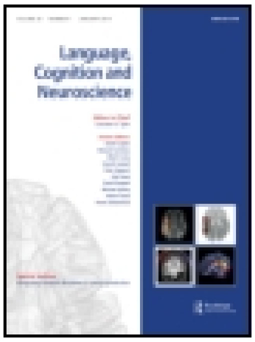

Language, Cognition and Neuroscience

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/plcp21

# Oscillatory neuronal dynamics during L2 sentence comprehension: the effects of sensory enrichment and semantic incongruency

Reza Pishghadam , Farveh Daneshvarfard & Shaghayegh Shayesteh

**To cite this article:** Reza Pishghadam , Farveh Daneshvarfard & Shaghayegh Shayesteh (2021): Oscillatory neuronal dynamics during L2 sentence comprehension: the effects of sensory enrichment and semantic incongruency, Language, Cognition and Neuroscience

**To link to this article:** https://doi.org/10.1080/23273798.2021.1886312 https://doi.org/10.1080/23273798.2021.1886312

REGULAR ARTICLE

# Oscillatory neuronal dynamics during L2 sentence comprehension: the effects of sensory enrichment and semantic incongruency

Reza Pishghadam, Farveh Daneshvarfard and Shaghayegh Shayesteh

Department of English, Ferdowsi University of Mashhad, Mashhad, Iran

**ABSTRACT**

Given the association between multisensory information and inner attention, the quality of multisensory information is hypothesised to modulate the neuronal activity associated with language comprehension. To verify, we investigated the interaction effect between multisensory quality (sensory enrichment) and semantic (in)congruency during L2 sentence comprehension. English words were selected for the subjects to learn according to the sensory-based emotioncy model. The words were embedded in an acceptability judgment task with 216 sentences under congruent and semantically incongruent conditions. Twenty-two subjects performed the task while their EEG was being recorded. Based on the time–frequency analysis results, in the 300–850 ms window, only lower delta power (1.7–2.2 Hz) showed an enhanced increase after sentences with semantic incongruency. This increase was more pronounced in the sentences with limited multisensory quality. To make up for the insufficient multisensory knowledge and maintain concentration, irrelevant cortical areas were deactivated as a result of lower delta wave synchronisation.

**ARTICLE HISTORY**
Received 20 October 2020
Accepted 30 January 2021

**KEYWORDS**
Semantic incongruency; emotioncy; sentence comprehension; delta oscillations; time-frequency analysis

## 1. Introduction

Based on the rapidly growing literature, sentence comprehension, whether in L1 or L2, involves the retrieval of lexical information from the long-term memory (the retrieval operation) and the integration of the information into a robust, coherent whole (the unification operation; Bastiaansen & Hagoort, 2006; Hagoort, 2013; Zheng & Lemhöfer, 2019). The cognitive architecture underlying this inherently dynamic process has been investigated through different techniques, the most popular of which is the classical event-related brain potentials (ERPs). However, such a well-established analysis of time–frequency representations provides a limited view on non-phase-locked (induced) activities cancelled out through the averaging procedure (Kielar et al., 2014). Therefore, to capture the neurocognitive aspects of the sentence comprehension mechanism that are not evident using ERPs, the findings need to be complemented with the ones obtained from time–frequency analysis (TFA) about which not much research is available in the language domain (Hajra et al., 2018; Regel et al., 2014).

Most of the EEG research studies conducted on sentence processing using ERP and TFA methods investigated semantic incongruency as an experimental manipulation and looked into the L1 comprehension mechanism. Hitherto, few ERP experiments are available in L2, most of which invest in examining the discrepancies between bilinguals' L1 and L2 systems (e.g. Duñabeitia et al., 2016; Jankowiak & Rataj, 2017). As the pioneers in this area, Ardal et al. (1990) checked semantically incongruent L2 sentences and came up with a 40 ms delay in the appearance of N400 as a result of reduction in the automaticity of semantic processing in bilinguals. Similarly, Zheng and Lemhöfer (2019) reported the attenuation of the N400 and LPC amplitudes to L2 comprehension, which according to, Miao (2013) and Liang and Chen (2020) largely depends on the level of L2 proficiency. Shifting their focus toward the primary sources of input as a requirement for proficiency, Shayesteh et al. (2020) revealed that sensory-enriched input facilitates L2 sentence processing in the LPC time window.

Overall, evidence suggests that retrieval and unification operations during L1 and L2 semantic processing give rise to a biphasic ERP signature (N400 followed by LPC; Brouwer et al., 2016; Brouwer & Hoeks, 2013; Delogu et al., 2019; Zheng & Lemhöfer, 2019) and distinct neuronal synchronisation patterns in the brain's language network. While, according to L1 findings, the former operation is commonly accompanied by an increase in the theta-band activity (4–7 Hz) and a

**CONTACT** Reza Pishghadam pishghadam@um.ac.ir Faculty of Letters and Humanities, Ferdowsi University of Mashhad, Azadi Sq., Mashhad, Iran
Supplemental data for this article can be accessed https://doi.org/10.1080/23273798.2021.1886312

decrease in the alpha (8–12 Hz) frequency range, the latter operation leads to an increase in the beta (13–30 Hz) and gamma (above 30 Hz) frequency bands (; Hagoort et al., 2004; Hald et al., 2006; Hanslmayr et al., 2012; Willems et al., 2008). Slightly different from the reports outlined above, desynchronizations in the theta frequency band was observed by Allefeld et al. (2005) in response to semantically incongruent sentences. The reductions in the alpha and beta frequency bands following semantic incongruency were believed to mirror the increase in the activity of the brain regions responsible for reprocessing of linguistic input (Hajra et al., 2018; Kielar et al., 2014). It was basically assumed that alpha power modulations tackle the over-engagement of brain networks and deactivate the cortical areas which do not contribute to doing a given task (Hanslmayr et al., 2012; Klimesch, 1999; Wang et al., 2012). Comparably similar to the functional characterisation of the alpha power, delta oscillations (0.5–3.5 Hz), about which relatively little is understood, appear to increase as a result of concentrated attention in order to inhibit the operational processes which interfere with carrying out a mental task (Harmony, 2013). In addition, this slow-wave changes in oscillatory amplitude as a function of semantic incongruency (Kielar et al., 2014; Kielar et al., 2015).

Despite the progress in brain research and several attempts made specifically over the last two decades to shed light on oscillatory dynamics during sentence processing, not much is yet clear about the sensitivity of different frequency bands. In order to add a further dimension to the previous findings, we hypothesise that senses and their combinations may modulate the oscillatory dynamics associated with language comprehension. This proposition may stem from the idea that individuals' sensory experiences influence their comprehension (Pishghadam et al., 2017; Shayesteh et al., 2020), which is an outcome of syntactic, semantic, and pragmatic processing (Salmon & Pratt, 2002). The idea is further supported by the tenets of embodied cognition that senses shape cognition (Foglia & Wilson, 2013; Leitan & Chaffey, 2014). As such, cognitive processing is not limited to the brain but involves the body and the surrounding world as well (Adams, 2010; Shapiro, 2011). Therefore, the integration of information from different sensory modalities leads to high body involvement, which, as a result, modulates the neurocognitive processing engaged in different brain activities, including the ones pertaining to language.

Sensory information may predominantly vary in quality and richness according to the number of senses combined (Ernst & Bülthoff, 2004; Mahoney et al., 2011). These combinations, as Rao (2018), Pishghadam (2016), and Mahoney et al. (2011) put forward, contribute to memory formation and characterise the vividness of our mental representations, which are retrieved during the process of language comprehension and may eventually hinder or hasten this cognitive process. Accumulated behavioural (Karami et al., 2019; Makiabadi et al., 2019) and cognitive evidence (Murray et al., 2016; Rao, 2018; Shams et al., 2011; Shams & Seitz, 2008) corroborate the inevitable role of multiple senses in optimising language-related operations. While Murray et al. (2016) explain that multisensory integration improves memory, Quak et al. (2015) adopt a more detailed approach and point out the same process underlying both memory and attention, claiming that there is a close link between working memory, inner attention, and multisensory processing. As such, multisensory information captures more attention, which, as a result, facilitates later free-recall and retention. Critically, almost all of these observations substantiate the advantages of information obtained from different modalities over unisensory input. To our best knowledge, the only electrophysiological experiments available on the contribution of three- and five-sense combinations to sentence comprehension are the ones conducted by Shayesteh et al. (2020) and Pishghadam et al. (2021). Their investigations revealed that information from the combination of three modalities puts the brain through a deeper, more demanding reanalysis phase during the later stages of L2 comprehension (i.e. the LPC time window). Their findings gave rise to the assumption that information from the combination of five senses involves less internal concentration during semantic unification.

Now, a central question is whether power modulations reflect the distinction between various degrees of multisensory input or what we refer to as sensory enrichment when the subjects encounter incongruency at the semantic level during sentence comprehension. To address this research gap, Pishghadam's (2016) sensory-oriented emotioncy model was applied as a framework for gaining knowledge about a list of vocabulary items. Having its intellectual roots in the primary assumptions of embodied cognition, the model accentuates the close ties between the body (the senses) and the mind (cognition). It features two major combinations of senses (representing the two levels of sensory enrichment) coined as *exvolvement* and *involvement*, constituting three (auditory, visual, & kinesthetic) and five senses (auditory, visual, kinesthetic, olfactory, & gustatory), respectively. In addition to exvolvement and involvement, the model introduces avolvement in which no sensory knowledge of a certain item exists, and no sensory enrichment takes place. In particular, Pishghadam (2016) believes that different concepts and items in the world may be perceived through different modalities, leaving individuals with various kinds of sensory experiences. In accordance, he hypothesises that moving from null emotioncy (when one has no sensory experiences of an item) to auditory (when one has heard about an item), visual (when one has heard about and seen an item), kinesthetic (when one has heard about, seen, and touched an item), inner (when one has heard about, seen, touched, smelled, and tasted an item), and arch emotioncies (when one has complete sensory involvement and does some research on the items/concepts to fully internalised them), the quality of sensory experiences improves gradually. Pishghadam (2016) further maintains that the combination of more senses leads to the formation of a more vivid picture of reality.

To control the form and amount of the sensory knowledge conveyed, a short, semi-formal learning session was held, and the subjects learned some L2 words, about which they had no previous information (either in their L1 or L2), using three and five senses. Since learners have stronger emotional responses in the native language (Dylman & Bjärtå, 2019), which can affect the results of the study, English (as the foreign language of the subjects) vocabulary items were selected and embedded in a series of semantically incongruent and congruent sentences. Therefore, it was possible to simulate learning new concepts with respect to both form and meaning. The sentences were put into a visual sentence acceptability judgment task designed based on the protocols used in similar experiments (e.g. Hagoort et al., 2004; Hald et al., 2006; Kos et al., 2012). The EEG activity of the subjects was recorded as they were reading the sentences appearing word by word on the computer screen.

Altogether, the current study seeks to both confirm and extend the prior studies by scrutinising the effects of semantic (in)congruency and sensory enrichment from two complementary perspectives. Under the effect of senses, we first compare the ERP and oscillatory neural responses to semantically incongruent sentences with those of the congruent ones to verify if the responses to both linguistic conditions conform. Thereafter, under the linguistic condition, we explore the electrophysiological and event-related power changes as the function of the three levels of sensory enrichment to see if involvement entrains oscillatory activity that is qualitatively different from that of exvolvement. It should be noted that the fast temporal dynamics of neural activity between the sensory conditions have been investigated in detail in prior observations by Pishghadam and his colleagues (Pishghadam et al., 2021; Shayesteh et al., 2020); therefore, the main objective of this study is to provide a brief report on the reinforcement of those electrophysiological findings and place extra emphasis on capturing event-related differences in oscillatory power.

In brief, like the previous ERP studies on L1 (Kolk et al., 2003; Kos et al., 2012; Schacht et al., 2014) and L2 (Liang & Chen, 2020; Newman et al., 2012; Pishghadam et al., 2021; Shayesteh et al., 2020; Zheng & Lemhöfer, 2019), a biphasic pattern consisting of an N400 and LPC is predicted in semantically incongruent L2 sentences. Moreover, based on the functional characterisations of the waves described in preceding language-oriented studies, the following oscillatory differences are expected between 1. the sentences with and without semantic incongruency, and 2. the sentences with avolved, exvolved, and involved words.

1. Qualitative differences in the alpha, theta, and delta oscillations are expected in semantically incongruent sentences relative to the congruent condition (frequencies above 25 Hz were filtered out for a better SNR). While in semantically incongruent sentences, theta and delta waves are likely to increase in amplitude (Burgess & Ali, 2002; Hagoort et al., 2004; Hanslmayr et al., 2012; Kielar et al., 2014; Kielar et al., 2015; Willems et al., 2008), alpha oscillations may show a different reactivity (Kielar et al., 2014).
2. Qualitative differences in delta frequency range are expected in semantically incongruent sentences under various degrees of sensory enrichment, with involvement showing a less marked increase. It is hypothesised that enriched sensory input, as compared with limited or no sensory input, facilitates retention and comprehension, and reduces the cognitive demand for internal concentration (Harmony, 2013; Quak et al., 2015; Rao, 2018).

## 2. Methods

### 2.1. Subjects

The EEG signals of 22 subjects (10 males and 12 females) who met our inclusion criteria (see Table 1) were analysed for the purpose of the present study. The subjects were native Persian speakers, learning English as a foreign language for an average of 4.5 years. In fact, they had learned English formally in class. They were aged between 18 and 30 years (M = 25.3, SD = 2.14), right-handed, with normal or corrected-to-normal vision and no language or neurological impairment. The level of their English language proficiency was intermediate (Allan, 1992), and their scores on the working

**Table 1.** Inclusion Criteria.

| Criteria | Instrumentation Used | Description | Included Range |
|---|---|---|---|
| Emotioncy Level | The Emotioncy Scale (Borsipour, 2016) | The scale measures individuals' knowledge of the vocabulary items to see whether they have heard about, seen, touched, smelled, and/or tasted them. The range varies between 0 (no knowledge) to 5 (complete knowledge of the items). | 0 |
| Proficiency Level | The Oxford Quick Placement Test (Allan, 1992) | The test includes 60 questions (40 multiple choice and 20 cloze test items). | 30–40 |
| Working Memory Span | The Digit Span subtest of the Wechsler Adult Intelligence Scale III (Wechsler, 1981) | The test checks immediate rote recall and memory span. | 11–12 |
| Handedness | The Edinburgh Inventory of Handedness (Oldfield, 1971) | The inventory measures the individuals' hand laterality through 12 questions. | 11–12 |

memory test (Wechsler, 1981) ranged from 11 to 12 ($M = 11.3$, $SD = .21$). They provided written informed consent and received gifts or course credits for taking part in the experiment. The study was approved by the Ferdowsi University of Mashhad Ethics Committee, Mashhad, Iran.

### 2.2. Inclusion criteria

In order to control the role of intervening variables, we set some inclusion criteria, encapsulated in Table 1.

### 2.3. Sensory enrichment

Thirty-two subjects participated in the pre-experiment session a few days before the ERP recording and took the pretests (see Table 1). Those who met the inclusion criteria (22 subjects) were invited to take part in the main experiment. During this session, the subjects first learned a list of English words through sensory enrichment, and after an hour, they went for the ERP recording. To provide different degrees of sensory enrichment during the experiment session, Pishghadam's (2016) sensory-oriented emotioncy model was employed (Figure 1).

The 9 target words included the name of novel foods, vegetables, and tropical fruits (Figure 2), about which the subjects had no previous information either in their L1 or L2. The subjects were supposed to learn 6 of the 9 target words in 20 mins. According to the emotioncy model, different degrees of sensory enrichment were provided. Three words were instructed using exvolvement (i.e. with three senses), three words were instructed using involvement (i.e. with five senses), and three words received no sensory enrichment (i.e. avolvement) and served as the control group to make sure that the effects we see are related to the multisensory input the subjects received before the experiment. Specifically, all subjects received all the words in a counterbalanced way, meaning that the avolved words for some subjects were exvolved or involved for others. Moreover, all subjects received the words in the same amount of time and with the required sensory enrichment. Details of the sensory enrichment paradigm (i.e. avolvement, exvolvement, and involvement) for the nine words were as follows. For the avolved words, the subjects received no sensory involvement. For the exvolved words, however, the subjects could see the real object and touch it while listening to some auditory explanations about its physical features (auditory + visual + kinesthetic). For the involved words, the subjects could further cut, smell, and taste the items in addition to the auditory explanations they received (auditory + visual + kinesthetic + olfactory + gustatory). According to the emotioncy model, for the involved words, the subjects could search the three words online (1 min each) to internalise the sensory information they had already received.

### 2.4. Semantic (In)congruency (Linguistic stimuli)

The nine target words (each containing 5–10 characters) were embedded in 108 sentence pairs with 3–5 words each. Each pair consisted of a congruent sentence (e.g. "A longan is round.") and a semantically incongruent sentence (e.g. "A longan is quiet."). Moreover, to prevent conditioning, 54 pragmatically incongruent sentences (e.g. "A gorilla is purple.") along with 54 congruent sentences (e.g. "A gorilla is hairy.") of similar length, structure, and complexity, were added as fillers. They were congruent/incongruent sentences with words other than the learned target words. These sentences were not included in the analyses since it was not possible to control the amount of sensory knowledge the subjects had for the embedded words.

All sentences were matched on different linguistic dimensions, including the "article-noun-verb-adjective" structure. Moreover, length effects were matched across pairs and sensory conditions. In addition to sentences, the final words of the sentence pairs were matched for their characters' average length,

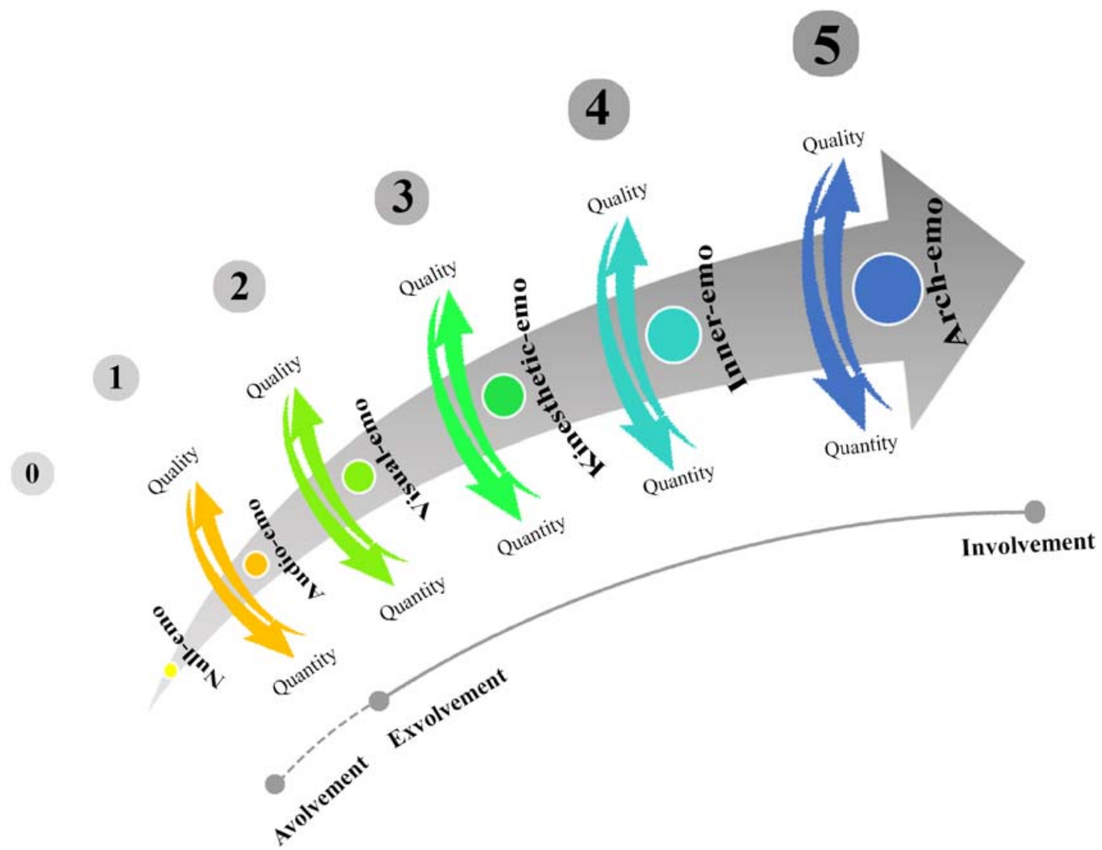


**Figure 1.** Emotioncy levels (Reprinted with permission from "Emotioncy, extraversion, and anxiety in willingness to communicate in English", by Pishghadam, 2016, Proceedings of the 5th International Conference on Language, Education, and Innovation. London, UK).

orthographic factors, bigram frequency, cloze probability, and word class. Cloze probabilities for the final words of all the sentences were checked by 2 native speakers, which resulted in the predictability of 100% for congruent and 0% for semantically incongruent sentences, respectively. A sentence acceptability judgment task was created (according to the ones implemented in the seminal studies of Hagoort et al. (2004), Hald et al. (2006), and Kos et al. (2012)) using Psychophysics Toolbox Version 3 (PTB-3) for MATLAB (version 2015a, The MathWorks, MA). The subjects were asked to decide on the acceptability of the sentences; congruent conditions were supposed to be considered as acceptable, and the semantically incongruent conditions were assumed as unacceptable items. All the sentences were randomised into four experimental blocks of 65 trials and a block of 64 trials, with inter-block intervals of 5 min. The words were presented in black lowercase letters on a light gray background with 36 pt Times New Roman font. They subtended an approximate visual angle of 3° horizontally and 0.5° vertically. Each word appeared in the centre of the computer screen for 750–850 ms, followed by a 300 ms blank page. The final word of every sentence was followed by a 2800 ms blank page for the subjects to press the pre-defined keys. An eye image was presented next, which allowed the subjects to blink for 3 s before the beginning of the next trial (Figure 3).

All the sentences were checked for their clarity through a pilot study (a paper and pencil test), several days before the main experiment. Some sentences were revised according to the comments of 15 participants (not included in the ERP study). The timings (e.g. 2800 ms response time) were also confirmed based on the results of a pilot computer test on 11 participants not included in the ERP study.

### 2.5. EEG recording and preprocessing

Recording of the EEG signals was performed in a sound-attenuated and dimly lit environment. Prior to the main experiment, the subjects performed a practice block of 20 trials similar to the main trials to become familiar with the condition of the experiment.

The signals were recorded from 23 active Ag/AgCl sintered electrodes embedded in an elastic electrode cap (g.GAMMAcap from g.tec medical engineering GmbH). The sampling rate was 250 Hz, and the electrodes (Fz,

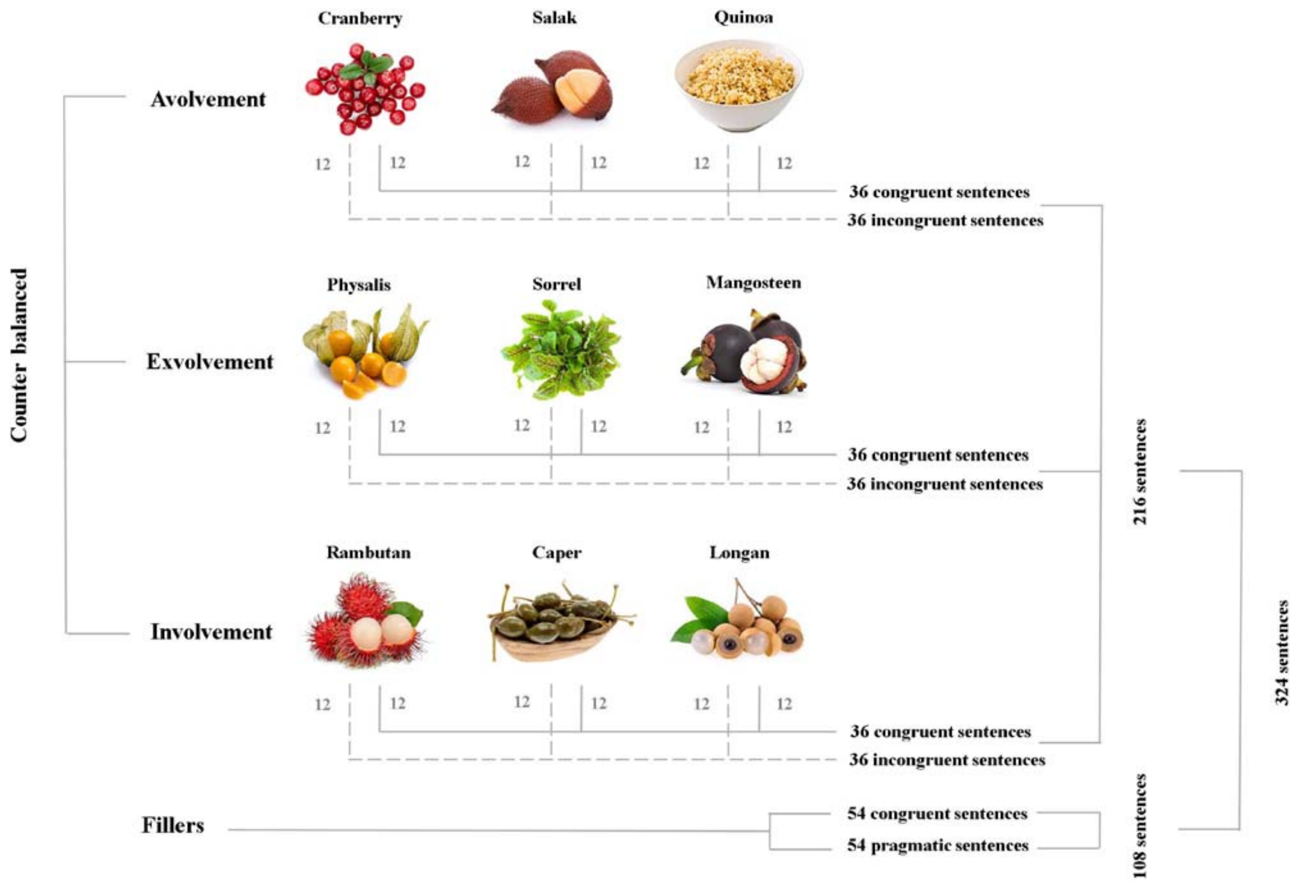


**Figure 2.** Sensory Involvement Protocol.

FCz, Cz, Pz, Oz, AF3/4, F3/4, F7/8, P3/4, P7/8, FC3/4, FT7/8, C3/4, P3/4 and P7/8, PO7/8) were located according to the 10–20 international system. The ground electrode was placed over the AFz. Moreover, three other electrodes were placed above, below, and on the outer canthus of the left eye to monitor vertical and horizontal eye movements. The recording was performed with reference to the left mastoid. Impedances of all the electrodes were kept below 5 kΩ, and the recordings were amplified with a g.Nautilus wireless biopotential amplifier (gtec, Austria). Furthermore, they were filtered using a bandpass filter between 0.1 and 70 Hz and a notch filter of 50 Hz.

EEG signals were re-referenced to the average of the linked-mastoids and low pass filtered at 25 Hz. Poor channels, mostly located at parieto-occipital and occipital sites, were interpolated (two channels for each subject at most). Trials with eye movements, EMG artifacts, and electrode drifting were rejected using the Artifact Subspace Reconstruction (ASR) algorithm. The signals were segmented into epochs ([−200 + 1100 ms]) time-locked to the onset of the final word of each

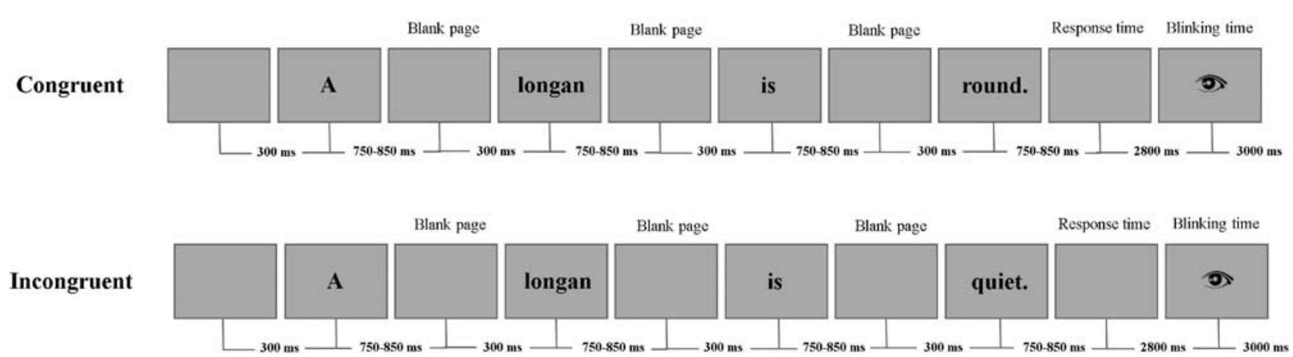


**Figure 3.** Samples of Stimuli for the Congruent and Incongruent Sentences Presented on the Computer Screen.

sentence, and baseline corrected (using a −200–0 ms prestimulus interval). Epochs with an absolute amplitude greater than 70 µv were rejected. Moreover, a linear algorithm (200 ms pre-stimulus onset to 3 s after that) was applied, as removing the mean value, for detrending the epochs. On average, 81.4% of the epochs remained after the artifact rejection (83.4% for avolvement, 79.2% for exvolvement, and 81.7% for involvement), which were averaged for each subject to obtain the ERPs.

## 2.6. Temporal analysis

The N400 and LPC potentials were quantified as the mean values of the ERPs' amplitude in the time interval of 300–550 and 600–850 ms, respectively. These time intervals were selected based on inspecting the grand average responses for these components as well as the findings of the previous studies (e.g. Brouwer & Crocker, 2017; Danko et al., 2014; Justus et al., 2011; Molinaro et al., 2016; Volz et al., 2019). The components' mean amplitudes were extracted for three representative frontal (Fz), central (Cz), and parietal (Pz) channels. Statistical analyses were conducted on the data collected from these three electrodes for a pair of reasons: 1. The selected electrodes are shown to present the maximal effects adequate for characterising the components' effects in sentences with incongruencies (Allen et al., 2003; Tanner et al., 2014; Tanner et al., 2017); 2. The small number of electrodes used in the analyses reduces Type I error in the ANOVA results (Tanner et al., 2017).

A series of three-way repeated measure ANOVAs was conducted to investigate the main effects and interactions of three within-subject variables, including sensory enrichment (avolvement, exvolvement, and involvement), as well as the semantic (in)congruency as the linguistic stimulus (congruent, incongruent) and location (Fz, Cz, Pz) on the N400 and LPC responses. Data processing was performed by means of MATLAB R16, and statistical analyses were conducted using IBM SPSS Statistics 24.

## 2.7. Wavelet-based time-frequency analysis

Wavelet-based time–frequency representations (TFRs) were created to investigate the EEG power changes between different degrees of sensory enrichment and semantic (in)congruency. TFRs were obtained using analytic Morlet wavelet with frequencies ranging from 1 to 30 Hz corresponding to 42 logarithmic scales. The power values obtained (i.e. squared amplitude) were expressed as a relative value to the power in a baseline interval from −200 to 0 ms prior to the onset of each sentence's final word. This normalisation was performed to reduce the individual differences in EEG power and differences in absolute power between different frequency bands.

# 3. Results

## 3.1. The effect of semantic (in)congruency

### 3.1.1. N400 and LPC responses

Grand average responses at Fz to congruent and semantically incongruent sentences are presented in Figure 4 for different degrees of sensory enrichment. Furthermore, scalp topographies of the N400 and LPC are presented in this figure for the two types of sentences in each sensory condition.

N400 and LPC potentials in response to semantic incongruency can be detected in the exvolved and involved conditions. A three-way repeated-measures ANOVA was conducted to investigate the effect of three within-subject variables, including sensory enrichment (avolvement, exvolvement, involvement), semantic (in)congruency (congruent, incongruent), and channel (Fz, Cz, Pz) on the N400 response. No significant interaction was observed for the sensory enrichment × semantic (in)congruency × channel. However, significant interactions were observed for sensory enrichment × semantic (in)congruency ($F(2,42) = 29.88$, $p = 0.005$, $\eta_p^2 = 0.23$, $1–\beta = 0.85$), as well as semantic (in)congruency × channel ($F(2,42) = 12.51$, $p < 0.001$, $\eta_p^2 = 0.37$, $1–\beta = 0.95$).

Regarding the significant interaction between sensory enrichment and semantic (in)congruency, further pairwise comparisons revealed the following results. For the avolved condition, no significant difference was observed between the N400 responses to the congruent and incongruent stimuli. For the exvolved condition, the negativity of the N400 for the incongruent sentences ($M = .91\ \mu V$) was significantly larger than that of the congruent ones ($M = 2.77\ \mu V$, $p < 0.001$). Similarly, for the involved condition, the negativity of the N400 for the incongruent sentences ($M = 0.52\ \mu V$) was significantly larger than that of the congruent one ($M = 2.85\ \mu V$, $p < 0.001$).

Regarding the significant interaction between the semantic (in)congruency and channel, the following results were obtained. For channel Fz, the negativity of the N400 elicited by semantically incongruent sentences ($M = 0.47\ \mu V$) was significantly larger than that of the congruent ones ($M = 1.49\ \mu V$, $p < 0.001$). Similarly, for channel Cz, the negativity of the N400 elicited by semantically incongruent sentences ($M = 0.40\ \mu V$) was

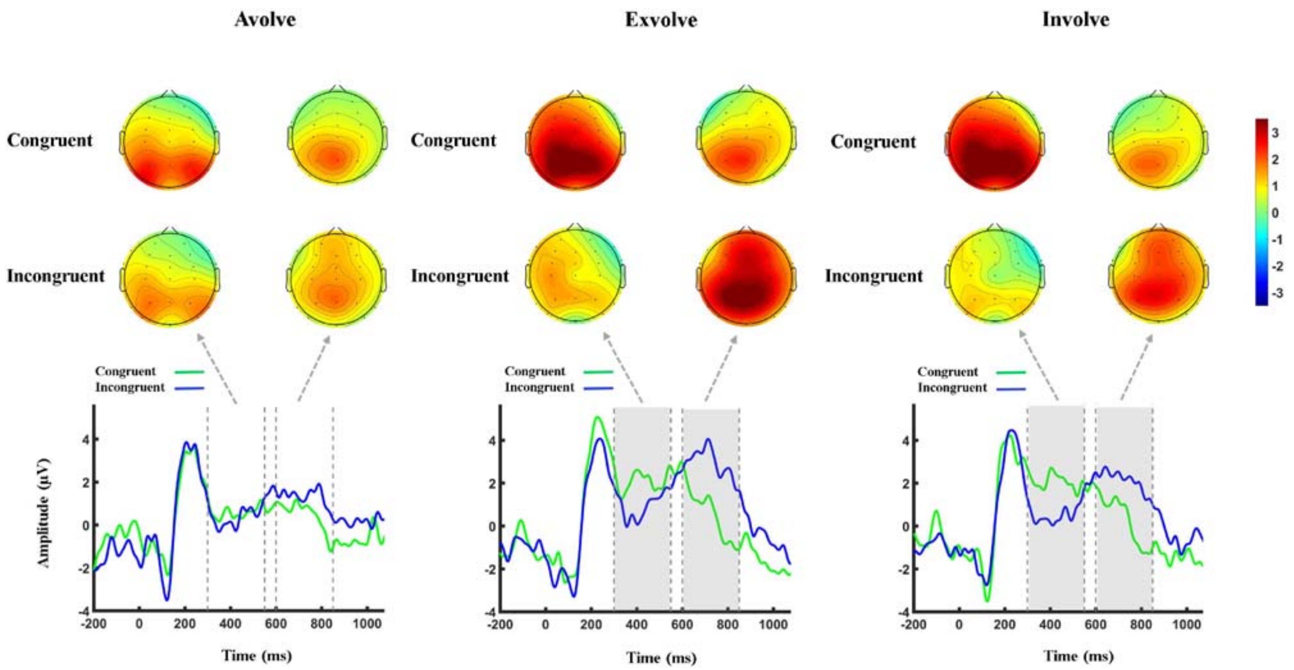


**Figure 4.** Grand Average ERPs at Fz and Scalp Topographies of the N400 and LPC in Response to Congruent and Semantically Incongruent Sentences in Different Sensory Enrichment Conditions.

significantly larger than that of the congruent ones (M = 2.14 $\mu$V, $p < 0.001$). A similar pattern was observed for channel Pz, where the negativity of the N400 elicited by semantically incongruent sentences (M = 1.19 $\mu$V) was significantly larger than that of the congruent ones (M = 3.19 $\mu$V, $p < 0.001$). To compare between the channels, for the congruent sentences, the negativity of the N400 for Fz (M = 1.49 $\mu$V) was significantly larger than that of the Cz (M = 2.14 $\mu$V, $p < 0.01$), and negativity of the Cz was significantly larger than that of the Pz (M = 3.19 $\mu$V, $p = 0.002$). For the semantically incongruent sentences, the negativity of the N400 for Cz (M = 0.40 $\mu$V) was significantly larger than that of Pz (M = 1.19 $\mu$V, $p = 0.005$).

A three-way repeated-measures ANOVA was also conducted to investigate the effect of within-subject variables on the LPC. No significant interaction was observed for the sensory enrichment × semantic (in)congruency × channel. However, significant interactions were observed for the sensory enrichment × semantic (in)congruency ($F(2,42) = 5.00$, $p = 0.01$, $\eta_p{}^2 = 0.19$, $1–\beta = 0.78$), as well as semantic (in)congruency × channel ($F(2,42) = 18.15$, $p < 0.001$, $\eta_p{}^2 = 0.46$, $1–\beta = 0.99$).

Regarding the significant interaction between sensory enrichment and semantic (in)congruency, further pairwise comparisons revealed the following results. For the avolved condition, no significant difference was observed between the LPC responses to the congruent and incongruent sentences. For the exvolved condition, the LPC amplitude for the semantically incongruent sentences (M = 3.14 $\mu$V) was significantly larger than that of the congruent one (M = 1.40 $\mu$V, $p = 0.001$). Similarly, for the involved condition, the LPC amplitude for the semantically incongruent sentences (M = 2.40 $\mu$V) was significantly larger than that of the congruent ones (M = 1.02 $\mu$V, $p = 0.004$).

Regarding the significant interaction between the semantic (in)congruency and channel, the following results were obtained. For channel Fz, the LPC amplitude for the semantically incongruent sentences (M = 2.21 $\mu$V) was significantly larger than that of the congruent ones (M = 0.42 $\mu$V, $p < 0.001$). Similarly, for channel Cz, the LPC amplitude for semantically incongruent sentences (M = 2.34 $\mu$V) was significantly larger than that of the congruent ones (M = 1.15 $\mu$V, $p = 0.005$). Moreover, for channel Pz, the LPC amplitude for the semantically incongruent sentences (M = 2.85 $\mu$V) was larger than that of the congruent ones (M = 2.08 $\mu$V, $p = 0.05$). To compare between the channels, for the semantically incongruent sentences, the LPC amplitude at Pz (M = 2.85 $\mu$V) was significantly larger than that of the Fz (M = 2.21 $\mu$V, $p = 0.05$) and marginally larger than that of the Cz (M = 2.34 $\mu$V, $p = 0.06$).

### 3.1.2. Oscillatory brain responses

Grand average ERPs and difference time–frequency plots of the power changes in response to semantically incongruent sentences compared to the congruent ones are presented in Figure 5. The results are presented for three representative channels in the avolved condition.

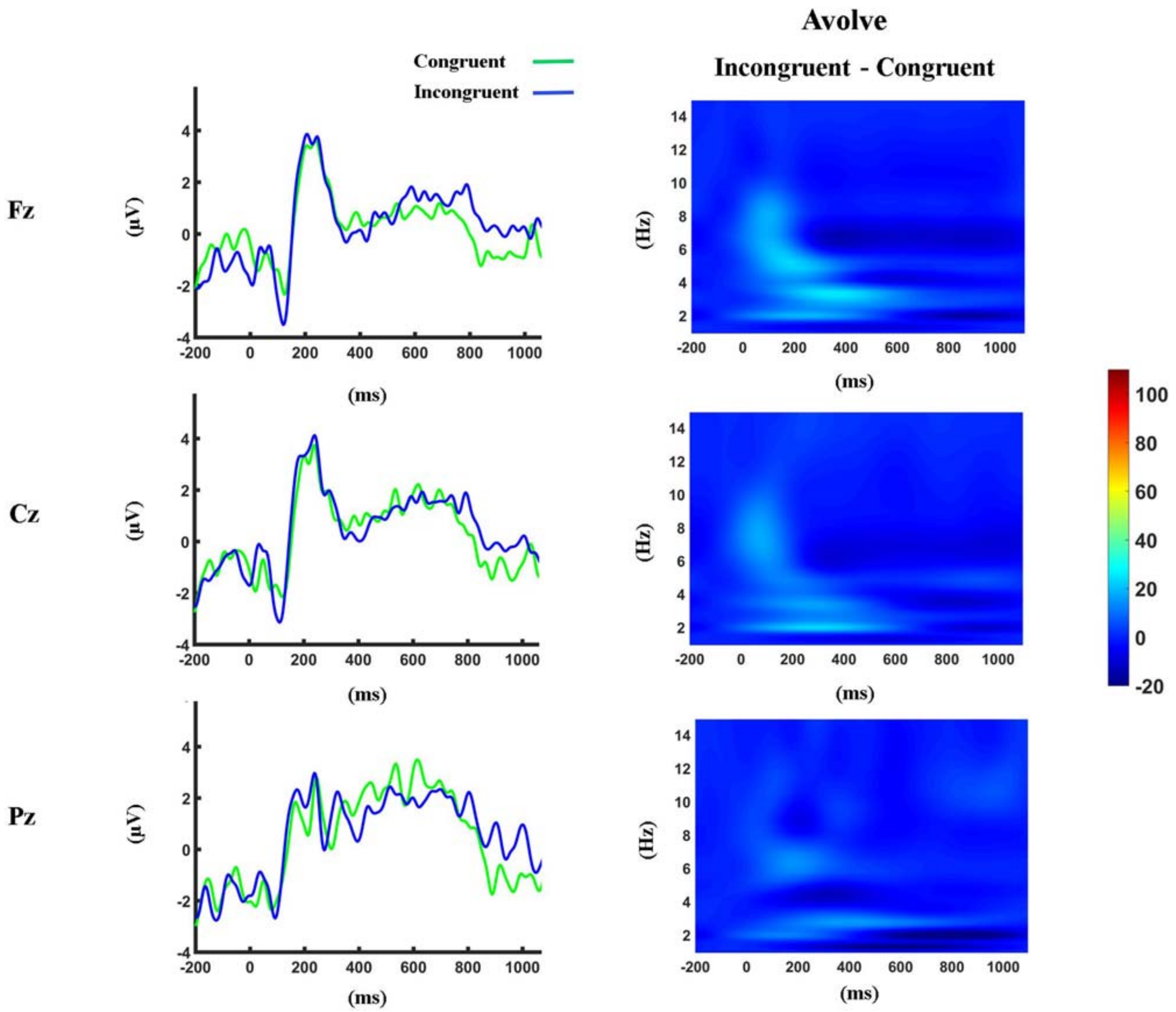


**Figure 5.** Grand Average ERPs and Difference Time-Frequency Plots of the Power Changes in Response to Semantically Incongruent Sentences Compared to the Congruent Ones. The Results are Presented for Three Representative Channels in the Avolved Condition. No Differences Were Observed at High Frequencies in All Figures. Therefore, Frequencies Higher than 15 Hz Were Removed For a Better Visualisation.

No significant power changes were observed between two different stimuli.

Similar illustrations, including the grand averages ERPs and difference time–frequency plots, are presented in Figure 6(a) for the exvolved condition. Differences can be observed in the time–frequency presentations at low frequencies. Figure 5(b) presents the scalp topographies of the lower delta power (1.7–2.2 Hz) changes in response to the congruent and incongruent sentences, averaged over a time interval of 300–850 ms after the final word onset.

The same illustrations are presented in Figure 7(a) for the involved condition. Power differences can be observed at low frequencies similar to the exvolved condition. Figure 7(b) presents the scalp topographies of the lower delta power (1.7–2.2 Hz) changes in response to the congruent and semantically incongruent sentences, averaged over a time interval of 300–850 ms after the final word onset.

A three-way repeated-measures ANOVA was conducted to investigate the effect of within-subject variables on the lower delta power. No significant interaction was observed for sensory enrichment × semantic (in)congruency × channel. However, significant interactions were observed for sensory enrichment × semantic (in)congruency ($F(2,42) = 11.20$, $p < 0.001$, $\eta_p^2 = 0.34$, $1–\beta = 0.97$). Moreover, no significant main effect was observed for the channel. Post-hoc analyses further revealed the following results. For the avolved condition, no significant difference was observed

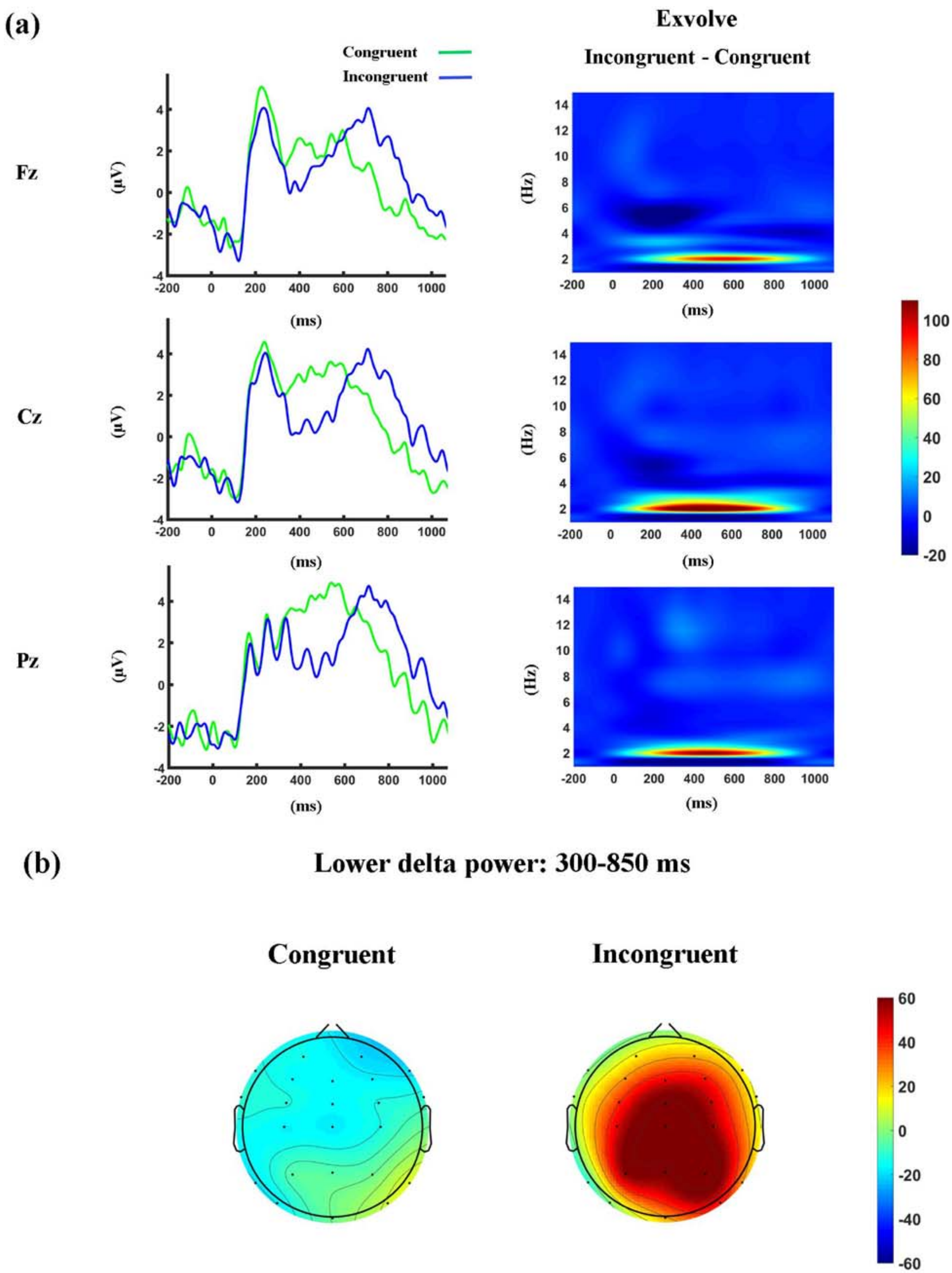


**Figure 6.** (a) Grand Average ERPs and Difference Time-Frequency Plots of The Power Changes in Response to Semantically Incongruent Sentences Compared to the Congruent Ones. The Results are Presented for Three Representative Channels in the Exvolved Condition. No Differences Were Observed at High Frequencies in All Figures. Therefore, Frequencies Higher than 15 Hz Were Removed for a Better Visualisation. (b) Scalp Topography of the Lower Delta Power Changes (1.7–2.2 Hz) in Response to the Congruent and Semantically Incongruent Sentences in the Exvolved Condition, Averaged over a Time Interval of 300–850 ms after the Final Word Onset.

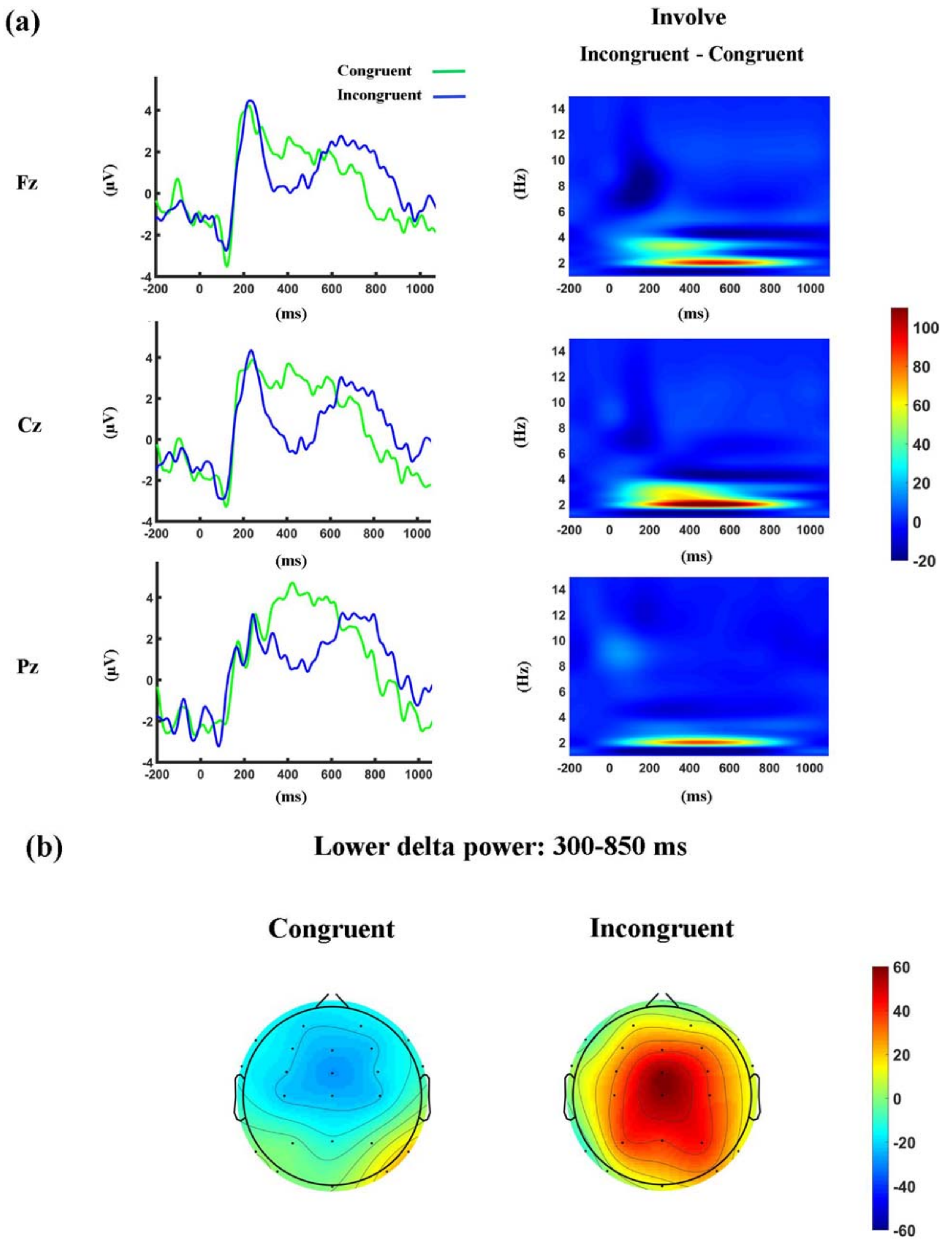


**Figure 7.** (a) Grand Average ERPs and Difference Time-Frequency Plots of The Power Changes in Response to Semantically Incongruent Sentences Compared to the Congruent Ones. The Results are Presented for Three Representative Channels in the Involved Condition. No Differences Were Observed at High Frequencies in All Figures. Therefore, Frequencies Higher than 15 Hz Were Removed for a Better Visualisation. (b) Scalp Topography of the Lower Delta Power Changes (1.7–2.2 Hz) in Response to the Congruent and Semantically Incongruent Sentences in the Exvolved Condition, Averaged over a Time Interval of 300–850 ms after the Final Word Onset.

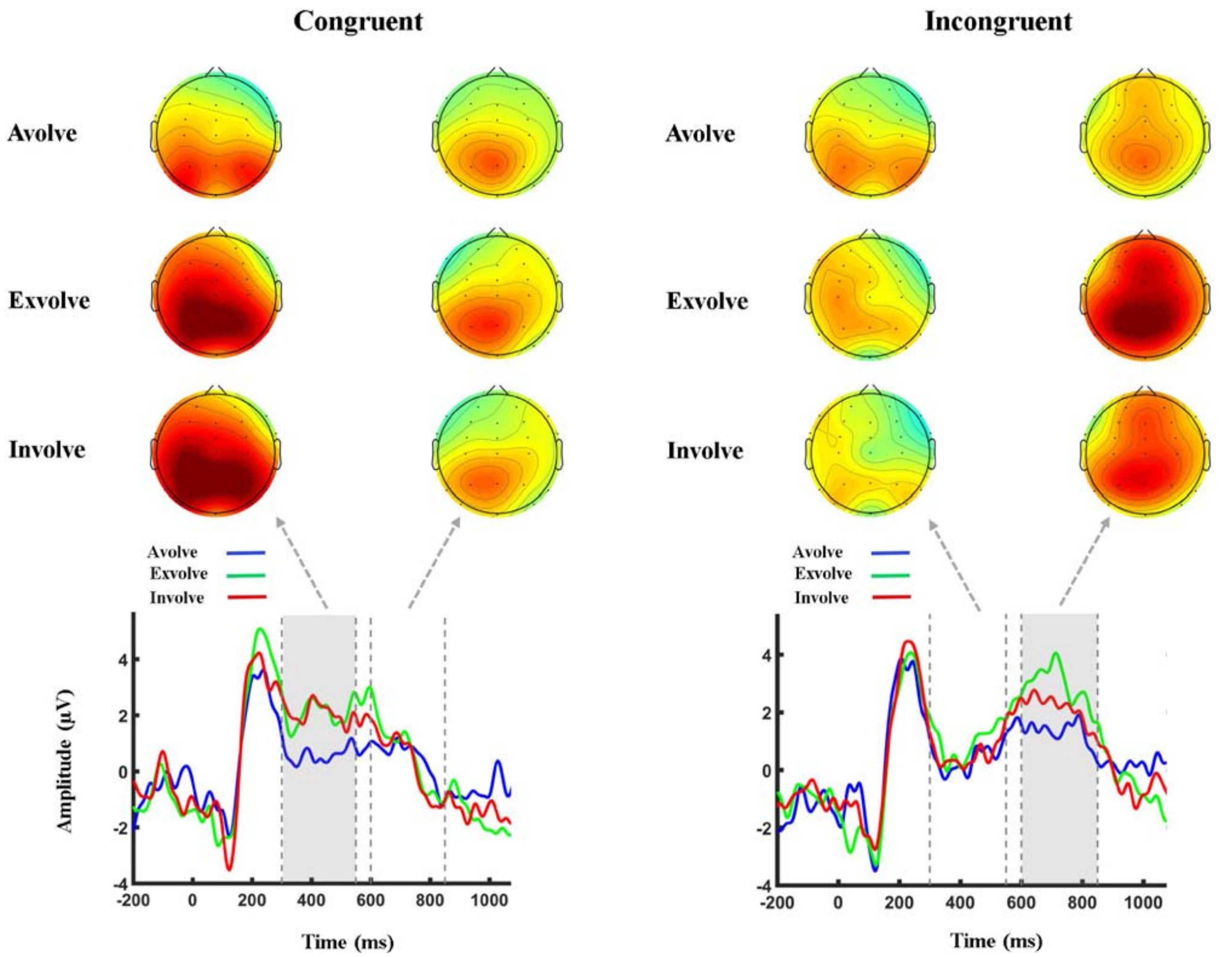


**Figure 8.** Grand Average ERPs at Fz and Topographic Maps of N400 and LPC in Response to the Congruent and Semantically Incongruent Sentences Replotted to Compare between Different Sensory Involvement Conditions.

between the lower delta power of the congruent and incongruent sentences. For the exvolved condition, the lower delta power of semantically incongruent sentences (M = 84.20) was significantly larger than that of the congruent ones (M = −18.21, $p < 0.001$). Similarly, for the involved condition, the lower delta power of semantically incongruent sentences (M = 46.91) was marginally larger than that of the congruent ones (M = −0.25, $p = 0.06$).

## 3.2. The effect of sensory enrichment

### 3.2.1. N400 and LPC responses

To compare different degrees of sensory enrichment, corresponding grand average responses at Fz and topographic maps of N400 and LPC are replotted in Figure 8 for the congruent and semantically incongruent sentences.

For the congruent condition, the negativity of the N400 for avolvement (M = 1.21 $\mu$V) was significantly larger than that of exvolvement (M = 2.77 $\mu$V, $p < 0.001$) and involvement (M = 2.85 $\mu$V, $p = 0.003$). Moreover, no significant difference was observed between the exvolved and involved conditions. For the incongruent condition, there was no significant effect of sensory enrichment on the N400 amplitude. Concerning the LPC response, which was only observed in the incongruent condition, the amplitude of exvolvement (M = 3.41 $\mu$V) was larger than that of the avolvement (M = 1.60 $\mu$V, $p < 0.001$) and involvement (M = 2.40 $\mu$V, $p < 0.05$).

### 3.2.2. Oscillatory brain responses

Grand average ERPs and difference time–frequency plots of the power changes for the avolved, exvolved, and involved conditions are presented in Figure 9(a). The results are presented for three channels in response to the congruent sentences. No significant power changes were observed between different degrees of sensory enrichment.

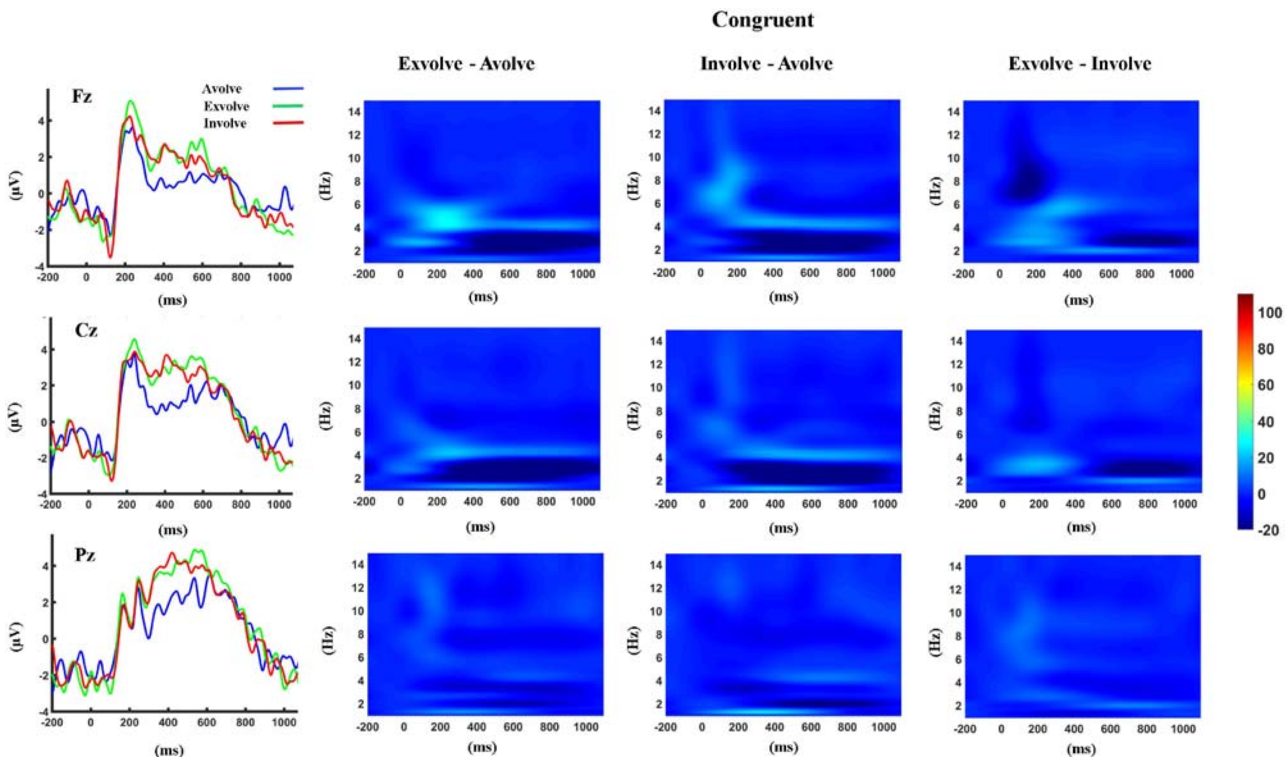


**Figure 9.** Grand Average ERPs and Difference Time-Frequency Plots of the Power Changes for the Avolved, Exvolved, and Involved Conditions. The Results are Presented for Three Representative Channels in Response to the Congruent Sentences. No Differences Were Observed at High Frequencies in All Figures. Therefore, Frequencies Higher than 15 Hz Were Removed for a Better Visualisation.

Similar illustrations are presented in Figure 10(a) for the semantically incongruent sentences. Power differences can be observed at low frequencies. Figure 10(b) presents the scalp topographies of the lower delta power (1.7–2.2 Hz) changes in the avolved, exvolved, and involved conditions averaged over a time interval of 300–850 ms after the final word onset. No significant interaction was observed for sensory enrichment × channel. The following pattern was observed for the three channels. The lower delta power of the avolved condition ($M = -4.62$) was significantly smaller than that of the exvolved ($M = 84.20$, $p < 0.001$) and involved ($M = 46.91$, $p < 0.05$) conditions. Moreover, the lower delta power of the exvolved condition was marginally larger ($p = 0.06$) than that of the involved one.

Representative individual-level results for different conditions and channels are presented in the supplementary file. General patterns, similar to the grand average results, can be observed in the figures.

## 4. Discussion

In order to discover the interaction effect between semantic (in)congruency and sensory enrichment, changes in the neural correlates and oscillatory synchrony during L2 sentence comprehension were analysed. While the ERP results rendered the differences between the variables, the statistical analysis of wavelet-based time–frequency data revealed no contrast in the synchronisation and desynchronisation patterns of alpha, theta, or delta frequency ranges in the N400 and LPC latency windows. Therefore, we combined the two ERP windows to target the retrieval-unification process as a whole, analysing the oscillatory neural activity in the 300–850 ms interval. Such an account yielded delta power modulations over a large number of electrodes. It should be noted that differences in all other frequency ranges and time intervals, except those reported in the results section, were not significant. In what follows, we interpret the interaction results of semantic (in)congruity and sensory enrichment from two interrelated perspectives.

### 5.1. Semantic (In)congruency

Under various degrees of sensory enrichment, there was a significant difference between the neurocognitive mappings underlying the processing of congruent and semantically incongruent sentences. That is, regardless of how rich the sensory input was, semantically incongruent sentences, relative to the congruent ones, elicited a single stream neural architecture comprising a

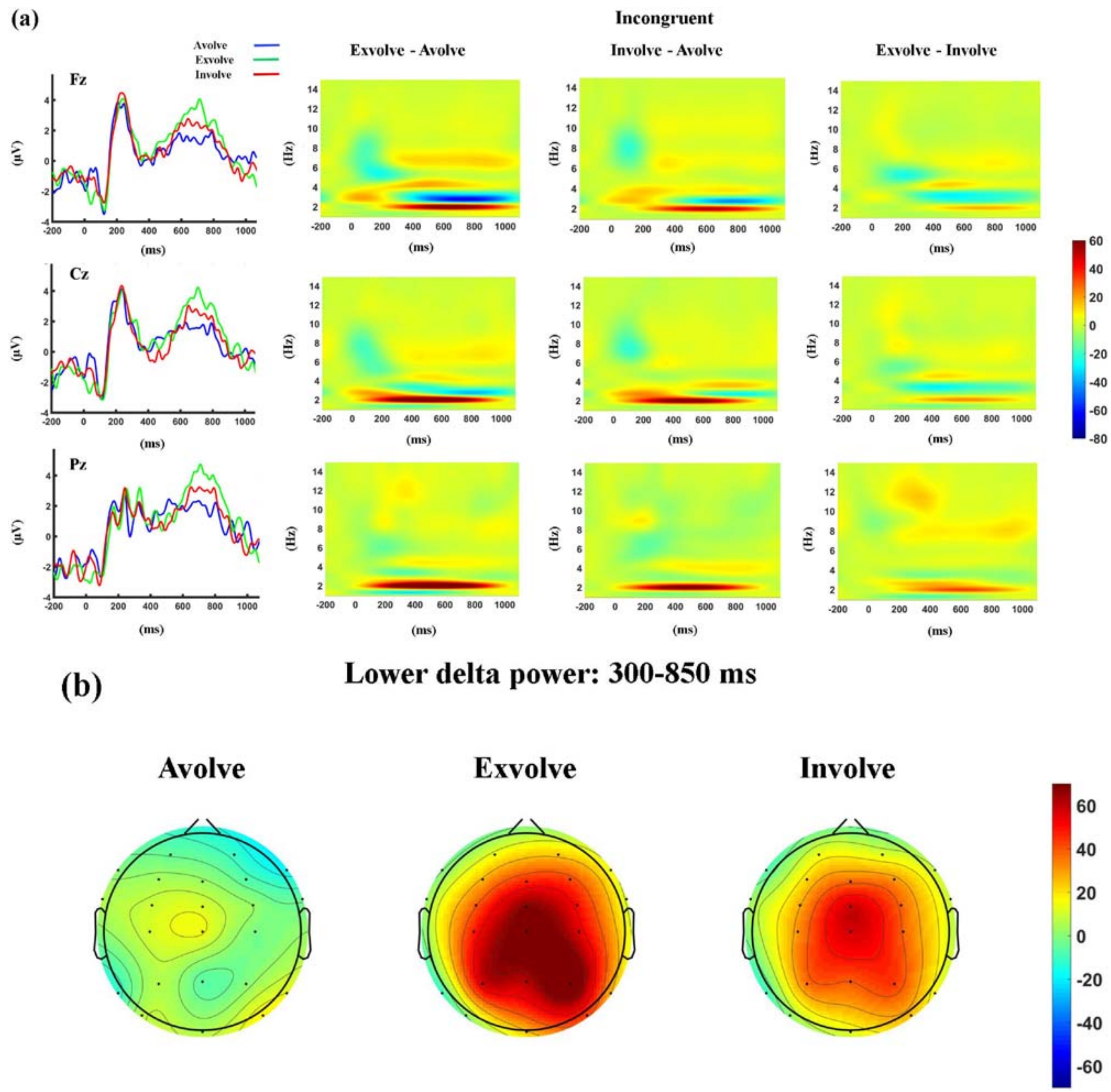


**Figure 10.** (a) Grand Average ERPs and Difference Time-Frequency Plots of the Power Changes for the Avolved, Exvolved, and Involved Conditions. The Results are Presented for Three Representative Channels in Response to Semantic Incongruency. No Differences Were Observed at High Frequencies in All Figures. Therefore, Frequencies Higher than 15 Hz were Removed for a Better Visualisation. (b) Scalp Topography of the Lower Delta Power Changes (1.7–2.2 Hz) in the Avolved, Exvolved, And Involved Conditions, Averaged over a Time Interval of 300–850 ms after the Final Word Onset.

frontally-peaked N400 (please see Voss and Federmeier (2011) for more information) followed by a broadly-distributed LPC with its maximum over the posterior cortical areas. The finding confirmed our ERP hypothesis formed earlier in this study and substantiated that, like the incongruent sentences in L1 (Brouwer et al., 2016; Brouwer & Hoeks, 2013; Delogu et al., 2019), and L2 (Liang & Chen, 2020; Pishghadam et al., 2021; Shayesteh et al., 2020; Zheng & Lemhöfer, 2019), semantic incongruency provoked a late positivity preceded by a negativity.

In line with our first hypothesis, the wavelet-based TFA yielded a lower delta band power (1.7–2.2 Hz) increase in the 300–850 ms latency range subsequent to the final word onset for congruent and semantically incongruent sentences. This broadly distributed effect was significantly more pronounced in the incongruent sentences, under exvolved and involved conditions.

This enhanced synchronisation is difficult to interpret since most paradigms about delta band responses are associated with sleeping. Consequently, little is known about the functional characteristics of the respective frequency band in the paradigms that are not associated with sleeping. Kielar et al. (2014) proposed that semantic incongruency leads to power increases in the 1–5 Hz frequency band (Kielar et al., 2014). Some experimental data (e.g. Kielar et al., 2014; Kielar et al., 2015) speak to the proposition that synchronisation in slow-wave oscillations signal increases in cognitive demand and the attention paid to the incongruent structure.

Unlike the sentences with exvolved and involved words, no qualitative differences in low frequency oscillatory neural activity were detected between the congruent and semantically incongruent trials under the avolved condition. Since the subjects had no information about the avolved target words, they were not able to detect sentence-embedded semantic incongruencies; hence no significant lower delta modulation was observed between the two linguistic conditions.

Although a number of studies have reported the alpha and theta wave reactivity in the LPC latency window in semantically incongruent sentences compared to their congruent version (Burgess & Ali, 2002; Hagoort et al., 2004; Hald et al., 2006; Hanslmayr et al., 2012; Willems et al., 2008), we observed no qualitative differences in this time range between the sentences with and without semantic incongruency. A possible justification could be that sensory enrichment effects might have modulated the power reactivities which were not controlled in previous L2 comprehension studies.

### *5.2. Sensory enrichment*

While there was no significant distinction between the N400 amplitude of exvolvement and involvement in semantically incongruent sentences, exvolvement turned out to be more positive in the LPC time range. It implies that, although various degrees of sensory enrichment do not manipulate the semantic retrieval operation, they have a role in the later stages of sentence comprehension dealing with integration and control. Considering LPC as a reflection of semantic reanalysis, we confirm Shayesteh et al.'s (2020) and Pishghadam et al.'s (2021) recent findings that exvolvement, due to being limited in sensory richness, produces increased executive function and attention demands on the subjects' memory to recheck the accuracy of a given sentence. In such a reanalysis process, the obtained knowledge might be reviewed "to establish adequate utterance meanings for this sentence context" (Regel et al., 2014, p. 9). It should further be noted that, regarding the incongruent sentences of the avolved condition, we did not observe the N400 and LPC indexes since the subjects did not have the knowledge of the target words and were not able to detect the incongruency in the sentences.

A time–frequency analysis of the ERPs revealed that, in agreement with our second hypothesis, in the time window of 300–850 ms, avolvement, exvolvement, and involvement were found to slightly differ in the lower delta frequency band (1.7–2.2 Hz) such that a marginally significant, more pronounced increase in amplitude was observed for exvolvement. The lower delta power synchronisation in exvolvement and involvement, mapped against avolvement, is a reflection of deactivation inherent to the slow-wave oscillatory activity (Harmony, 2013; Harmony et al., 1996). To delineate, the delta wave is not only the main characteristic of sleep, but its amplitude changes have a part in sensory processing during wakefulness as well (Başar & Düzgün, 2016; Liu et al., 2020). It is, in fact, believed that to ignore irrelevant sensory input and provide internal concentration (Quak et al., 2015; Rao, 2018), inhibition-based oscillations, wiring many neurons across large brain areas (Buzsáki, 2006; Harmony, 2013) become active. Such an approach highly correlates the functional characteristic of delta wave with cortical deafferentation and the inhibition of non-relevant neural networks that need to be inactive while doing a certain mental activity (Harmony, 2013; Harmony et al., 1996). Therefore, the bigger delta amplitude in exvolvement may signify that due to limited sensory enrichment, more internal concentration was necessary during semantic processing.

The smallest delta amplitude belonged to the avolved condition, in which the subjects had no knowledge of the target words. This may indicate that not much attention demand was required to retrieve information and comprehend the sentence whose main element is unknown. Processing information limited in multisensory richness exerts an extra cognitive burden on the brain. However, since in the avolved condition, the brain lacks the representation of the target word, the subjects skip the rest of the sentence without trying to reach full comprehension.

Based on the results and the similar topographical distributions of the delta oscillation under sensory enrichment and semantic incongruency, similar neural assemblies might be involved in both processes. Note, however, that scalp EEG is not a well-suited tool for spatial analysis of patterns. More importantly, the most striking finding of this study is that besides LPC whose responsiveness to different combinations of senses has been reported earlier by Shayesteh et al. (2020), lower delta wave seems to exhibit some sensitivity to sensory richness of the input. In particular, as the brain processes the multisensory input from the combination of three sensory channels, delta oscillations increase to interrupt the function of irrelevant cortical regions, allowing for the brain to maintain extra internal concentration and make up for the lack of sensory information. Therefore, promoting the sensory quality of the input by incorporating all the five senses produces a lower mental load and reduces the need for delta synchronisation. This finding provides an update on the characterisation of this low-frequency wave during language-related cognitive processes and its activity at the conscious level.

However, a word of caution regarding the final conclusion of the study is needed. Although the results were indicative of a small qualitative difference between exvolvement and involvement, the effect reported here is required to be replicated prior to making any strong claim. In order to further extend the findings of this study, as well as our understanding of the role of multisensory integration on the comprehension mechanism, future research needs to address the following gaps. First, given that actual learning was not checked in this study, future studies can be conducted to measure learning in short and long terms. Moreover, to eliminate high-frequency noise inherently embedded in a long EEG recording, the frequencies above 25 Hz were filtered out for a better SNR. Therefore, we were not able to examine the discrepancies between different levels of sensory enrichment in high beta and gamma frequency ranges. Future research can address this limitation and extend the current findings. Besides, since the present methodological framework revealed synchronisation changes within individual nodes of language-related networks, coherence analysis is highly desirable to arrive at fine-grained information about synchronisation between these particular functional networks. An additional suggestion could be to detect the sources of electrophysiological and oscillatory responses to semantic information obtained through different degrees of sensory enrichment. As the objective of this study was not to compare the processes underlying L1 and L2 sentence comprehension, future research would investigate these differences further. Last but not least, various combinations of senses are possible, among which we chose two only. Future experiments could form other combinations and evaluate the results accordingly.

## Acknowledgments

We appreciate the support provided by Pishghadam Testing and Language Aptitude Measurement Center to collect the data.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

## Funding

This work was supported by Ferdowsi University of Mashhad: [grant number 1399].

## ORCID

*Reza Pishghadam* http://orcid.org/0000-0001-6876-5139

## References

Adams, F. (2010). Embodied cognition. *Phenomenology and the Cognitive Sciences*, *9*(4), 619–628. https://doi.org/10.1007/s11097-010-9175-x

Allan, D. (1992). *The Oxford quick placement test*. Oxford: Oxford University Press.

Allefeld, C., Frisch, S., & Schlesewsky, M. (2005). Detection of early cognitive processing by event-related phase synchronisation analysis. *Neuroreport*, *16*(1), 13–16. https://doi.org/10.1097/00001756-200501190-00004

Allen, M., Badecker, W., & Osterhout, L. (2003). Morphological analysis in sentence processing: An ERP study. *Language and Cognitive Processes*, *18*(4), 405–430. https://doi.org/10.1080/01690960244000054

Ardal, S., Donald, M. W., Meuter, R., Muldrew, S., & Luce, M. (1990). Brain responses to semantic incongruity in bilinguals. *Brain and Language*, *39*(2), 187–205. https://doi.org/10.1016/0093-934X(90)90011-5

Başar, E., & Düsgün, A. (2016). Links of consciousness, perception, and memory by means of delta oscillations of brain. *Frontiers in Psychology*, *7*, 275. https://doi.org/10.3389/fpsyg.2016.00275

Bastiaansen, M., & Hagoort, P. (2006). Oscillatory neuronal dynamics during language comprehension. *Progress in Brain Research*, *159*, 179–196. https://doi.org/10.1016/S0079-6123(06)59012-0

Borsipour, B. (2016). Emotioncy and willingness to read: A case of Iranian EFL learners (Unpublished master's thesis). Ferdowsi University of Mashhad, Mashhad, Iran.

Brouwer, H., & Crocker, M. W. (2017). On the proper treatment of the N400 and P600 in language comprehension. *Frontiers in Psychology*, *8*, 1327. https://doi.org/10.3389/fpsyg.2017.01327

Brouwer, H., Crocker, M. W., Venhuisen, N. J., & Hoeks, J. C. (2016). A neurocomputational model of the N400 and the P600 in language processing. *Cognitive Science*, *41*, 1318–1352. https://doi.org/10.1111/cogs.12461

Brouwer, H., & Hoeks, J. C. J. (2013). A time and place for language comprehension: Mapping the N400 and the P600 to a minimal cortical network. *Frontiers in Human*

*Neuroscience*, *7*, 758. https://doi.org/10.3389/fnhum.2013.00758

Buzsáki, G. (2006). *Rhythms of the brain*. Oxford University Press.

Danko, S. G., Boytsova, J. A., Solovjeva, M. L., Chernigovskaya, T. V., & Medvedev, S. V. (2014). Event-related brain potentials when conjugating Russian verbs: The modularity of language procedures. *Human Physiology*, *40*(3), 237–243. https://doi.org/10.1134/S0362119714030050

Delogu, F., Brouwer, H., & Crocker, M. W. (2019). Event-related potentials index lexical retrieval (N400) and integration (P600) during language comprehension. *Brain and Cognition*, *135*, 103569. https://doi.org/10.1016/j.bandc.2019.05.007

Duñabeitia, J. A., Dimitropoulou, M., Dowens, M. G., Molinaro, N., & Martin, C. (2016). The electrophysiology of the bilingual brain. In R. R. Heredia, J. Altarriba, & A. B. Cieślicka (Eds.), *Methods in bilingual reading comprehension research* (pp. 265–312). Springer.

Dylman, A. S., & Bjärtå, A. (2019). When your heart is in your mouth: The effect of second language use on negative emotions. *Cognition and Emotion*, *33*(6), 1284–1290. https://doi.org/10.1080/02699931.2018.1540403

Ernst, M. O., & Bülthoff, H. H. (2004). Merging the senses into a robust percept. *Trends in Cognitive Sciences*, *8*(4), 162–169. https://doi.org/10.1016/j.tics.2004.02.002

Foglia, L., & Wilson, R. A. (2013). Embodied cognition. *Wiley Interdisciplinary Reviews: Cognitive Science*, *4*(3), 319–325. https://doi.org/10.1002/wcs.1226

Hagoort, P. (2013). MUC (memory, unification, control) and beyond. *Frontiers in Psychology*, *4*, 416. https://doi.org/10.3389/fpsyg.2013.00416

Hagoort, P., Hald, L., Bastiaansen, M., & Petersson, K. M. (2004). Integration of word meaning and world knowledge in language comprehension. *Science*, *304*(5669), 438–441. https://doi.org/10.1126/science.1095455

Hajra, S. G., Liu, C. C., Song, X., Fickling, S. D., Cheung, T. P., & D'Arcy, R. C. (2018). Multimodal characterisation of the semantic N400 response within a rapid evaluation brain vital sign framework. *Journal of Translational Medicine*, *16* (151), 1–11. https://doi.org/10.1186/s12967-018-1527-2

Hald, L. A., Bastiaansen, M. C., & Hagoort, P. (2006). EEG theta and gamma responses to semantic violations in online sentence processing. *Brain and Language*, *96*(1), 90–105. https://doi.org/10.1016/j.bandl.2005.06.007

Hanslmayr, S., Staudigl, T., & Fellner, M. C. (2012). Oscillatory power decreases and long-term memory: The information via desynchronisation hypothesis. *Frontiers in Human Neuroscience*, *6*, 74. https://doi.org/10.3389/fnhum.2012.00074

Harmony, T. (2013). The functional significance of delta oscillations in cognitive processing. *Frontiers in Integrative Neuroscience*, *7*, 83. https://doi.org/10.3389/fnint.2013.00083

Harmony, T., Fernández, T., Silva, J., Bernal, J., Díaz-Comas, L., Reyes, A., & Marosi, E. (1996). EEG delta activity: An indicator of attention to internal processing during performance of mental tasks. *International Journal of Psychophysiology*, *24* (1-2), 161–171.

Jankowiak, K., & Rataj, K. (2017). The N400 as a window into lexico-semantic processing in bilingualism. *Posnan Studies in Contemporary Linguistics*, *53*(1), 119–156. https://doi.org/10.1515/psicl-2017-0006

Justus, T., Larsen, J., Yang, J., de Mornay Davies, P., Dronkers, N., & Swick, D. (2011). The role of Broca's area in regular past-tense morphology: An event-related potential study. *Neuropsychologia*, *49*(1), 1–18. https://doi.org/10.1016/j.neuropsychologia.2010.10.027

Karami, M., Pishghadam, R., & Baghaei, P. (2019). A probe into EFL learners' emotioncy as a source of test bias: Insights from differential item functioning analysis. *Studies in Educational Evaluation*, *60*, 170–178. https://doi.org/10.1016/j.stueduc.2019.01.003

Kielar, A., Meltser, J. A., Moreno, S., Alain, C., & Bialystok, E. (2014). Oscillatory responses to semantic and syntactic violations. *Journal of Cognitive Neuroscience*, *26*(12), 2840–2862. https://doi.org/10.1162/jocn_a_00670

Kielar, A., Panamsky, L., Links, K. A., & Meltser, J. A. (2015). Localisation of electrophysiological responses to semantic and syntactic anomalies in language comprehension with MEG. *NeuroImage*, *105*, 507–524. https://doi.org/10.1016/j.neuroimage.2014.11.016

Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: A review and analysis. *Brain Research Reviews*, *29*(2-3), 169–195. https://doi.org/10.1016/S0165-0173(98)00056-3

Kolk, H. H., Chwilla, D. J., Van Herten, M., & Oor, P. J. (2003). Structure and limited capacity in verbal working memory: A study with event-related potentials. *Brain and Language*, *85*(1), 1–36. https://doi.org/10.1016/S0093-934X(02)00548-5

Kos, M., Van den Brink, D., & Hagoort, P. (2012). Individual variation in the late positive complex to semantic anomalies. *Frontiers in Psychology*, *3*, 318. https://doi.org/10.3389/fpsyg.2012.00318

Leitan, N. D., & Chaffey, L. (2014). Embodied cognition and its applications: A brief review. Sensoria: A Journal of Mind, Brain and Culture, 10(1), 3-10. https://doi.org/10.7790/sa.v10i1.384

Liang, L., & Chen, B. (2020). The impact of language proficiency on the time course and neural basis of L2 semantic access in bilinguals. *International Journal of Bilingualism*, *24*(4), 840–860. https://doi.org/10.1177/1367006919897851

Liu, C. C., Hajra, S. G., Pawlowski, G., Fickling, S. D., Song, X., & D'Arcy, R. C. (2020). Differential neural processing of spontaneous blinking under visual and auditory sensory environments: An EEG investigation of blink-related oscillations. *NeuroImage*, *218*, 116879. https://doi.org/10.1016/j.neuroimage.2020.116879

Mahoney, J. R., Li, P. C. C., Oh-Park, M., Verghese, J., & Holtser, R. (2011). Multisensory integration across the senses in young and old adults. *Brain Research*, *1426*, 43–53. https://doi.org/10.1016/j.brainres.2011.09.017

Makiabadi, H., Pishghadam, R., Naji Meidani, E. N., & Khajavy, G. H. (2019). Examining the role of emotioncy in willingness to communicate: A structural equation modeling approach. *Revista de Psicodidáctica (English ed.)*, *24*(2), 120–130. https://doi.org/10.1016/j.psicoe.2019.03.003

Miao, J. (2013). An ERP study of semantic anomalies in second language processing. In D. Liu, C. Alippi, D. Shao, & A. Hussain (Eds.), *International conference on brain inspired cognitive systems* (pp. 38–45). Springer.

Molinaro, N., Su, J. J., & Carreiras, M. (2016). Stereotypes override grammar: Social knowledge in sentence comprehension. *Brain and Language*, *155–156*, 36–43. https://doi.org/10.1016/j.bandl.2016.03.002

Murray, M. M., Lewkowics, D. J., Amedi, A., & Wallace, M. T. (2016). Multisensory processes: A balancing act across the lifespan. *Trends in Neurosciences*, *39*(8), 567–579. https://doi.org/10.1016/j.tins.2016.05.003

Newman, A. J., Tremblay, A., Nichols, E. S., Neville, H. J., & Ullman, M. T. (2012). The influence of language proficiency on lexical semantic processing in native and late learners of English. *Journal of Cognitive Neuroscience*, *24*(5), 1205–1223. https://doi.org/10.1162/jocn_a_00143

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*(1), 97–113.

Pishghadam, R. (2016). Emotioncy, extraversion, and anxiety in willingness to communicate in English. In W. A. Lokman, F. M. Fasidah, I. Salahuddin, & I. A. W. Mohd (Eds.), *Proceedings of the 5th international conference on language, education, and innovation* (pp. 1–5). Infobase Creation Sdn Bhd.

Pishghadam, R., Baghaei, P., & Seyednosadi, S. (2017). Introducing emotioncy as a potential source of test bias: A mixed Rasch modeling study. *International Journal of Testing*, *17*(2), 127–140. https://doi.org/10.1080/15305058.2016.1183208

Pishghadam, R., Jajarmi, H., & Shayesteh, S. (2021). Sense combinations influence the neural mechanism of L2 comprehension in semantically violated sentences: Insights from emotioncy. *Journal of Neurolinguistics*, *58*, 100962. https://doi.org/10.1016/j.jneuroling.2020.100962

Quak, M., London, R. E., & Talsma, D. (2015). A multisensory perspective of working memory. *Frontiers in Human Neuroscience*, *9*, 197. https://doi.org/10.3389/fnhum.2015.00197

Rao, A. R. (2018). An oscillatory neural network model that demonstrates the benefits of multisensory learning. *Cognitive Neurodynamics*, *12*(5), 481–499. https://doi.org/10.1007/s11571-018-9489-x

Regel, S., Meyer, L., & Gunter, T. C. (2014). Distinguishing neurocognitive processes reflected by P600 effects: Evidence from ERPs and neural oscillations. *PloS One*, *9*(5), e96840. https://doi.org/10.1371/journal.pone.0096840

Salmon, N., & Pratt, H. (2002). A comparison of sentence- and discourse-level semantic processing: An ERP study. *Brain and Language*, *83*(3), 367–383. https://doi.org/10.1016/S0093-934X(02)00507-2

Schacht, A., Sommer, W., Shmuilovich, O., Martíens, P. C., & Martín-Loeches, M. (2014). Differential task effects on N400 and P600 elicited by semantic and syntactic violations. *PLoS One*, *9*(3), Article e91226. https://doi.org/10.1371/journal.pone.0091226

Shams, L., & Seits, A. R. (2008). Benefits of multisensory learning. *Trends in Cognitive Sciences*, *12*(11), 411–417. https://doi.org/10.1016/j.tics.2008.07.006

Shams, L., Wosny, D. R., Kim, R. S., & Seits, A. (2011). Influences of multisensory experience on subsequent unisensory processing. *Frontiers in Psychology*, *2*, 264. https://doi.org/10.3389/fpsyg.2011.00264

Shapiro, L. (2011). *Embodied cognition*. Routledge.

Shayesteh, S., Pishghadam, R., & Khodaverdi, A. (2020). FN400 and LPC responses to different degrees of sensory involvement: A study of sentence comprehension. *Advances in Cognitive Psychology*, *16*(1), 45–58. https://doi.org/10.5709/acp-0283-6

Sheng, X., & Lemhöfer, K. (2019). The "semantic P600" in second language processing: When syntax conflicts with semantics. *Neuropsychologia*, *127*, 131–147. https://doi.org/10.1016/j.neuropsychologia.2019.02.010

Tanner, D., Grey, S., & van Hell, J. G. (2017). Dissociating retrieval interference and reanalysis in the P600 during sentence comprehension. *Psychophysiology*, *54*(2), 248–259. https://doi.org/10.1111/psyp.12788

Tanner, D., Nicol, J., & Brehm, L. (2014). The time-course of feature interference in agreement comprehension: Multiple mechanisms and asymmetrical attraction. *Journal of Memory and Language*, *76*, 195–215. https://doi.org/10.1016/j.jml.2014.07.003

Vols, K., Stark, R., Vaitl, D., & Ambach, W. (2019). Event-related potentials differ between true and false memories in the misinformation paradigm. *International Journal of Psychophysiology*, *135*, 95–105. https://doi.org/10.1016/j.ijpsycho.2018.12.002

Voss, J. L., & Federmeier, K. D. (2011). FN400 potentials are functionally identical to N400 potentials and reflect semantic processing during recognition testing. *Psychophysiology*, *48*(4), 532–546. https://doi.org/10.1111/j.1469-8986.2010.01085.x

Wang, L., Jensen, O., Van den Brink, D., Weder, N., Schoffelen, J. M., Magyari, L., Hagoort, P., & Bastiaansen, M. (2012). Beta oscillations relate to the N400 during language comprehension. *Human Brain Mapping*, *33*(12), 2898–2912. https://doi.org/10.1002/hbm.21410

Wechsler, D. (1981). Wechsler adult intelligence scale: WAIS-R manual. Harcourt Brace Jovanovich [for] the Psychological Corporation.

Willems, R. M., Oostenveld, R., & Hagoort, P. (2008). Early decreases in alpha and gamma band power distinguish linguistic from visual information during spoken sentence comprehension. *Brain Research*, *1219*, 78–90. https://doi.org/10.1016/j.brainres.2008.04.065