 0.45). As expected, there was a significant difference in cloze probability between the conditions, as evidenced by an independent samples t-test ($t(88) = 19.98$, $p < 0.001$), such that targets in the highly constraining context had a larger cloze probability than targets in the minimally constraining context.

The target was always placed at the end of the sentence and the number of words preceding this final word was controlled across conditions (highly constraining condition: M = 21.27, SD = 5.65, range from 10 to 30; minimally constraining condition: M = 19.09, SD = 6.10, range from 10 to 32). An independent samples t-test indicated that, within a given sentence, there was no significant difference in the number of words preceding the target items in the highly constraining and minimally constraining conditions ($t(88) = 1.52$, $p = 0.13$). For each condition, example sentences used in the experiment are reported below:

> ***Highly constraining condition:***
>
> En 1999, fuentes rusas aseguraron que Laika sobrevivió por lo menos cuatro días, y que después pereció por el sobrecalentamiento de la **nave**.
>
> [*In 1999, Russian sources assured that Laika survived for at least four days, and that later she perished due to the overheating of the* ***spacecraft***.]

Minimally constraining condition:

El objetivo era relativamente simple: alcanzar la superficie de la luna mediante un impacto directo y recolectar la mayor cantidad de información gracias a la tecnología de la **nave**.

[*The goal was relatively simple: reach the surface of the moon by direct impact and collect the most information thanks to the technology of the* ***spacecraft****.*]

Although the target words for the highly and minimally constraining conditions were matched, they were uttered at different instances by the speaker (i.e., within different sentences), so they were not exactly the same acoustic stimulus. To check whether the acoustic properties of the target words were balanced in the two semantic categories, we statistically compared the envelope of the words within the highly and the minimally constraining contexts. First, to obtain the envelope of the speech signal, we applied the Hilbert transform to construct the complex-valued analytic signal. The envelope was extracted by taking the absolute value of the analytic signal (Molinaro and Lizarazu, 2018; Lizarazu et al., 2021). This speech envelope was downsampled to 1000 Hz, filtered with a high-pass filter at 0.1 Hz and segmented –0.5 s before and 1 s after the onset of each target word. For each of the time points between –0.5 s and 1 s, envelope amplitude values were compared between the two semantic categories using a two-tailed t-test. No significant differences were observed between the envelope of the highly and minimally constraining conditions (all *p*s > .05; Figure 1, right panel). In addition, we computed the power spectrum of the speech envelope (expressed in dB) for the frequencies that phase-synchronized with the electrophysiological brain activity (i.e., < 15 Hz; Figure 1, left panel). The more prominent amplitude modulations were below 10 Hz, as expected from previous studies (Gross et al., 2013; Lizarazu et al., 2019; Bourguignon et al., 2020). Importantly, no statistical differences emerged between the highly and minimally constraining conditions at any frequency (all *p*s > .05).

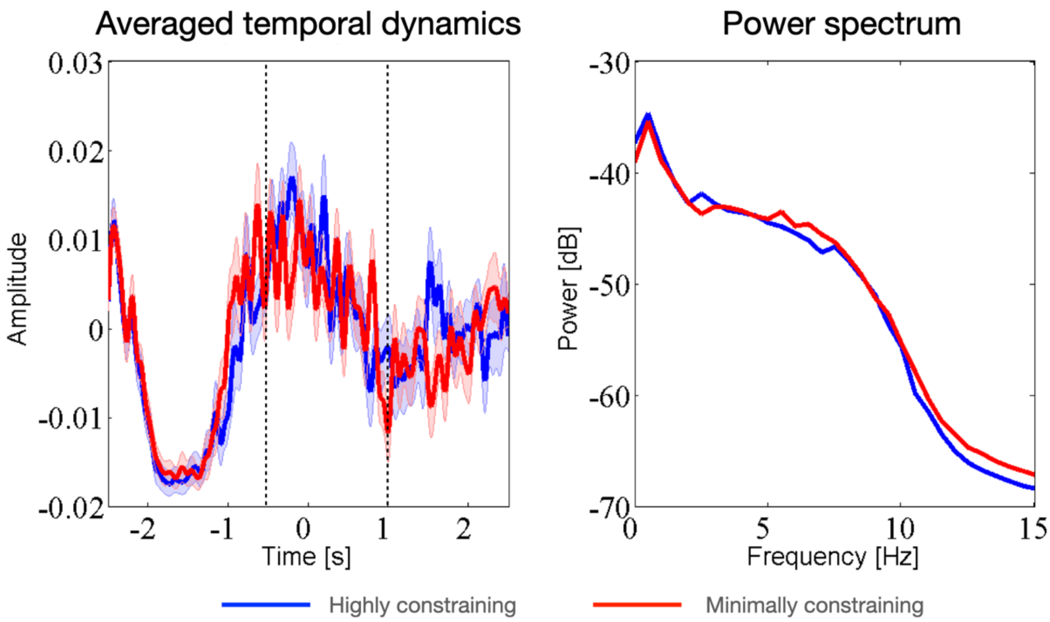

Figure 1. Temporal and spectral characteristics of the speech envelope. Left panel: Average amplitude of the speech envelope time-locked to the 45 target words in the highly constraining (blue) and minimally constraining (red) contexts. Shaded areas around the curves reflect the standard error. Dotted lines indicate the time interval of the envelope considered in the present study. Right panel: Power spectrum (0-15 Hz) of the speech envelope in the time interval of interest for the two experimental conditions.

2.3. EEG data acquisition and preprocessing

The participants were instructed to sit in a comfortable position in front of the computer screen and asked to limit their movements as much as possible during recording. They were asked to stare at a fixation cross while listening attentively to the stimuli and were not required to complete any additional task. Stimuli were presented through loudspeakers at 80 dB SPL using *Psychopy* (Peirce, 2009).

EEG data was acquired using a BrainAmp amplifier and BrainVision Recorder software (BrainProducts, Germany). EEG was recorded at 32 electrodes that were positioned according to the international 10-20 system (Jasper, 1958). Scalp-electrode impedance was kept below 5 kΩ for scalp electrodes and under 10 kΩ for reference and EOG electrodes to ensure high-quality EEG recordings. EEG data was sampled at 1000 Hz and band-pass filtered online from 0.1 to 1000 Hz. The recording was referenced to electrode FCz and re-referenced off-line to the average of the left and the right mastoids. Electrode AFz served as the ground. Additionally, two electrodes at the outer canthi of the eyes recorded horizontal eye movements and two electrodes above and below the left eye recorded vertical eye movements.

All the following processing steps were implemented in Fieldtrip (Oostenveld et al., 2011). Data were segmented from –0.5 s to 1 s after the onset of the target word. Trials were low-pass filtered below 35 Hz, since we did not expect any effect above this threshold (see Gross et al., 2013). Visual inspection of the recordings was performed to detect bad channels, which were substituted with interpolated values computed as the average of the neighboring electrodes obtained through the triangulation method implemented in Fieldtrip. Electrooculogram and electrocardiogram artifacts were detected using Independent Component Analysis (ICA) and linearly subtracted from recordings. The ICA decomposition was performed using the Infomax algorithm implemented in the Fieldtrip toolbox (Oostenveld et al., 2011). Furthermore, trials were visually inspected to discard any remaining artifacts. A minimum of 75 % artifact-free trials per participant was required for inclusion in subsequent analyses; all of the final 27 participants were above this threshold. On average, 8.49% (SD = 6.17) of trials were rejected with no significant difference ($t(26) = -1.521$, $p = 0.14$) between the highly constraining (M = 40.41, SD = 2.95) and minimally constraining conditions (M = 41.04, SD = 2.93).

2.4. Event Related Potentials

Artifact-free trials were grouped together for the highly constraining and the minimally constraining conditions, which we then averaged to obtain the ERPs. Baseline correction was applied to the evoked data using the 0.5 s data prior to the onset of the target word.

2.5. Phase Locking Value (PLV)

We used PLV to evaluate the cortical tracking of speech around the target words. Specifically, we calculated PLV between the artifact-free trials and the envelope of the corresponding target words from –0.5 s to 1 s. For each participant, condition, and sensor, the PLV was defined as the absolute value of the circular mean of the phase difference between two signals (Lachaux et al., 1999; Lizarazu et al., 2015, 2021):

$$PLV(t) = \frac{1}{N}\left|\sum_{1}^{N} e^{e^{i(ph(n,t)-phs(n,t))}}\right|, \quad (1)$$

where *ph(n,t)* is the instantaneous phase of the EEG data and *phs(n,t)* is the instantaneous phase of the speech envelope for the n^{th} trial at time point *t*. The sum is performed across the N artifact-free trials. According to this formula, if EEG and speech envelope phases were perfectly aligned across trials, phase locking would reach a value of 1. By contrast, if the phases were totally unaligned, the PLV would be 0.

2.6. Statistical analysis of brain measures

For each brain measure (baseline corrected *ERPs* and *PLVs*), paired-sample *t*-tests (two-tailed) were used to test the null hypothesis of no difference between the two conditions in time and sensor locations. In order to control for the family-wise error rate in the context of multiple comparisons over time points and sensors, a cluster-based non-parametric permutation statistic was performed (Maris & Oostenveld, 2007). Accordingly, clusters of channels and time samples with significant differences ($p < .025$) were created by temporal and spatial adjacency (at least two neighboring channels). The neighborhood definition was based on the template for the *easycap M1* system provided in the Fieldtrip toolbox. A set of 1000 permutations was created by randomly assigning condition labels and then *t* values were computed for each permutation. A cluster was considered to have a statistically significant effect if the sum of *t*-values in the original dataset was greater than the 95th percentile ($p < .05$) of the distribution of the corresponding values in the randomized data.

2.7. Correlation analysis

In order to evaluate the direct relation between the ERPs and the PLV effects, we additionally ran a linear correlation analysis between the ERP and PLV difference values for the two conditions across participants, in the time interval identified by the cluster-based approach and independently for each electrode. Our aim with this approach was to reveal the topographical distribution of electrodes where the correlation was highest

3. Results

The grand-averaged ERPs showed a qualitatively distinct pattern across the two conditions (see Figure 2A). We observed that targets embedded in the minimally constraining contexts elicited larger negative amplitudes than targets in the highly constraining contexts between approximately 100 and 450 ms over central and posterior electrodes. Results from the cluster-based permutation test confirmed a significant negative effect with a consistent spatiotemporal configuration ($p = 0.03$), starting 250 ms and ending 450 ms after the onset of the target word (Figure 2B). This effect can be recognized as a N400 that is larger for the minimally than for the highly constraining condition.

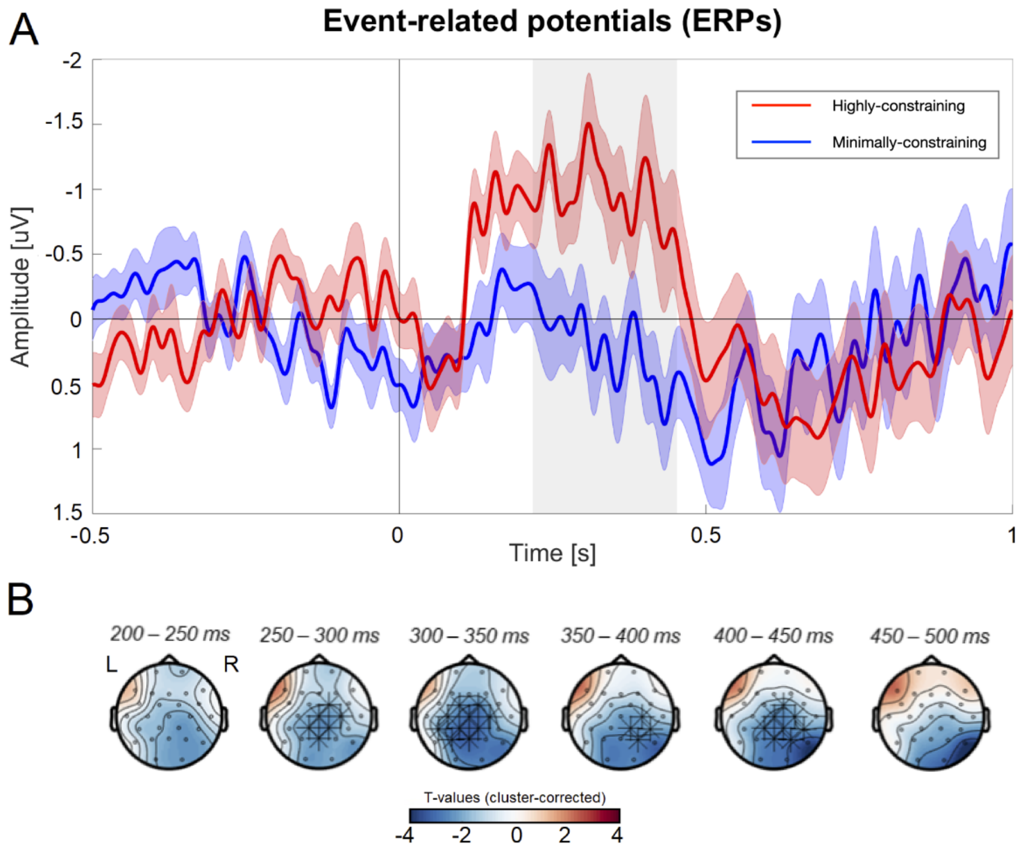

Figure 2. Event-related potential analysis. (A) Grand-average ERPs averaged across electrodes identified by the statistical procedure (FC1, FC2, C3, Cz, C4, CP5, CP1, CP2, CP6, P3, Pz, P4, Pz) for the highly constraining (blue) and minimally constraining (red) conditions, time-locked to the onset of the target word (shaded areas around the curves reflect the standard error). Negative amplitude values are plotted upward. The grey shaded time interval corresponds to the statistically identified spatiotemporal cluster. (B) Scalp distribution of cluster-corrected t-values in the 200 ms to 500 ms time interval. Electrodes identified by the statistical procedure (*p* < .05) are marked with an asterisk. Abbreviations: L, left hemisphere; R, right hemisphere.

The speech-brain PLV analysis time-locked to the target word highlighted a larger increase in PLV values for the minimally constraining than for the highly constraining condition in the time interval between 400 and 450 ms (Figure 3). The effect was maximal over central electrodes, reflecting a temporary increase in the PLV for the minimally constraining compared to the highly constraining condition, which did not peak at that time. Thus, the effect emerged by the end of the time interval that characterized the N400 ERP effect described above.

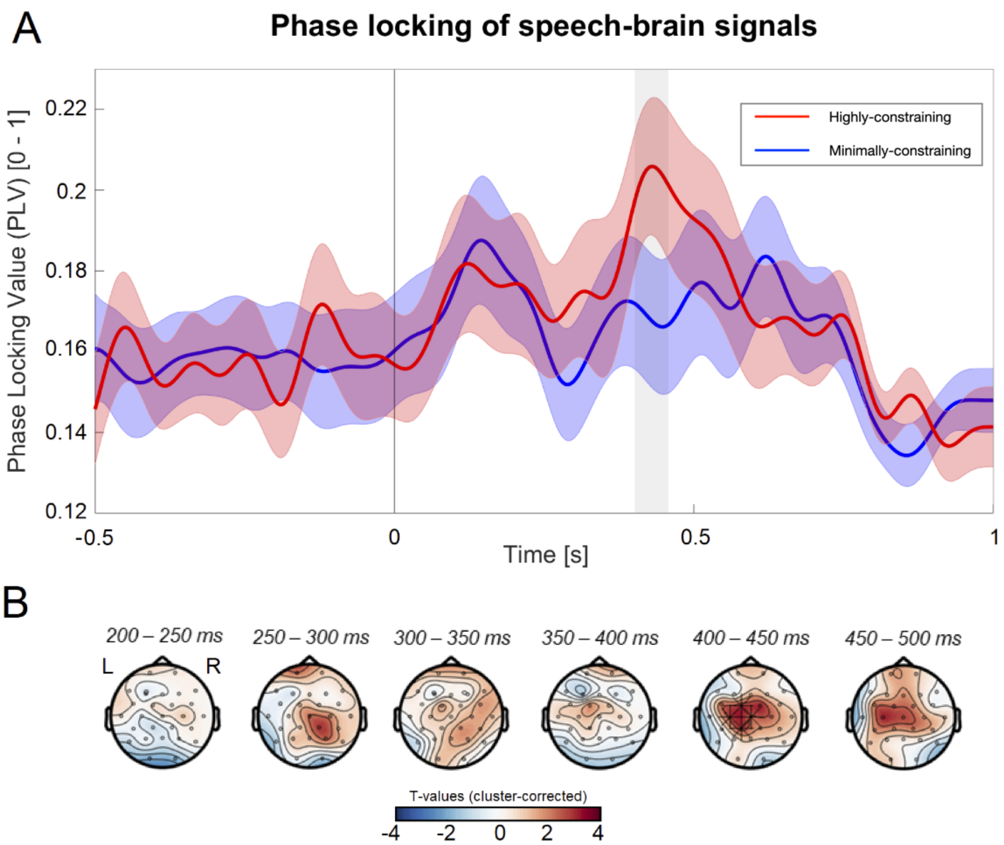

Figure 3. Phase locking value (PLV) analysis. (A) Grand-average instantaneous PLVs between the speech envelope around the target words and the brain signal, averaged across electrodes identified by the statistical procedure (FC1, C3, Cz, C4, CP1, CP2, CP6, P4) for the highly constraining (blue) and minimally constraining (red) conditions, time-locked to the onset of the target word (shaded areas around the curves reflect the standard error). The grey shaded time interval corresponds to the statistically identified spatiotemporal cluster. (B) Scalp distribution of cluster-corrected t-values in the 200 ms to 500 ms time interval. Electrodes identified by the statistical procedure (*p* < .05) are marked with an asterisk. Abbreviations: L, left hemisphere; R, right hemisphere.

Additionally, we used a correlation analysis to evaluate the relationship between the ERP and the PLV effects that we observed. The mean amplitude of the difference between the highly and minimally constraining conditions (i.e., mean amplitude of the N400 *effect*) in the 250-450 ms and mean difference in PLV between the conditions in the 400-450 ms was calculated for each sensor. Then, the relationship between these measures was calculated using Pearson correlations. Significant (ps < 0.02, |r|s > 0.46) negative correlations emerged in central sensors (C3, FC5, FC1 and CP2) (Figure 4A and 4B), such that the more negative the N400 difference between conditions, the stronger the PLV enhancement for the minimally constraining compared to the highly constraining condition.

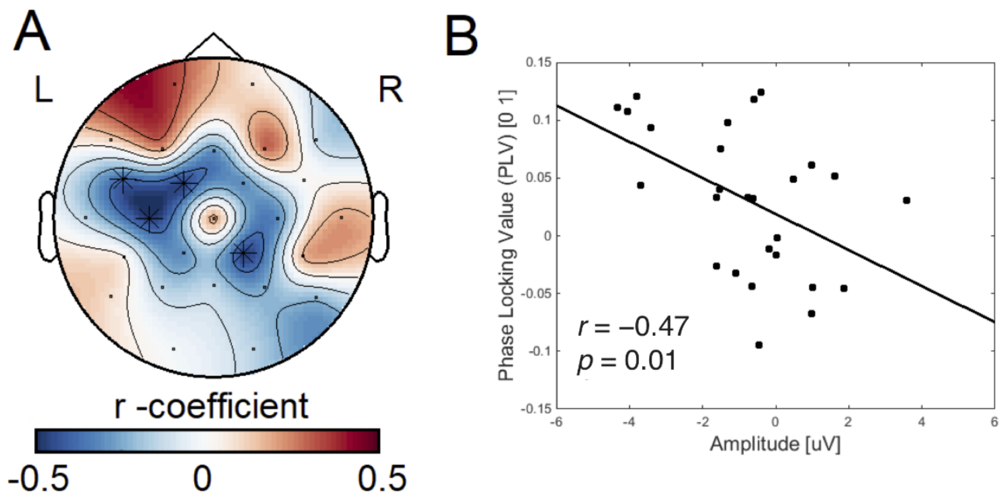

Figure 4. Correlation analysis. (A) Scalp distribution of the correlation between the value extracted from the ERP and PLV analyses. Specifically, mean difference in amplitude between the conditions in the 250–450 ms were correlated with mean difference between the conditions in PLVs in the 400–450 ms interval. Electrodes revealing significant *r* values (*p* < .05) are marked with an asterisk. (B) Scatter plot and linear regression showing the relationship between the ERPs and the PLVs for a representative channel (C3). Abbreviations: L, left hemisphere; R, right hemisphere.

4. Discussion

The present study investigates the effect of semantic predictability on cortical entrainment to speech during a *more* naturalistic discourse comprehension setting compared to sentence comprehension studies. First, target words embedded in a minimally constraining context elicited an increase in negative polarity in the time window from 250 to 450 ms after stimulus onset, compared to words in a highly constraining condition. Second, this effect was accompanied by a difference in phase locking values (PLVs) between the two conditions at around 400-450 ms. In particular, brain activity showed larger phase-alignment to the speech envelope of the acoustic stimuli in the minimally constraining than in the highly constraining condition. All the effects observed were visible at central-scalp electrodes.

Our study replicated and extended previous findings on prediction during speech comprehension. The observed negative ERP effect for words within minimally constraining contexts is in line with prior literature and can be interpreted as a typical N400 effect (see Kutas & Federmeier, 2011). Importantly, our study overcomes one of the main limitations in the N400 literature, namely the use of highly controlled stimuli and a generally unecological setting (for a discussion, see Hamilton & Huth, 2020). We showed that the N400 effect can also be observed under more naturalistic conditions, i.e., when people listen to coherent discourse without violations or overt task demands. Finding this effect also confirms the robustness of our contextual predictability manipulation. As noted, we decided not to include any task during the experiment so as to ensure the experimental situation resembled natural listening conditions as much as possible. It could be argued that we therefore cannot exclude the possibility that some participants did not pay attention to the stimuli. However, if this were the case, we would not have observed any changes in brain potentials due to our semantic manipulation. In our experiment we did observe a very clear increase in negative polarity for targets embedded in minimally constraining compared to highly constraining sentence contexts around 400 ms after word onset. As a result, we can confirm that our participants were indeed processing the semantic meaning of the presented discourse.

The main aim of our study was to test the relationship between semantic predictability and cortical tracking of speech. Previous studies have already shown that coupling between brain activity and the rhythmic regularities of the speech stimulus can be influenced by prediction (Donhauser & Baillet, 2020; Golumbic et al., 2013; Meyer & Gumbert, 2018). For example, results from Golumbic and colleagues (2013) suggested that a more predictive experimental scenario should enhance speech-envelope neural entrainment as measured by PLV (*facilitation* hypothesis). However, and in line with the *cost minimization* hypothesis (Donharuse & Baillet, 2020), our results showed the opposite trend: the phase of neural activity was more synchronized to the envelope of the speech stimulus when participants listened to words embedded in less semantically constraining than in more semantically constraining sentence contexts. It should be underscored that this increased synchronization cannot be an effect of the acoustic properties of the stimuli since the speech envelope did not differ between the two conditions.

Although, on the basis of our experimental paradigm, we cannot claim that there is a causal relationship between our ERP and PLV effects, we believe that a tentative discussion of the putative link between these phenomena deserves further discussion. This is warranted specifically because our observed effects occurred sequentially and were significantly correlated. Indeed, a possible interpretation of our results would be that semantic prediction and speech-entrainment are two complementary mechanisms, with speech-entrainment increasing when semantic prediction does not provide a sufficiently accurate representation of an upcoming word. In other words, if top-down semantic prediction does not support speech comprehension (i.e., previous information does not sufficiently constrain an upcoming word, as shown by the larger negativity elicited in the typical N400 window), enhancement of bottom-up information processing might be triggered (as reflected in the increase in PLV to incoming auditory input at the end of the typical N400 window). The hypothesized process for the phase alignment is somehow reminiscent of eye-movement effects observed during reading: highly predictable words are skipped more often than less predictable words (e.g., Rayner et al., 2011). Similarly, highly expected words may be "auditorily skipped" during speech perception as indicated by the lower precision observed in neural tracking of the speech envelope. In summary, the effect of semantic predictability on speech-entrainment occurred towards the end of the observed N400 effect, which was significant until 450 ms. It is important to underscore that exact time limits are hard to determine given the present analytic approach and, more importantly, statistical evaluation (Sassenhagen & Draschkow, 2019).

Overall, our interpretation is supported by previous investigations reporting a link between neural entrainment to speech and higher-level, top-down linguistic mechanisms in the fields of syntactic (Meyer & Gumbert, 2018) and semantic (Donhauser & Baillet, 2020) prediction. Furthermore, in our study, the likelihood of this relation is reinforced by the fact that in electrodes where the PLV effect was maximal, a negative correlation emerged in the N400 effect: the larger the negativity difference between the two experimental conditions in the N400 window (250-450 ms), the stronger the PLV enhancement for the minimally constraining compared to the highly constraining condition in the final period of that window (400-450 ms).

Importantly, our study extends previous results in several ways. First of all, in the study by Meyer & Gumbert (2018), a classical violation paradigm was deployed to test syntactic prediction. This left open the possibility that the observed syntactic prediction effect was related to prediction error rather than more naturalistic pre-activation operations not involving violations. Second, while a more predictable syntactic context led to enhanced phase alignment with the stimulus, our results showed a reversed effect with semantic predictability. In fact, when semantic prediction increases (i.e., negativity in the N400 window reduces), phase alignment decreases. Donhauser & Baillet (2020) did not directly evaluate the relation between their entrainment effects and more classical evidence on semantic predictability based on ERPs (i.e., N400 and P600). In the present study, we report functionally related N400 and speech-brain synchronization effects based on the *same* EEG data. This strengthens the claim that top-down semantic prediction modulates lower-level processes: only the information that is not predictable based on previous context receives additional processing support based on phase alignment.

It is worth noting that due to the fact that most of the previous literature focused on entrainment at one specific frequency band (e.g., delta, < 3 Hz, or theta, 3-8 Hz), results from those studies cannot directly be linked to the present findings. We explored the potential role of those frequencies by computing the PLV on the band-passed signals in delta and theta (Supplementary Figure 1). This analysis, however, did not provide conclusive results: even if the difference was larger in the delta band, no statistically significant effect between conditions was observed in any of the frequency bands. A potential explanation for this result is that the "overall PLV" analyses revealed the cumulative influence of these two tracking mechanisms, possibly including a larger contribution from the delta tracking effect (Luo & Poeppel, 2007; Obleser & Kayser, 2019; Donhauser & Baillet, 2020). Future studies could analyze the exact frequency bands involved in the change of phase locking to the incoming stimulus as a function of predictability.

A final point that we consider of interest for future investigations is how the present results could differ in individuals with lower speech processing abilities such as children or dyslexic readers. It has been shown that speech tracking is disrupted in individuals with dyslexia compared to controls (Di Liberto et al., 2018; Molinaro et al., 2016; Power et al., 2013). This reduced synchronization, which might be the cause of phonological and reading impairments, is found consistently throughout development. Repeating the present study with a between-group design that compares the effects of semantic predictability on speech-tracking in dyslexic reading and controls could give us more insight into this reading disorder. Because speech-tracking is overall less effective in dyslexic readers, we might expect the effects of predictability on the PLV to also be lower, with dyslexic readers relying overall more on top-down processing during the course of speech-processing. Evidence from a naturalistic listening paradigm such as the one employed here could provide an answer to this issue.

Conclusions

The present study provides evidence for a link between top-down semantic prediction and bottom-up speech tracking during language comprehension. In particular, semantic contexts that did not enable the listener to predict upcoming words led to a larger difference in negativity in the typical N400 window, signaling "failure" to (top-down) predict upcoming linguistic material, and then to increased speech tracking, which we have interpreted as enhanced processing of incoming bottom-up information. On the other hand, richer semantic contexts that enabled prediction, as suggested by the reduced N400 effect, relieved the brain of further processing costs, thus minimizing neural entrainment. Our data support the idea that the language prediction mechanisms can influence processing at lower levels of representation, such as temporal sampling of auditory stimuli. In turn, this trade-off between top-down and bottom-up processes could boost and support language perception and comprehension.

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Appendix A: Transcription of the speech passage.

F = Filler, HC = Highly Constraining; MC = Minimally Constraining

ID	Context	Target	Predictability
1	La carrera espacial dio comienzo cuando los estadounidenses lanzaron la bomba atómica en Hiroshima y Nagasaki, dando lugar a un punto de inflexión, al origen de la	guerra	HC
2	Lo que resultaría decisivo para obtener el poder y la influencia ya no sería el esfuerzo humano, sino la	tecnología	MC
3	Los soviéticos dedicaron los siguientes cuatro años a la producción de una	bomba	MC
4	En definitiva, las dos potencias estaban desarrollando, quizá de manera inconsciente, un nuevo concepto de	guerra	MC
5	Se trató de una época en la que, gracias a la experiencia de la II GM, se avanzó muchísimo en la fabricación de	armas	HC
6	Con sus más y sus menos, las décadas que siguieron iban a determinar la visión que la humanidad tenía de la	Tierra	MC
7	Sería una historia apasionante que encogería el corazón de los pobladores de nuestro planeta, pero sobre todo, sería una historia llena de peripecias en el	espacio	MC
8	A lo largo de la Guerra Fría, la carrera espacial entre los Estados Unidos y la Unión Soviética tuvo como consecuencia el desarrollo de tremendos avances en	tecnología	HC
9	Afortunadamente, en los territorios estadounidense y soviético no llegó a impactar ninguna	bomba	HC
10	En 1957, la Unión Soviética lanzaba al espacio el Sputnik 1, el primer satélite artificial de la historia, según hizo público el gobierno ruso a través de una comunicación a la	prensa	HC
11	Empleando todos los recursos de los que disponían, los soviéticos tardaron varios años en preparar el	viaje	MC
12	Este satélite sería el primero de una serie de cuatro satélites del programa Sputnik que la Unión Soviética planteó para celebrar un año marcado por la ausencia de	problemas	MC

13	Este primer satélite de la serie se encargó de obtener información sobre la densidad de las capas altas de la	atmósfera	HC
14	El 3 de noviembre de 1957, el Sputnik 2 se ponía en órbita en torno a la	Tierra	HC
15	Durante el entrenamiento de la perrita que viajaba en su interior, Laika, se combinaron diferentes técnicas, pero para adiestrarla se utilizó sobre todo un	hueso	MC
16	La nave no llevaba ningún tipo de cámara, por lo que no existen imágenes de Laika durante el que sería su último	viaje	HC
17	En 1999, fuentes rusas aseguraron que Laika sobrevivió por lo menos cuatro días, y que después pereció por el sobrecalentamiento de la	nave	HC
18	Finalmente, se reveló que Laika había muerto entre cinco y siete horas después del despegue por el sobrecalentamiento de la nave y por la	presión	HC
19	La historia adquirió un carácter aún más turbio por la intervención de la	prensa	MC
20	No obstante, Laika dio a los soviéticos otra victoria propagandística y a los estadounidenses otro quebradero de	cabeza	HC
21	La pérdida de la perrita obligó a los soviéticos a afrontar en primera persona los grandes sacrificios que lleva intrínsecos todo	comienzo	MC
22	Y sobre todo, demostró que no bastaba exclusivamente con los avances científicos de la	humanidad	MC
23	Una de sus misiones consistió en emitir el mensaje navideño del presidente, que había sido grabado previamente en unas cintas magnetofónicas con las que estaba equipado el	satélite	HC
24	Más tarde, Estados Unidos puso en órbita el Vanguard 2, que se encargaría de recopilar información sobre la	atmósfera	MC
25	Quedaba patente de nuevo que un componente esencial para adelantarse en la carrera espacial era tener	cabeza	MC
26	Otra parte crucial de la historia de la carrera espacial la constituirían los intentos de ambas potencias por dominar nuestro	satélite	MC

F	Con este objetivo en mente, ambas potencias comenzaron a perfeccionar todo tipo de cohetes.		
27	El objetivo era relativamente simple: alcanzar la superficie de la luna mediante un impacto directo y recolectar la mayor cantidad de información gracias a la tecnología de la	nave	MC
28	Finalmente, en 1959, la Unión Soviética lanzaba la nave Luna 2, que conseguiría su objetivo dentro del programa espacial	Luna	MC
29	No obstante, el primer alunizaje controlado lo protagonizó el Luna 9 en el Océano de los	vientos	MC
30	A principios de los años 60, veinte cosmonautas que se entrenaban en secreto en una zona rural de Rusia iban a convertirse en una parte esencial de la	historia	MC
31	La zona en la que entrenaban se encontraba en una región muy húmeda que se veía a menudo azotada por fuertes	vientos	HC
32	Había que aprender a sobrevivir con lo mínimo, incluso con cantidades mínimas de	oxígeno	MC
33	Y lo peor de todo era la preparación para la eventualidad de que hubiera un fallo en la cápsula y los astronautas perdieran su	control	MC
34	Durante el intenso entrenamiento de los astronautas, cada segundo era la personificación de un	rival	MC
35	De entre todos los candidatos el ingeniero jefe termino eligiendo a uno de los	campesinos	MC
36	Es dudable que el joven campesino imaginara siquiera que su vida iba a adquirir un tinte tan celeste, dado que se contaba que ni siquiera había visto el	mar	HC
37	Los rumores cuentan que, aparte de que se trataba de un joven apuesto y afable, Yuri Gagarin fue elegido como tripulante de la cápsula Vostok por su	sonrisa	MC
38	El reto iba a ser importante para él, ya que había pasado la mayor parte de su vida en el	campo	HC
39	Dos eran los posibles resultados: un gran éxito o un rotundo	fracaso	HC

40	Dentro de la nave, el joven se sitúa en posición y, a las 9:07, los motores se ponen en funcionamiento y la misión da	comienzo	HC
F	La misión fue todo un éxito, pero hubo pequeñas dificultades con el aterrizaje.		
41	Yuri Gagarin aterrizó a varios cientos de kilómetros de la ubicación planeada, por lo que a su llegada no lo esperaba ningún equipo de	rescate	HC
42	La zona era una región rural en la que solo habitaban	campesinos	HC
F	La que lo encontró fue de hecho una anciana que se dirigía a unos cultivos cercanos.		
43	La anciana afirmó que el astronauta la recibió con un saludo militar y con los labios dibujando una	sonrisa	HC
44	La Unión Soviética volvió a hacer historia al poner en órbita a la primera mujer astronauta, hija de un gran empresario ruso que se dedicaba a la fabricación de	armas	MC
45	Continuando con la trayectoria de éxitos, en 1965 un ruso, Alekséi Leónov, se convertía en el protagonista del primer paseo por el	espacio	HC
46	A pesar de que se trataría de un hecho memorable e internacionalmente aclamado, la misión se vio dificultada por graves	problemas	HC
47	De hecho, Leónov terminó aterrizando con el sistema manual después de que el sistema de aterrizaje automático quedase fuera de	servicio	HC
48	Cuando sufrió este problema, la nave estaba sobrevolando una cordillera, por lo que tras el aterrizaje forzoso tuvo que sobrevivir durante dos días en medio del	campo	MC
49	La vida de Leonov fue bastante particular, y llegó a protagonizar una excéntrica historia en la que hubo implicado incluso el pago de un	rescate	MC
50	Sea como fuere, nunca llegó a alcanzar su sueño de explorar la atmósfera en	Marte	MC
51	Poco después, el ingeniero jefe del programa espacial soviético, su cerebro operativo, murió a causa de un infarto, dado que tenía problemas de	corazón	HC

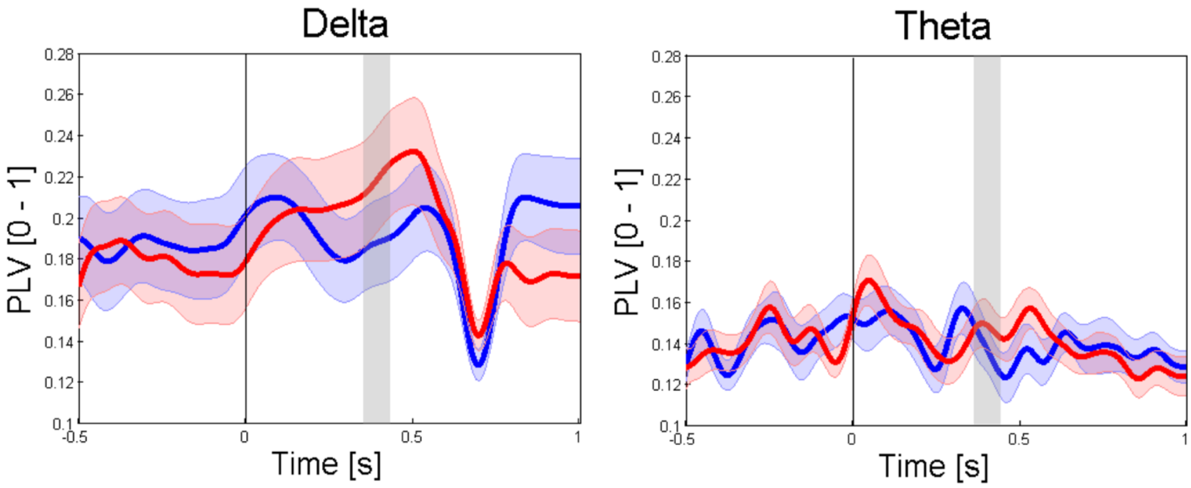
52	En 1965, la sonda Venera 3 se lanzó al espacio con el objetivo de obtener información sobre Venus, pero al equipo de ingenieros le preocupaba bastante un posible fallo del puente de	servicio	MC
53	De hecho, el aterrizaje fue fallido y, al parecer, todo se debió a un problema de	montaje	MC
54	Tras el impacto contra la superficie de Venus, los sistemas de comunicación quedaron totalmente inutilizados, por lo que hasta que no llegaron sondas posteriores no se pudo obtener más información sobre el	planeta	MC
55	La nave debía haber aterrizado en territorio soviético, pero los reiterados fallos de los sensores de navegación habían impedido una reentrada bajo	control	HC
56	A pesar de estos problemas, se trataba de la primera vez que una nave espacial viajaba hasta nuestro satélite, por lo que constituyó un gran	éxito	HC
F	Como era de esperar, los Estados Unidos aprovecharon estos reveses de la suerte de los soviéticos y se propusieron protagonizar el hito más mediático de la carrera espacial: pisar la Luna.		
57	El 21 de julio, el módulo de la Apolo11 alunizaba sin ningún tipo de problemas en el Mar de la	Tranquilidad	MC
58	Así, Neil Armstrong se convirtió en el primer ser humano en pisar la superficie de la	Luna	HC
F	Aun así, la misión no estuvo exenta de contratiempos.		
59	Por un momento, los astronautas parecían encerrados dentro de la nave porque no se podían abrir las	puertas	HC
60	Por suerte, todo salió como se esperaba y, mientras millones de personas veían las imágenes por televisión, el astronauta Neil Armstrong dio su gran paso para la	humanidad	HC
61	Para hacer honor a la verdad, también hay que mencionar que algunos creyeron que las imágenes eran falsas y que en realidad se trató solo de un	montaje	HC

62	Sea como fuere, la posibilidad de fracaso era tan alta que la Casa Blanca preparó una carta que sería leída por el presidente Richard Nixon en caso de fracaso de la	misión	HC
63	La mayor preocupación era que hubiera algún fallo con las	puertas	MC
F	Por ello, se hicieron todo tipo de preparaciones para la eventualidad de fracaso de la misión.		
64	El plan era que el presidente hiciera una retransmisión en directo tras el desastre y calmase al país con un mensaje de	tranquilidad	HC
65	*"El destino ha querido que los hombres que fueron a la Luna a explorar pacíficamente, se quedaran en la Luna a descansar en*	paz	HC
66	*Los héroes de nuestra patria serán llorados por sus familiares y*	amigos	HC
F	*El hombre ha soñado con viajar por el espacio desde tiempo inmemoriales*		
67	*En la actualidad, hacemos lo mismo, pero nuestros héroes son hombres de carne y*	hueso	HC
68	*Otros seguirán, y no cabe duda de que encontrarán su camino de vuelta a*	casa	HC
69	*La búsqueda del hombre no parará, pero estos hombres fueron los primeros, y se mantendrán como los más importantes en nuestro*	corazón	MC
70	El deseo de los astronautas era que sus cenizas fueran esparcidas por las olas, por lo que la idea era simular su diseminación en el	mar	MC
71	Desde entonces se multiplicaron las misiones en el espacio, y a finales de los 70 los americanos se decidieron a obtener más información sobre el planeta rojo, esto es, sobre	Marte	HC
72	La Mariner 9 llegó a Marte y consiguió claras fotografías de su superficie y datos relativos a la presión, densidades y composición de la atmósfera que reinaba en el	planeta	HC
73	El final de la carrera espacial llegó cuando ambos países decidieron hacer una	misión	MC

F	Para este cometido conjunto, ambos países se esforzaron tremendamente en aras de conseguir un acuerdo.		
74	No obstante, muchos de los que participaron en las negociaciones afirmaron que era difícil aguantar aquellos niveles de	presión	MC
75	La misión, que consistiría en el acoplamiento de dos naves, conllevó un considerable trabajo para los	países	MC
76	Dos días después del lanzamiento tenía lugar el acoplamiento, que quedó inmortalizado en el apretón de manos entre los	astronautas	MC
F	No obstante, la maniobra se complicó por el fallo de un sistema de control que provocó la apertura de una brecha en la nave norteamericana.		
77	Se evitó un desenlace más grave gracias al uso de máscaras de	oxígeno	HC
78	Se trató de un error humano, ya que los que tenían que apagar el sistema de control eran los tripulantes de la nave, o sea, los	astronautas	HC
79	Gracias a esta operación conjunta, los Estados Unidos pudieron conocer por primera vez los detalles del programa espacial soviético, que antes eran considerados alto	secreto	HC
80	Sin embargo, los planes más ambiciosos para colaborar en la construcción de estaciones espaciales o viajar a Marte jamás vieron la	luz	HC
81	Más que una hazaña espacial, esta operación constituyó la primera vez en la que las potencias se olvidaron de su afán individualista por el	éxito	MC
82	La llegada del hombre a la luna pareció dar la victoria a los americanos, pero gracias a sus innumerables logros, la Unión Soviética logró vencer repetidas veces a su eterno	rival	HC
83	Sin embargo, el riesgo de aislamiento del gigante ruso catapultó la colaboración entre potencias, aunque pocos apostaran a que después de aquella historia de enconada rivalidad pudieran ser	amigos	MC
84	En este esfuerzo conjunto, lo que estaba claro era que no cabía un	fracaso	MC

85	Tras décadas de enfrentamiento, la misión se convertiría en una de las primeras consecuencias materiales de la	paz	MC
86	Al principio, los planes estuvieron velados por la cautela y el	secreto	MC
F	Uno de los hitos de esta relación entre los países fue la apertura de la MIR a personal norteamericano.		
87	Como primer paso, astronautas estadounidenses fueron a vivir y trabajar a la MIR, y luego se sumaron decenas de representantes de diferentes	países	HC
88	Por primera vez en la historia, las potencias caminaban juntas hacia una suerte de	luz	MC
89	Los avances de la ciencia no han hecho dudar de que la Tierra sea el único lugar que podemos llamar	casa	MC
90	De hecho, la carrera espacial es y seguirá siendo uno de los acontecimientos más emblemáticos de la	historia	HC

Supplementary Figure 1



Supplementary Figure 1: Phase locking value (PLV) analysis in delta and theta bands. PLV between the speech envelope and the EEG activity in the sensors of interest: i.e., sensors showing significant differences between conditions in the main PLV analysis (Figure 3) (FC1, C3, Cz, C4, CP1, CP2, CP6, P4). For the highly (blue) and minimally (red) constraining conditions, signals were band-passed filtered in the delta (< 3 Hz) and the theta (3-8 Hz) bands before measuring PLV. Shaded areas around the curves reflect the standard error. The grey shaded windows represent the time intervals where we found a condition effect in the main PLV analysis.