Short Communication

Ways of making-sense: Local gamma synchronization reveals differences between semantic processing induced by music and language

Paulo Barraza [a], Mario Chavez [b], Eugenio Rodríguez [c],*

[a] Centro de Investigación Avanzada en Educación, CIAE, Universidad de Chile, 8330014 Santiago, Chile
[b] CNRS-UMR-7225, Hôpital Pitié Salpêtrière, 75013 Paris, France
[c] Laboratorio de Neurociencias, Escuela de Psicología, Pontificia Universidad Católica de Chile, 8940000 Santiago, Chile

ARTICLE INFO

ABSTRACT

Similar to linguistic stimuli, music can also prime the meaning of a subsequent word. However, it is so far unknown what is the brain dynamics underlying the semantic priming effect induced by music, and its relation to language. To elucidate these issues, we compare the brain oscillatory response to visual words that have been semantically primed either by a musical excerpt or by an auditory sentence. We found that semantic violation between music–word pairs triggers a classical ERP N400, and induces a sustained increase of long-distance theta phase synchrony, along with a transient increase of local gamma activity. Similar results were observed after linguistic semantic violation except for gamma activity, which increased after semantic congruence between sentence–word pairs. Our findings indicate that local gamma activity is a neural marker that signals different ways of semantic processing between music and language, revealing the dynamic and self-organized nature of the semantic processing.

1. Introduction

Music is a highly complex human experience. Like language, music has its own syntactic structure (Patel, 2003), and can bring forth meanings to the mind (Nattiez, 1990). According to Koelsch (2011), the musical meaning can range from extra-musical association (e.g. notion of a national identity during the listening of a national anthem) to interpretations of physical, emotional, and self-related experiences (e.g. subjective feeling of "calm" during the listening of an adagio), suggesting a pragmatic rather than semantic nature of the musical meaning. In neurophysiological terms, recent studies (Koelsch et al., 2004; Steinbeis & Koelsch, 2008) have shown that music can prime the meaning of a word, and evoke an event-related potential (ERP) N400 (Kutas & Hillyard, 1980), an electrophysiological index of semantic and pragmatic integration problems. Although ERP N400 provides fine-grained information about the time course of semantic and pragmatic processing, it is not very informative about the organization of oscillatory brain dynamics underlying the semantic processing of a word primed by a musical context, and its relation with linguistic semantic processing.

Numerous studies support the fundamental role played by oscillatory brain dynamics in several cognitive functions (e.g., Barraza, Gómez, Oyarzún, & Dartnell, 2014; Fallani, Richiardi, Chavez, & Achard, 2014; Rodriguez et al., 1999). Regarding linguistic semantic processing, previous researches have linked local gamma oscillations with semantic unification/integration process (Bastiaansen & Hagoort, 2006), or alternatively with the level of predictability of incoming information (Wang, Zhu, & Bastiaansen, 2012). Interestingly, it has been observed that gamma oscillations differentiate between integration problems arising from the interpretation of semantic and pragmatic information (Hagoort, Hald, Bastiaansen, & Petersson, 2004). In a different line of evidence a number of studies (Bastiaansen, Oostenveld, Jensen, & Hagoort, 2008; Hald, Bastiaansen, & Hagoort, 2006; Mellem, Friedman, & Medvedev, 2013) have found the involvement of theta band during linguistic semantic processing. Hald et al. (2006) and Bastiaansen et al. (2008), using semantic-anomaly paradigm and lexical decision task respectively, found an increase of local theta power after semantic violation, which is interpreted as an index of retrieval of lexical semantic information. On the other hand, in a semantic priming experiment conduced by Mellem et al. (2013), they found an increase of long-distance theta synchronization after a linguistic semantic violation, indicating dynamic coupling of anterior and posterior areas for retrieval and post-retrieval processing.

* Corresponding author.
E-mail addresses: paulo.barraza@ciae.uchile.cl (P. Barraza), mario.chavez@upmc.fr (M. Chavez), erodrigb@uc.cl (E. Rodríguez).

To the best of our knowledge there are no studies on local or global neural synchrony during semantic processing of a word primed by music. However, there are some studies analyzing the oscillatory dynamics during musical syntactic processing (Ruiz, Koelsch, & Bhattacharya, 2009), and its effect on linguistic syntactic and semantic processing (Carrus, Koelsch, & Bhattacharya, 2011). Results of these studies show mainly changes in delta-theta spectral power related to syntactic processing in both domains. Interestingly, it has been observed that musical syntactic processing has no effect on the linguistic semantic processing (Carrus, Pearce, & Bhattacharya, 2013; Koelsch, Gunter, Wittfoth, & Sammler, 2005), suggesting that the music processing seems to be independent of linguistic semantic processing. The general pattern emerging of these sets of studies highlight the involvement of theta and gamma oscillations in semantic processing.

The purpose of the present study is to disentangle the oscillatory brain dynamics related to musical and linguistic semantic priming effect. To this end, and considering the above body of evidence, we formulate the following hypothesis: (a) both theta and gamma bands would be activated by semantic processing in both musical and linguistic domains; (b) gamma activity would differentiate between linguistic and musical semantic processing; (c) theta activity would emerge after both musical and linguistic semantic violations. To test these hypotheses, we recorded EEG signals in subjects engaged in a semantic priming task, consisting in the presentation of contextual prime stimuli (musical excerpts or spoken sentences) followed by a visually presented target word. After the target word, participants were asked to indicate whether the prime and the target were meaningfully related or not (Koelsch et al., 2004). As indicators of local and long-distance neural coordination (Varela, Lachaux, Rodriguez, & Martinerie, 2001), we measured the induced spectral power (Tallon-Baudry & Bertrand, 1999) and phase synchronization values (Lachaux, Rodriguez, Martinerie, & Varela, 1999). Additionally, we analyzed ERPs for comparison with previous results (Koelsch et al., 2004).

2. Results

2.1. ERP N400

The results are illustrated in Fig. 1. A repeated-measures ANOVA revealed that the target words that were preceded by semantically unrelated musical ($F_{1,18} = 4.702$, $p = 0.044$, $\eta^2 = 0.207$; 1.019 μV difference) and linguistic primes ($F_{1,18} = 19.824$, $p = 0.0003$, $\eta^2 = 0.524$; 2.343 μV difference) elicited a negative deflection of the ERP activity, from 430 ms to 550 ms after target word onset. These results indicate that the N400 effect was present in both linguistic and musical domains, which is consistent with the previously reported by Koelsch et al. (2004).
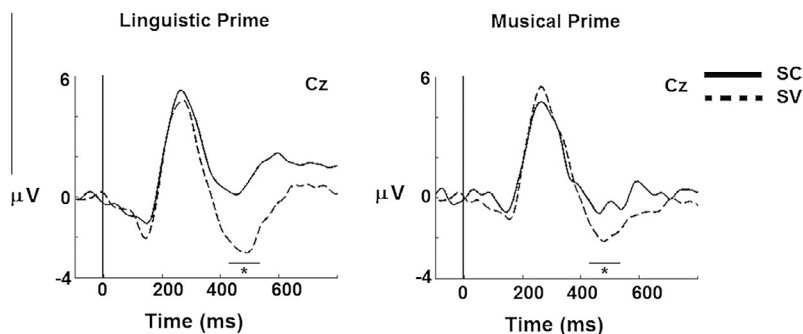
2.2. Spectral power

The results are illustrated in Fig. 2. A repeated-measures ANOVA revealed that target words that were preceded by semantically unrelated musical primes lead to an increase of gamma spectral power (35–45 Hz) from 100 ms to 200 ms ($F_{1,18} = 11.626$, $p = 0.003$, $\eta^2 = 0.392$) after target word onset, with a topographical distribution over frontal and right temporal-parietal sites. Unlike musical priming condition, we found that target words that were preceded by semantically related sentences induced an increase of the local gamma synchrony (35–45 Hz), between 50–120 ms ($F_{1,18} = 26.071$, $p = 0.00007$, $\eta^2 = 0.592$), 280–420 ms ($F_{1,18} = 19.727$, $p = 0.0003$, $\eta^2 = 0.523$) and 500–600 ms ($F_{1,18} = 5.599$, $p = 0.029$, $\eta^2 = 0.237$) after target word onset, with a topographical distribution beginning over left parietal-occipital and right parietal-frontal electrodes, then changing to left central and right occipital-parietal regions, and finalizing over left occipital and right parietal-frontal sites.

Additionally, direct comparisons between linguistic and musical conditions were performed. Repeated-measures ANOVA revealed that, compared to musical semantic congruence, the linguistic semantic congruence induce a higher increase of local gamma activity (35–45 Hz), between 100–160 ms ($F_{1,18} = 4.969$, $p = 0.039$, $\eta^2 = 0.216$) and 200–420 ms ($F_{1,18} = 11.769$, $p = 0.003$, $\eta^2 = 0.395$) after target word onset, with a topographical distribution over left parietal-occipital and frontal regions. In the case of semantic violation, we found that music, more than language, induce a higher increase of local gamma activity (35–45 Hz), between 40 and 120 ms ($F_{1,18} = 5.981$, $p = 0.025$, $\eta^2 = 0.249$) after target word onset, with a topographical distribution mainly over right parietal-occipital sites.

2.3. Phase synchrony

The results are illustrated in Fig. 3. A repeated-measures ANOVA revealed that target words that were preceded by semantically unrelated musical primes lead to a sustained and late increase of long-distance theta synchronization (4–6 Hz), between 300 and 500 ms ($F_{1,18} = 8.032$, $p = 0.011$, $\eta^2 = 0.309$) after target word onset, with a connectivity patterns distributed mainly between right central-parietal electrodes. On the linguistic domain, target words that were semantically unrelated to prime sentences induced an early increase of theta phase synchrony (6–7 Hz), between 50 and 300 ms ($F_{1,18} = 5.071$, $p = 0.037$, $\eta^2 = 0.220$) after target word onset, with a connectivity patterns between left central-frontal and right parietal electrodes.

Direct comparisons between linguistic and musical conditions reveal that, compared to music, linguistic semantic congruence induce a higher increase of long-distance theta synchrony

Fig. 1. The N400 effect during musical and linguistic semantic priming tasks. Each graph shows the waveforms for the semantic congruence (SC: solid line) and semantic violation (SV: segmented line) conditions, in both musical and linguistic domains. Voltage (in microvolts) and time (in milliseconds) are respectively indicated in the y and x axes of the graphs. Vertical lines indicate the onset of the target word. The asterisks delimit time windows showing significant differences between conditions ($p < 0.05$).
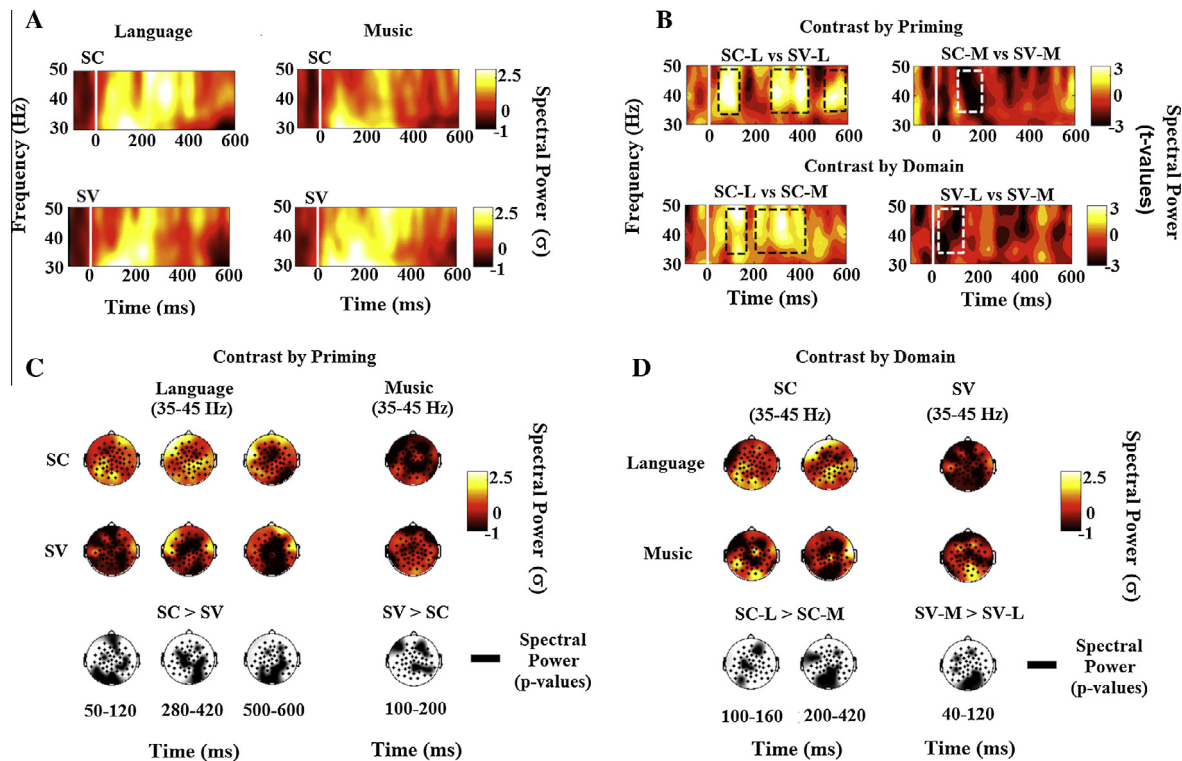
Fig. 2. Gamma activity charts, contrast between conditions, and its topographic distribution during musical and linguistic semantic priming tasks. (A) The time–frequency plot shows the grand average of all electrodes. Frequency range and time are respectively indicated in the y and x-axis of the maps. Color bars at the right side of the maps show amplitude values (in standard deviation units). White vertical lines indicate the target word onset. Semantic congruence (SC) and semantic violation (SV) conditions are indicated at the top of the each map. (B) Contrasts between conditions. The segmented black and white rectangles delimit time–frequency windows showing significant differences between conditions (p < 0.05) (Linguistic semantic congruence/violation: SC-L/SV-L; Musical semantic congruence/violation: SC-M/SV-M). Color bars at the right side of the maps show t-values. (C and D) Topographic distribution of the induced gamma spectral power. Top and middle rows represent the conditions. Color bars at the right side of the heads show amplitude values (in standard deviation units). Bottom row represent the statistical difference between conditions. Black regions over the heads displaying significant difference of gamma activity (p < 0.05, FDR corrected) averaged in the time windows identified in (B).

(4–6 Hz), between 100 and 500 ($F_{1,18}$ = 6.439, p = 0.021, η^2 = 0.263) after target word onset, with a topographical distribution between left temporal-parietal and right frontal electrodes.

3. Discussion

The present study was designed to examine the brain dynamic underlying the semantic processing of a word primed by musical and linguistic context. Our results showed that semantic violation in both domains evoke an ERP N400 and an increase of long-distance theta neural synchronization. Furthermore, we observed that local gamma activity was differentially modulated by musical and linguistic contexts. Below we discuss the principal findings and their implications in more detail.

The phase synchrony analysis revealed that semantic violation between both music–word and sentence–word pairs induced a strong increase of long-distance theta synchronization. Previous researches have related large-scale theta synchrony with verbal working memory (Schack & Weiss, 2005) and semantic retrieval processes (Mellem et al., 2013). Alternatively, theta phase synchrony has been associated with a cognitive control mechanism emerging after error detections (Cavanagh, Cohen, & Allen, 2009). Concerning the role played by theta phase synchrony during the processing of a word semantically unrelated to musical or linguistic prime, we propose that it is linked to the transient emergence of a functional neural network, involved in the active maintenance of meaningful information in working memory, due to the difficulty to integrate the context with the meaning of the incoming word.

This difficulty seems to be greater in the case of music–word pairs, because the meanings emerging during the listening of musical excerpts are less concrete, than those generated by the auditory sentences, which would be reflected in the sustained increase of long-distance theta synchrony, densely distributed over right central-parietal sites, while in the case of language the increase was early, transient, and with a less dense connectivity pattern distributed over left central-frontal and right parietal electrodes.

The power spectral analysis showed a differential effect of local gamma activity between music and language. Specifically, semantic violation between music–word pairs and semantic congruence between sentence–word pairs induced an increase of local gamma activity. Traditionally, gamma spectral power has been associated with perceptual binding (Csibra, Davis, Spratling, & Johnson, 2000; Tallon-Baudry & Bertrand, 1999) and working memory process (Howard et al., 2003; Roux, Wibral, Mohr, Singer, & Uhlhaas, 2012). In semantic linguistic studies, local gamma activity has been proposed as an index of integration/unification process (Bastiaansen & Hagoort, 2006), semantic representations activation (Mellem et al., 2013), and predictability of the incoming information (Wang et al., 2012). Interestingly, also it has been observed an increase of local gamma activity after pragmatic violation (Hagoort et al., 2004). Lewis, Wang, and Bastiaansen (2015) suggest that pragmatic violations would induce a change of cognitive strategy, paying more attention to bottom-up processing rather than top-down predictive processing, which would affect the pattern of gamma results. As for the role of local gamma activity in the present study, we believe that the predictive hypothesis is the one that best fits our results. In the case of the semantic congruence
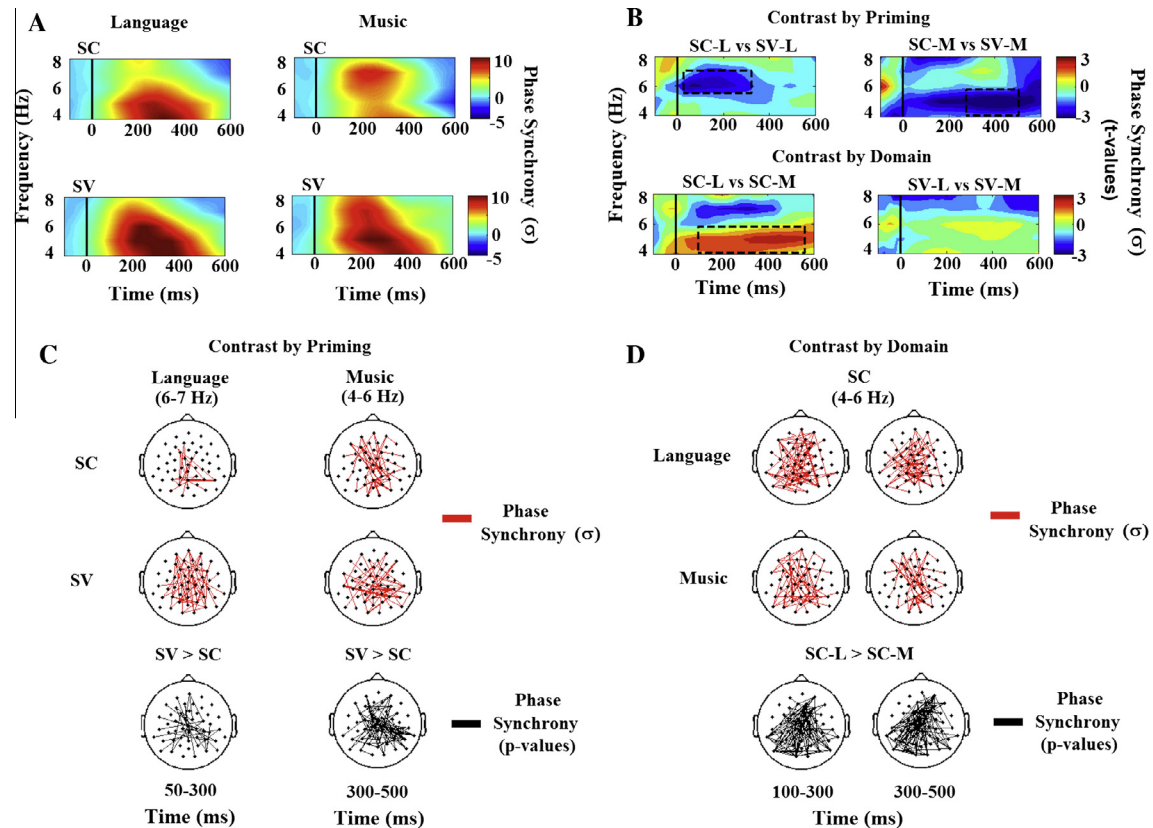
Fig. 3. Theta phase synchrony charts, contrast between conditions, and its topographic distribution during musical and linguistic semantic priming tasks. (A) The phase synchrony plot shows the grand average of all electrodes pairs. Frequency range and time are respectively indicated in the y and x-axis of the maps. Color bars at the right side of the maps show phase synchrony values (in standard deviation units). Black vertical lines indicate the target word onset. Semantic congruence (SC) and semantic violation (SV) conditions are indicated at the top of the each map. (B) Contrasts between conditions. The segmented black rectangles delimit time–frequency windows showing significant differences between conditions ($p < 0.05$) (Linguistic semantic congruence/violation: SC-L/SV-L; Musical semantic congruence/violation: SC-M/SV-M). Color bars at the right side of the maps show t-values. (C and D) Topographic distribution of the theta phase synchronization. Top and middle rows represent the conditions. Red lines over the heads show phase synchrony between electrodes (above 18 SD). Bottom row represent the statistical difference between conditions. Black lines over the heads displaying significant difference of theta phase synchrony ($p < 0.05$, FDR corrected) averaged in the time windows identified in (B).

between sentences-word pairs, the early increase of local gamma activity, distributed over left parietal-occipital and right central-frontal sites, reflects the match between the semantic expectation generated by the linguistic context and the actual incoming word. Subsequently, late local gamma increases distributed mainly over central and posterior sites, are associated with post-processing of semantic information (Herrmann, Munk, & Engel, 2004). On the other hand, the increase of local gamma activity after the semantic violation between music–word pairs, suggests the presence of a different cognitive strategy for the musical priming condition. As the musical meaning is much more general and diffuse than the linguistic meaning, the possibility that the musical context pre-activates specific memory representations and evokes concrete predictions, are low. Thus, increased gamma oscillations over frontal and right temporal-parietal site, after semantic violations between music–word pairs, can be explained as the arising of a cognitive strategy focused more on the lack of semantic relation between music and word, rather than the confirmation of a specific semantic prediction.

In conclusion, our findings reveal the organization of brain dynamics during the semantic processing of a word primed by a musical or linguistic context. In this regard, we observed differences in the way that music and language are processed. Specifically, semantic processing primed by musical contexts seems to be based on the gradual ongoing construction of a global meaning, while the linguistic semantic processing would rely on a predictive

mechanism that anticipates the meaning of the incoming word. Future experiments should directly address this issue.

4. Methods

4.1. Participants

Nineteen subjects (seven males, age range: 18–23 years, mean age = 20.05 years) participated in an EEG experiment. All participants gave written informed consent to participate in the study. All were native Spanish speakers, right handed, had normal hearing and normal or corrected to normal vision and had no history of neurological and/or psychiatric illness. None of the participants were musicians, or had participated in extra-curricular music lessons or performances.

4.2. Stimuli and procedure

Three hundred fifty-two pairs of prime-word stimuli were used. Primes were 88 excerpts of instrumental music (mean duration = 15 s) and 88 spoken sentences (mean duration = 2 s), and targets were 88 Spanish words. For each target word, four primes were chosen: (i) a semantically related musical excerpt, (ii) an unrelated musical excerpt, (iii) a related sentence, and (iv) an unrelated sentence (See Supplementary Audio 1–4 online for examples of musical stimuli; Construction of (un)related music–word pairs is

explained in Supplementary Material 1). Moreover, each prime was used twice: in one trial, the prime was semantically unrelated to a target word, and in another trial it was semantically related to a target word (the order was pseudo-randomly intermixed in each experiment). The editing of musical excerpts and sentences recording was performed using digital audio editor Audacity 1.2.6. Detailed methods have been published in Koelsch et al. (2004).

Prior to the experiment, participants read the instructions to perform the task. Each trial began with the auditory presentation of a musical excerpt or sentence, followed by a period of 500 ms without stimulation, ending by the presentation of a target word during 2 s. After the target word disappeared, a question mark appeared on the screen as a cue for the subject to respond. In this period, the subject had to indicate whether the target word was semantically related or not with the prime stimulus previously presented, by pressing one of two possible response buttons.

The EEG recording was performed inside a Faraday cage to reduce contamination of the EEG signal by external electromagnetic noises. The semantic priming task was programmed with the stimulus presentation software E-Prime version 1.1. The prime stimuli were presented binaurally via loudspeakers Logitech X-230, the target words were presented visually in the center of a monitor screen Dell Ultra Sharp 1708FP-BLK and behavioral responses were recorded with a response pad EGI 200. The monitor, loudspeakers, and the response pad were arranged on a table facing the subject, inside the Faraday cage.

4.3. Electrophysiological recording and analysis

EEG activity was recorded with a geodesic sensor net of 64 electrodes, referenced to vertex (Electrical geodesics, Eugene, OR, USA). The EEG was filtered online from 0.01 to 100 Hz, in order to eliminate DC fluctuations of the EEG recording and digitized at 1000 Hz. Before starting the recording the electrode's impedance was lowered to 40 kΩ or less as suggested by the manufacturer of the equipment (Ferree, Luu, Russell, & Tucker, 2001). Finally, the signal was digitized and stored for offline analysis.

4.3.1. ERP N400

The continuous EEG signal was filtered offline with a bandpass FIR filter (0.5–20 Hz) with a linear phase response. Then, the filtered signal was segmented in a series of 1100-ms-long epochs. Each epoch started 100 ms before the onset of the target word and ended 1000 ms later. Trials containing voltage fluctuations that exceeded ±200 μV, transients exceeding ±100 μV or electroocular activity larger than ±70 μV were rejected. Artifact-free trials (mean artifact-free trials: sentence–word related = 73.32; sentence–word unrelated = 78.37; music–word related = 47; music–word unrelated = 65.42) were re-referenced to the average activity of the two mastoids averaged in relation to the onset of the target word and baseline corrected over a 100 ms window before the onset of the target word.

4.3.2. Spectral power and phase synchrony

The raw EEG signal was first segmented into a series of epochs lasting 2000 ms including 1000 ms preceding the onset to target word. Peripheral electrodes placed near the eyes, face and neck, were excluded from the analysis in order to avoid ocular or muscular artifacts. The EEG was re-referenced off-line to average reference, in order to minimize artifactual sources of synchronization (Bertrand, Perrin, & Pernier, 1985; Nunez et al., 1997). Thus, we estimated spectral power and phase synchrony over 50 out of 64 channels only. The continuous 50 Hz (AC) components were filtered in each epoch with a zero-phase filter that keeps the biological 50 Hz signal. Time frequency (TF) distributions were obtained by means of the wavelet transform. The filtered signal $x(t)$ was convolved with a complex Morlet's wavelet function defined as $w(t, f_0) = Ae^{-t^2 / 2\sigma_t^2} e^{i2\pi f_0 t}$. Wavelets were normalized and thus $A = (\sigma_t \sqrt{\pi})^{-1/2}$ the width of each wavelet function $m = f_0 / \sigma_t$ was chosen to be 7; where $\sigma_f = \frac{1}{2}\pi\sigma_t$. TF contents was represented as the energy of the convolved signal: $E(t, f_0) = |w(t, f_0) \otimes x(t)|^2$. By this process we obtained amplitude and phase values for frequencies between 1 and 70 Hz with 1 Hz frequency resolution. Based on previously reported findings (Hagoort et al., 2004; Lewis et al., 2015; Mellem et al., 2013; Weiss & Mueller, 2003), theta (4–8 Hz) and low gamma band (30–50 Hz) were selected as interest frequency bands. Amplitude information was used to compute the induced spectral power, which is obtained by averaging the time–frequency energy across single trials (Tallon-Baudry & Bertrand, 1999), while the phase information was used to compute the phase-locking value (PLV) (Lachaux et al., 1999). In brief, the method involves computing the phase difference in a time window for an electrode pair and assessing the stability of such phase difference through all trials. If Φ_i and Φ_j are unitary vectors representing the phase of signals in electrodes **i** and **j**, then the phase difference between such electrodes is a unitary vector obtained by: $\Phi_{ij} = \Phi_i \text{conj}(\Phi_j)$. The PLV is thus the length of the vector resulting from the vector sum of difference vectors through the trials (with the sum operating throughout all of the trials), where N is the number of trials: $\text{PLV}_{ij} = \text{abs}(\Sigma\Phi_{ij})/N$.

The PLV index ranges from 0 to 1, with value 1 indicating perfect synchronization (phase difference is concentrated around a preferred value throughout the trials) and value 0 representing total absence of synchrony (under the null hypothesis of a uniformity of phase difference distribution). Spectral power and phase synchronization across the duration of the trial, for each frequency bin, was normalized to a 400 ms baseline before the onset of the target word. The normalized signal (S_N) was obtained by subtracting the average activity of the baseline (μ) from the filtered signal (S) and then dividing by the standard deviation of the baseline (σ), for each frequency band: $S_N = (S - \mu)/\sigma$.

4.4. Statistical analysis

4.4.1. ERP N400

Following previous research (Koelsch et al., 2004), we calculated the difference between the average amplitudes of a region of interest (C3, Cz, C4, CP3, CPz, CP4, P1, P5, Pz, P2, P6) between the different conditions (for spatial correspondence between geodesic sensor net and 10–10 system, see Luu & Ferree, 2000). For statistical analysis, these data were analyzed by means of paired t-test ($p < 0.05$) in search of statistically significant differences. False Discovery Rate ($q < 0.05$) was used to correct for multiple comparisons in each one of the entry matrix of p-values (Benjamini & Yekutieli, 2001). Subsequently, the significant time windows were analyzed with a within-subject ANOVA with Priming (Prime and Non-Prime) as within-subjects factors. The significance level was set at 0.05. When necessary we applied a Greenhouse-Geisser correction.

4.4.2. Spectral power and phase synchrony

Our statistical analyses involved pooling together all electrodes to produce a global index of gamma spectral power and theta phase synchronization. Thus, the averaging of the EEG oscillatory activity of all electrodes was performed. This resulted in a grand average time–frequency chart for each experimental condition per subject. Those charts were grouped by condition and analyzed by means of paired t-test ($p < 0.05$) in search of statistically significant differences. False Discovery Rate ($q < 0.05$) was used to correct for multiple comparisons in each one of the entry matrix of p-values (Benjamini & Yekutieli, 2001). Subsequently, the

significant time–frequency windows were analyzed with a within-subject ANOVA. The α level was set at 0.05 for all tests. We applied Greenhouse-Geisser correction when necessary.

Topographical analysis of spectral power and phase synchrony were restricted to the time–frequency window previously selected. We averaged the time–frequency window of interest over all electrodes. This resulted in arrays of electrode per subject, for each experimental condition. Then, those arrays were analyzed by means of paired t-test ($p < 0.05$) to contrast different conditions. False Discovery Rate ($q < 0.05$) was used to correct for multiple comparisons in each one of the entry matrix of p-values (Benjamini & Yekutieli, 2001). The analysis of spectral power and phase synchrony were performed with the computer program Matlab 7.0.4 (Mathworks, Inc).

Acknowledgments

Appendix A. Supplementary material

Music sample

File name	Name of extract to music	Semantically related word	Semantically unrelated word
mmc1.mp3	Chopin-Ballade No. 2 in F major, Op. 38.	Cradle	Mistery
mmc2.mp3	Poulenc, Le bal masqué (The masked ball), Op 60 V. La dame aveugle	Mistery	Cradle
mmc3.mp3	Beethoven-Sonata no. 8 in C minor, Op. 13 (Pathetique Sonata)	Patience	Anxiety
mmc4.mp3	Beethoven-Sonata no. 23 in F minor, Op. 57 (Appassionata Sonata)	Anxiety	Patience

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.bandl.2015.12.001.

References

Barraza, P., Gómez, D. M., Oyarzún, F., & Dartnell, P. (2014). Long-distance neural synchrony correlates with processing strategies to compare fractions. *Neuroscience Letters, 567*, 40–44.

Bastiaansen, M., & Hagoort, P. (2006). Oscillatory neuronal dynamics during language comprehension. *Progress in Brain Research, 159*, 179–196.

Bastiaansen, M. C., Oostenveld, R., Jensen, O., & Hagoort, P. (2008). I see what you mean: Theta power increases are involved in the retrieval of lexical semantic information. *Brain and Language, 106*(1), 15–28.

Benjamini, Y., & Yekutieli, D. (2001). The control of the false discovery rate in multiple testing under dependency. *Annals of Statistics*, 1165–1188.

Bertrand, O., Perrin, F., & Pernier, J. (1985). A theoretical justification of the average reference in topographic evoked potential studies. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section, 62*(6), 462–464.

Carrus, E., Koelsch, S., & Bhattacharya, J. (2011). Shadows of music–language interaction on low frequency brain oscillatory patterns. *Brain and Language, 119*(1), 50–57.

Carrus, E., Pearce, M. T., & Bhattacharya, J. (2013). Melodic pitch expectation interacts with neural responses to syntactic but not semantic violations. *Cortex, 49*(8), 2186–2200.

Cavanagh, J. F., Cohen, M. X., & Allen, J. J. (2009). Prelude to and resolution of an error: EEG phase synchrony reveals cognitive control dynamics during action monitoring. *The Journal of Neuroscience, 29*(1), 98–105.

Csibra, G., Davis, G., Spratling, M. W., & Johnson, M. H. (2000). Gamma oscillations and object processing in the infant brain. *Science, 290*(5496), 1582–1585.

Fallani, F. D. V., Richiardi, J., Chavez, M., & Achard, S. (2014). Graph analysis of functional brain networks: Practical issues in translational neuroscience. *Philosophical Transactions of the Royal Society B: Biological Sciences, 369*(1653), 20130521.

Ferree, T. C., Luu, P., Russell, G. S., & Tucker, D. M. (2001). Scalp electrode impedance, infection risk, and EEG data quality. *Clinical Neurophysiology, 112*(3), 536–544.

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.

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.

Herrmann, C. S., Munk, M. H., & Engel, A. K. (2004). Cognitive functions of gamma-band activity: Memory match and utilization. *Trends in Cognitive Sciences, 8*(8), 347–355.

Howard, M. W., Rizzuto, D. S., Caplan, J. B., Madsen, J. R., Lisman, J., Aschenbrenner-Scheibe, R., ... Kahana, M. J. (2003). Gamma oscillations correlate with working memory load in humans. *Cerebral Cortex, 13*(12), 1369–1374.

Koelsch, S. (2011). Towards a neural basis of processing musical semantics. *Physics of Life Reviews, 8*(2), 89–105.

Koelsch, S., Gunter, T. C., Wittfoth, M., & Sammler, D. (2005). Interaction between syntax processing in language and in music: An ERP study. *Journal of Cognitive Neuroscience, 17*(10), 1565–1577.

Koelsch, S., Kasper, E., Sammler, D., Schulze, K., Gunter, T., & Friederici, A. D. (2004). Music, language and meaning: Brain signatures of semantic processing. *Nature Neuroscience, 7*(3), 302–307.

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

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

Lewis, A. G., Wang, L., & Bastiaansen, M. (2015). Fast oscillatory dynamics during language comprehension: Unification versus maintenance and prediction? *Brain and Language*. http://dx.doi.org/10.1016/j.bandl.2015.01.003.

Luu, P., & Ferree, T. (2000). Determination of the Geodesic Sensor Nets' average electrode positions and their 10–10 international equivalents. *Technical Note*, 1–11.

Mellem, M. S., Friedman, R. B., & Medvedev, A. V. (2013). Gamma-and theta-band synchronization during semantic priming reflect local and long-range lexical–semantic networks. *Brain and Language, 127*(3), 440–451.

Nattiez, J. J. (1990). *Music and discourse: Toward a semiology of music.* Princeton University Press.

Nunez, P. L., Srinivasan, R., Westdorp, A. F., Wijesinghe, R. S., Tucker, D. M., Silberstein, R. B., & Cadusch, P. J. (1997). EEG coherency: I: statistics, reference electrode, volume conduction, Laplacians, cortical imaging, and interpretation at multiple scales. *Electroencephalography and Clinical Neurophysiology, 103*(5), 499–515.

Patel, A. D. (2003). Language, music, syntax and the brain. *Nature Neuroscience, 6*(7), 674–681.

Rodriguez, E., George, N., Lachaux, J. P., Martinerie, J., Renault, B., & Varela, F. J. (1999). Perception's shadow: Long-distance synchronization of human brain activity. *Nature, 397*(6718), 430–433.

Roux, F., Wibral, M., Mohr, H. M., Singer, W., & Uhlhaas, P. J. (2012). Gamma-band activity in human prefrontal cortex codes for the number of relevant items maintained in working memory. *The Journal of Neuroscience, 32*(36), 12411–12420.

Ruiz, M. H., Koelsch, S., & Bhattacharya, J. (2009). Decrease in early right alpha band phase synchronization and late gamma band oscillations in processing syntax in music. *Human Brain Mapping, 30*(4), 1207–1225.

Schack, B., & Weiss, S. (2005). Quantification of phase synchronization phenomena and their importance for verbal memory processes. *Biological Cybernetics, 92*(4), 275–287.

Steinbeis, N., & Koelsch, S. (2008). Shared neural resources between music and language indicate semantic processing of musical tension–resolution patterns. *Cerebral Cortex, 18*(5), 1169–1178.

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

Varela, F., Lachaux, J. P., Rodriguez, E., & Martinerie, J. (2001). The brainweb: phase synchronization and large-scale integration. *Nature Reviews Neuroscience, 2*(4), 229–239.

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

Weiss, S., & Mueller, H. M. (2003). The contribution of EEG coherence to the investigation of language. *Brain and Language, 85*(2), 325–343.