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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

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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).

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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

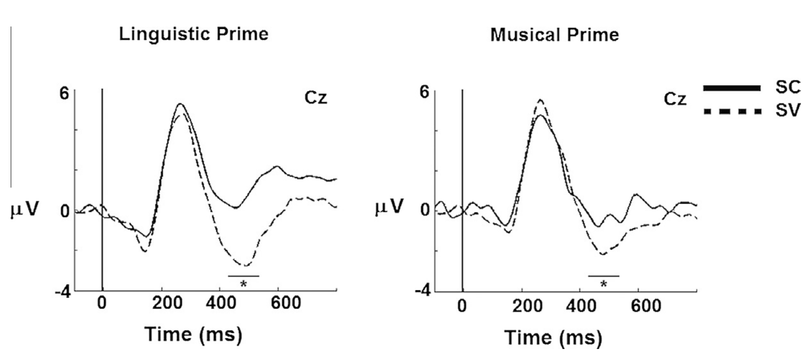

Fig. 1. The N400 effect during musical and linguistic semantic priming tasks. Each graph shows the waveforms for the semantic congruence (SC: solid line) and semantic violation (SV: segmented line) conditions, in both musical and linguistic domains. Voltage (in microvolts) and time (in milliseconds) 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 ($p < 0.05$).