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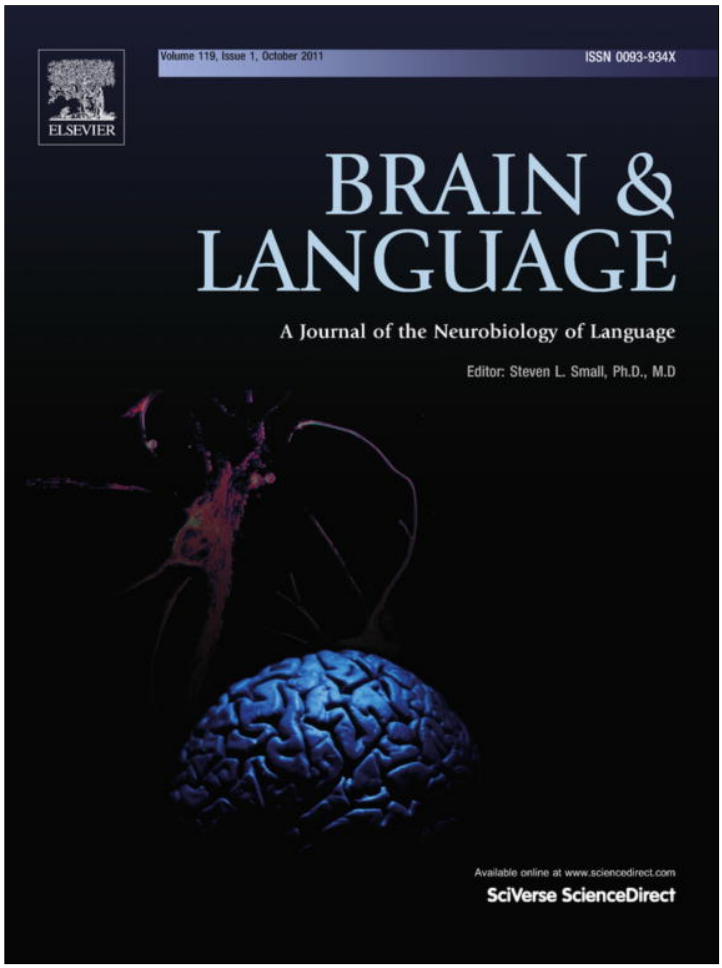

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Short Communication

Shadows of music–language interaction on low frequency brain oscillatory patterns

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ABSTRACT

Electrophysiological studies investigating similarities between music and language perception have relied exclusively on the signal averaging technique, which does not adequately represent oscillatory aspects of electrical brain activity that are relevant for higher cognition. The current study investigated the patterns of brain oscillations during simultaneous processing of music and language using visually presented sentences and auditorily presented chord sequences. Music-syntactically regular or irregular chord functions were presented in sync with syntactically or semantically correct or incorrect words. Irregular chord functions (presented simultaneously with a syntactically correct word) produced an early (150–250 ms) spectral power decrease over anterior frontal regions in the theta band (5–7 Hz) and a late (350–700 ms) power increase in both the delta and the theta band (2–7 Hz) over parietal regions. Syntactically incorrect words (presented simultaneously with a regular chord) elicited a similar late power increase in delta–theta band over parietal sites, but no early effect. Interestingly, the late effect was significantly diminished when the language-syntactic and music-syntactic irregularities occurred at the same time. Further, the presence of a semantic violation occurring simultaneously with regular chords produced a significant increase in later delta–theta power at posterior regions; this effect was marginally decreased when the identical semantic violation occurred simultaneously with a music syntactical violation. Altogether, these results show that low frequency oscillatory networks get activated during the syntactic processing of both music and language, and further, these networks may possibly be shared.

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1. Introduction

Music and language are human abilities, and the interest in their relationship has spanned many decades with research studies looking at how music and language processing overlap. Both music and language are regulated by a set of rules and principles forming the syntax (Koelsch & Friederici, 2003; Patel, 2003b). Syntactic rules allow the combination of discrete elements to form higher-order structures (e.g., sentences in language and chord progressions in tonal music) (Patel, 2003a). In both music and language, syntactic knowledge is acquired implicitly and requires no formal training (Bigand & Poulin-Charronnat, 2006; Brattico, Tervaniemi, Naatanen, & Peretz, 2006; Koelsch, Schroger, & Gunter, 2002; Loui, Grent-'t-Jong, Torpey, & Woldorff, 2005). Syntax in language, however, is conceptually different from syntactic rules in music. Nevertheless, recent neuroimaging evidence suggests that processing of music and language-syntactic information may draw on common neural resources (Koelsch, Gunter, Wittfoth, & Sammler, 2005; Patel, 2003a, 2008; Steinbeis & Koelsch, 2008b). Based on such findings, Patel (2003) proposed the Shared Syntactic Integration Resource Hypothesis (SSIRH), which argues for an overlap in the resources used for syntactic integration in language and music. The SSIRH was based on the observation that structural violations in music and language both produce a P600 response. The P600 is an event-related-potential (ERP) component thought to indicate processes of structural integration (Patel, Gibson, Ratner, Besson, & Holcomb, 1998). It is usually observed over parietal regions at approximately 500–600 ms after the occurrence of several types of structural violations (Patel et al., 1998; Rosler, Putz, Friederici, & Hahne, 1993).

Subsequent research suggested that syntactic music and language processing also overlap at earlier stages of syntactic processing. For example, electrophysiological studies consistently found that syntactic violations in music elicit an early right anterior negativity (ERAN), and syntactic violations in language elicit an early left anterior negativity (ELAN). The ERAN is an early electrophysiological index of syntactic processing in music, and is usually followed by an N5 component which is thought to reflect processes of harmonic integration (Koelsch et al., 2005). The ELAN reflects initial syntactic structure building, including word categorisation

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processes (Friederici, 2001, 2002; Koelsch et al., 2005; Poulin-Charronnat, Bigand, & Koelsch, 2006). Another electrophysiological marker of syntactic processing is the left anterior negativity (LAN), which can be elicited by morpho-syntactic violations (Osterhout & Holcomb, 1992). Both (E)LAN and ERAN are elicited at anterior electrode sites, have similar latency, polarity, and scalp distribution, and further, they may partly overlap at the neuroanatomical level (Caplan, Alpert, Waters, & Olivieri, 2000; Koelsch, 2006; Maess, Koelsch, Gunter, & Friederici, 2001; Sammler et al., 2009).

Until 2005, all studies on syntactic processing except one (Besson, Faita, Peretz, Bonnel, & Requin, 1998) have investigated either music (e.g., Friederici, 2001, 2002; Patel et al., 1998; Poulin-Charronnat et al., 2006; Ruiz, Koelsch, & Bhattacharya, 2009) or language processing (e.g., Bastiaansen, van Berkum, & Hagoort, 2002a, 2002b; Friederici, 2001, 2002; Gunter, Friederici, & Schriefers, 2000; Osterhout & Holcomb, 1992; Roehm, Schlesewsky, Bornkessel, Frisch, & Haider, 2004; Rosler et al., 1993; Ye, Luo, Friederici, & Zhou, 2006), but not the simultaneous processing of music and language. Patel's (2003) hypothesis makes predictions about interference at both the neural and behavioural level during the simultaneous presentation of music and language syntactic violations. Only four studies, two behavioural (Fedorenko, Patel, Casasanto, Winawer, & Gibson, 2009; Slevc, Rosenberg, & Patel, 2009) and two electrophysiological studies (Koelsch et al., 2005; Steinbeis & Koelsch, 2008b), have investigated simultaneous processing of language and music within-subjects to investigate the possibility of such interference. Fedorenko and colleagues (2009) showed that participants are less accurate on a task of language comprehension when both language and music are difficult to integrate. Slevc and colleagues (2009) showed that participants are slower in reading times on a self-paced reading paradigm when music and language were both structurally unexpected. Both EEG studies (Koelsch et al., 2005; Steinbeis & Koelsch, 2008b) showed that the presence of a music syntactic irregularity interferes with simultaneous processing of syntax in language by reducing the amplitude of the LAN. However, the study by Steinbeis and Koelsch (2008b) also showed that a syntactic violation in language interfered with the syntactic processing of music by reducing the amplitude of the ERAN. It could be noted that participants in this study attended to both language and music in contrast to the Koelsch et al. (2005)'s study, in which participants were instructed to pay attention to the language. The N400 amplitude, an ERP component indexing the processing of semantic information in language, was not modulated by the presence of a music syntactic violation, in either of these two studies.

So far, no published study has investigated such interactions between music and language at the oscillatory level, yet the transient patterns of neuronal oscillations are widely implicated in almost all cognitive tasks (Buzsáki, 2006; Klimesch, 1996; Ward, 2003). Both music and language processing involves dynamical integration of information (e.g., information about linguistic/musical syntax, semantics) that are presumably stored in different regions of the brain (Bastiaansen & Hagoort, 2006), and such communication between and within neuronal assemblies occurs by means of synchronization and desynchronization patterns of the oscillatory neural activity (Engel, Fries, & Singer, 2001; Friston, 2000; Pfurtscheller & Lopes da Silva, 1999; Singer, 1993). Synchronization of oscillatory activity is related to increases in amplitude: more neurons firing synchronously in-phase will increase the amplitude of the oscillatory EEG activity and those neurons will be recognized as belonging to the same local network or neuronal assembly. Since successful language and music processing relies predominantly on rapid integration of different sources of information, synchronous neuronal oscillations may play a crucial role in the neuronal communication occurring during processing of music and language (Bastiaansen & Hagoort, 2006; Ruiz et al., 2009).

The dynamic patterns of the underlying local synchronization can be revealed by wavelet-based time–frequency analysis (Tallon-Baudry & Bertrand, 1999; Tallon-Baudry, Bertrand, Delpuech, & Pernier, 1996). Traditional ERP analysis is not suitable to reveal this information as it destroys, through the averaging process, any neuronal activity that is not phase-locked to the experimental event. Studying oscillations will therefore provide information about changes in spectral power relative to a pre-event baseline period. The total oscillatory power can be estimated by applying the time–frequency analysis to individual EEG epochs followed by averaging. This results in a two-dimensional matrix containing total spectral power of the EEG at each frequency and time point. Total power is comprised of two types of oscillatory activities: evoked oscillations and induced oscillations. Evoked oscillations are strictly phase-locked to the stimulus onset across trials; they are calculated by applying the time–frequency analysis to the averaged ERP profile, thereby keeping the phase-locked activity across epochs. Induced oscillations are not necessarily phase-locked to the stimulus onset, and they are usually estimated by subtracting the evoked power from the total power.

There is an agreement that EEG oscillations are a reliable measure of neuronal excitability in thalamocortical systems during cortical information processing (Steriade & Llinas, 1988). The study of oscillations allows understanding of the communication occurring within neuronal populations; furthermore, it will be informative of whether specific local networks are formed and if these overlap during processing of music and language. Studying oscillations will also provide a clearer picture about the functional specificity of the frequency bands involved. For example, evidence suggests that theta and gamma band power increases are related to active processing of information (Bastiaansen, van der Linden, Ter Keurs, Dijkstra, & Hagoort, 2005).

Despite its importance in the understanding of the local dynamics of neuronal networks, the investigation of oscillatory activity related to simultaneous processing of music and language has not yet received much attention, with most studies being limited to isolated processing of music and language. Previous research on isolated violations in either music (Ruiz et al., 2009) or language (Bastiaansen, Magyari, & Hagoort, 2010; Bastiaansen, Oostenveld, Jensen, & Hagoort, 2008; Bastiaansen et al., 2002a, 2002b; Davidson & Indefrey, 2007; Hald, Bastiaansen, & Hagoort, 2006; Roehm et al., 2004), has shown an involvement of low frequency bands, particularly theta band. Ruiz and colleagues (2009) found that the ERAN was primarily represented by low frequency oscillations below 8 Hz. Specifically, a decrease in theta and delta band power over right-anterior electrode regions was noticed after the occurrence of music syntactical irregularities. The involvement of theta band has also been consistently reported in studies on sentence processing (Bastiaansen et al., 2002a, 2002b). Theta power was found to be related to all forms of language violations (gender disagreement, number disagreement, and also correct sentences) and power increase in fronto-central areas was elicited after syntactic violations and found for all syntactically-structured sentences (Bastiaansen et al., 2002a, 2002b). Other studies have also reported that grammatical violations lead to a higher degree of theta activity (Roehm et al., 2004). Larger theta activity was further reported during processing of semantically incongruous words (Davidson & Indefrey, 2007; Hald et al., 2006).

Because previous research shows the importance of studying oscillations for understanding local neuronal communication in language comprehension, and given that no previous studies have investigated oscillations with regard to interactions between language and music processing, the present study aims to fill this

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gap by investigating the oscillatory dynamics during simultaneous processing of music and language. Following the predominant role of low frequency brain oscillations in delta and theta band, it seemed strategically appropriate to investigate oscillatory dynamics in these frequency bands using a hypothesis-centred approach. Given the findings mentioned above, we hypothesized that (a) music syntactic violations would produce a decrease of spectral power in the upper theta band (6–8 Hz) at frontal brain regions in the ERAN time window (150–250 ms); (b) semantic as well as syntactic violations in language would produce theta power increases in the LAN (350–450 ms), N400 (350–450 ms) and P600 (around 450–700 ms) time windows; (c) such increase in theta power for syntactically incorrect words would be smaller when words are presented on syntactically irregular chord functions (compared to regular chords) in the time windows mentioned above; (d) theta band power in the N400 time window (elicited by semantically incongruous words) would not interact with music syntactic processing at the aforementioned time windows at posterior sites.

2. Results

2.1. Irregular chords, regular words

First we studied the main effect of syntactical violations in music by comparing effects of syntactically regular and irregular chord functions (all chords presented on syntactically and semantically correct words). Compared to regular (tonic) chords, irregular ("Neapolitan sixth") chords produced two effects (Fig. 1): (1) an early power decrease in the upper theta band (6–8 Hz) in the ERAN time window (150–250 ms) with anterior bilateral scalp distribution (see also Fig. 1b), and (2) a late power increase in the delta–theta bands (2–7 Hz) in the P600 time window ranging from 450–700 ms, which was maximal over posterior parieto-occipital sites (see also Fig. 1c). An ANOVA on the data measured in the ERAN time window in the upper theta band (6–8 Hz) with factors *chord-type* (regular, irregular) and *hemisphere* (left, right) for frontal electrode regions of interest (ROIs) showed a main effect of *chord-type*, $F(1, 24) = 4.31$, $p = 0.04$. An ANOVA on the data measured in the P600 time window (450–700 ms) in the delta and theta band (2–7 Hz) for posterior ROIs showed a main effect of *chord-type* in the P600 time window, $F(1, 24) = 6.77$, $p = 0.02$.

2.2. Syntactically irregular words, regular chords

Next we studied the effect of syntactical violations in language by comparing the effects of syntactically correct and incorrect words (all words presented on regular chords). Compared to (syntactically) correct words, incorrect words elicited a significant power increase in the delta–theta bands (2–7 Hz) (Fig. 1d) with a centro-parietal scalp distribution (Fig. 1e). This increase was observable at both frontal and posterior ROIs between 300 ms and 700 ms, thus covering both LAN and P600 time windows. An ANOVA on data measured in the LAN time window (350–450 ms) in the delta–theta bands (2–7 Hz) with factors *syntax* (correct, incorrect) and *hemisphere* indicated an effect of *syntax* at frontal ROIs, $F(1, 24) = 20.31$, $p < 0.0001$. This effect was also found at posterior regions, $F(1, 24) = 20.68$, $p < 0.0001$. Likewise, an ANOVA on data measured in the P600 time window (450–700 ms) in the

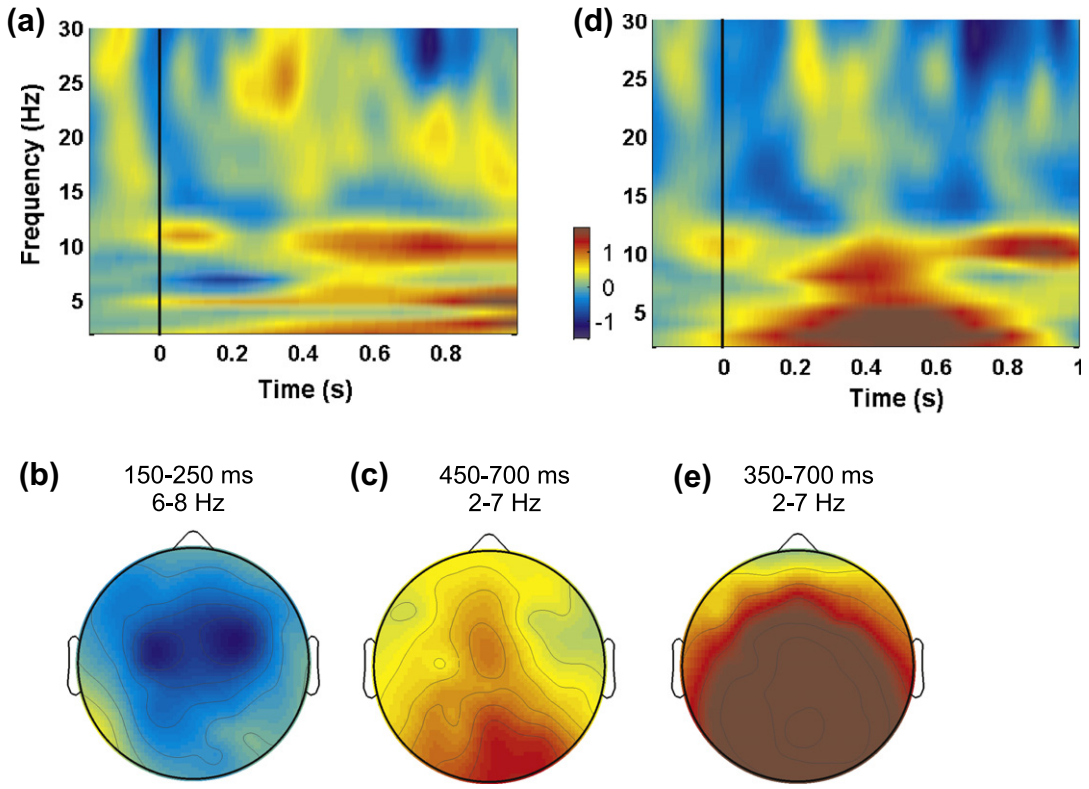

Fig. 1. (a) Time–frequency-representations (TFR) of the difference between irregular chords and regular chords both on correct/regular words. TFR was plotted after averaging across all electrodes. The vertical black line indicates the onset of the final chord/word. (b) Scalp map of upper theta band (6–8 Hz) for the ERAN time window (150–250 ms). (c) Scalp map of the delta–theta bands (2–7 Hz) power for the LAN time window (350–700 ms). Early upper theta decrease at anterior sites and late delta–theta increase at posterior sites were caused by the music-syntactic violation and language-syntactic violation, respectively. (d) TFR of the difference between (syntactically) incorrect words and (syntactically) correct words both on regular chords. TFR was plotted after averaging across all electrodes. The vertical black line indicates the onset of the final chord/word. (e) Scalp map of the delta–theta bands (2–7 Hz) power for a broad time window (350–700 ms).

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delta–theta bands (2–7 Hz) showed an effect of *syntax* at posterior ROIs $F(1, 24) = 21.32$, $p < 0.0001$, and this was analogously found on data measured at frontal ROIs $F(1, 24) = 19.69$, $p < 0.0001$.

2.3. Semantically irregular words, regular chords

We also studied the effect of semantic low-cloze probability in language by comparing effects of words with semantic high-cloze probability (i.e., semantically highly congruous words) and of words with semantic low-cloze probability (i.e., semantically less congruous words; all words were presented on regular chords). Compared to semantically congruous words, less congruous words elicited a sustained increase in delta–theta band power, which was largest at around 450 ms (N400 window) and remained visible until approximately 900 ms (Fig. 2a). This effect showed a centro-parietal predominance (Fig. 2b). An ANOVA with factors cloze-probability and *hemisphere* indicated an effect of *cloze-probability* at posterior sites over the N400 time window between 350–450 ms, $F(1, 24) = 6.84$, $p = 0.01$).

2.4. Interaction between chords and syntax

Next we investigated whether the oscillatory activity elicited by syntactically incorrect words (compared to syntactically correct words) would interact with the processing of music-syntactic information. Therefore we specifically looked at whether delta–theta band power would be influenced by the regularity of chords. In order to do this, we compared two difference waves, namely: (a) syntactically incorrect words presented on regular chords minus syntactically correct words on regular chords (i.e., the LAN and P600 effects elicited during the presentation of regular chords), with (b) syntactically incorrect words presented on irregular chords minus syntactically correct words on irregular chords (i.e., the LAN and P600 effects elicited during the presentation of irregular chords). These two difference waves (Fig. 3a) showed that the spectral power in delta–theta bands for the LAN and P600 time windows was weaker when elicited on incorrect chords when compared to the spectral power for the LAN and P600 time windows elicited on correct chords. An ANOVA for the posterior ROIs for the LAN time window showed an effect of *syntax* [$(F(1, 24) = 24.14$, $p = .00]$ and also an interaction between the two factors [$(F(1, 24) = 5.08$, $p = .03]$. An ANOVA for the P600 time window at posterior sites showed an effect of *syntax*, $F(1, 24) = 27.92$, $p = 0.00$, and a marginal interaction between the two factors, $F(1, 24) = 4.28$, $p = 0.05$. There was no significant interaction at frontal ROIs for the P600 time window [$F(1, 24) = .22$, $p = .64$].

Next we investigated whether language-syntactic processing would modulate the oscillatory activity elicited during the ERAN time window. An ANOVA on the spectral power in the upper theta band (6–8 Hz) at frontal ROIs for the ERAN time window with factors *chord-type* and *syntax* showed an effect of *chord-type*, $F(1, 24) = 8.75$ $p = 0.007$, but not a two-way interaction, $F(1, 24) = 0.77$, $p = 0.84$.

These results suggest that oscillatory activity related to music syntactic processing did not interact with language-syntactic processing during the ERAN time window (150–250 ms). At posterior ROIs, the oscillatory activities related to music and language syntactic processing interfered during the LAN (350–450) and P600 (450–700 ms) time windows.

2.5. Interaction between chords and semantics

Next we investigated whether the oscillatory activity elicited by the effect of semantically irregular words compared to semantically regular words would interact with music-syntactic processing. Therefore, we specifically looked at whether delta–theta band power elicited during the N400 effect (i.e., the effect of semantically irregular words compared to semantically regular words) would interact with the music-syntactic information, that is, whether the N400 effect would be influenced by the correctness of chords. Therefore, we compared two difference waves, namely: (a) low-cloze probability words presented on regular chords minus high-cloze probability words on regular chords (i.e., the N400 effect elicited during the presentation of regular chords), with (b) low-cloze probability words presented on irregular chords minus high-cloze probability words on irregular chords (i.e., the N400 effect elicited during the presentation of irregular chords. The resulting two difference waves are shown in Fig. 3b. During the N400 time window (350–450 ms), the main effect of *cloze-probability* was found to be significant, $F(1, 24) = 5.82$, $p = 0.02$, but no interaction between the two factors (*chord-type*, *cloze-probability*) was found. The difference between the two waves (Fig. 3b) became prominent at a later time window (450–700 ms) during which a marginal interaction between the two factors was found over posterior sites, $F(1, 24) = 3.92$, $p = 0.06$.

2.6. Oscillatory effects: evoked or induced?

The TFR results, thus far, represented total (evoked and induced) oscillations (Tallon-Baudry & Bertrand, 1999), and it was

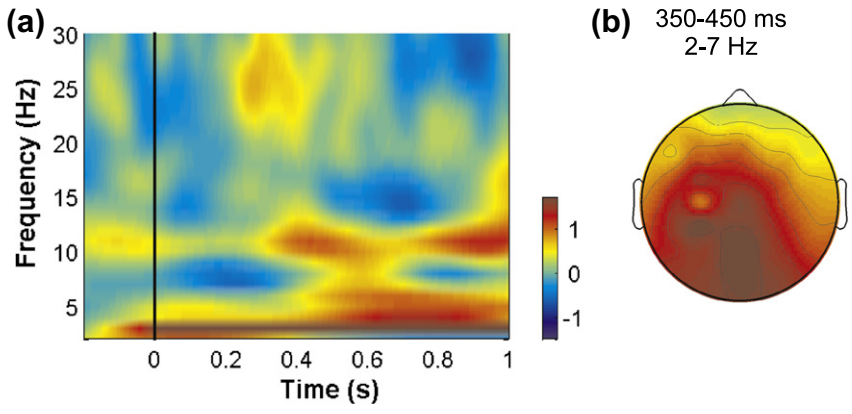

Fig. 2. (a) TFR of the difference between (semantically) irregular words and (semantically) regular words both on regular chords. TFR was plotted after averaging across all electrodes. The vertical black line indicates the onset of the final chord/word. (b) Scalp map of delta–theta band (2–7 Hz) power for the time period of 350–700 ms. Late delta–theta power increase at posterior sites was caused by semantic irregular words with low cloze probability.

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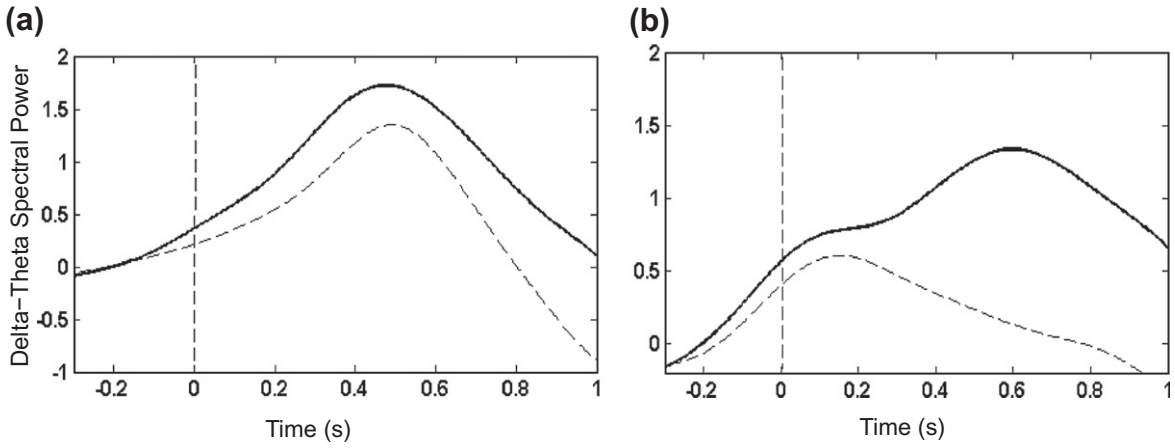

Fig. 3. (a) Profiles of delta–theta band power (difference between syntactically incorrect words and syntactically correct words) for the conditions in which words were presented on regular chords (solid line) and on irregular chords (dashed line). (b) Profiles of delta–theta band power (difference between semantically incorrect words and semantically correct words) for the conditions in which words were presented on regular chords (solid line) and on irregular chords (dashed line). In both plots, vertical line indicates the onset of the final word/chord.

not clear whether the reported effects were predominantly represented by the phase-locked evoked oscillatory activity or by the non-phase-locked induced oscillatory activity. Therefore, wavelet analysis was applied to the ERP to investigate evoked oscillations, which were then subtracted from total oscillatory power to yield induced oscillations. The total oscillatory activities, especially in the later stages of processing, were conspicuously similar to the induced oscillations (see Supplementary Figures 1–3). Next we statistically analysed the evoked oscillatory activities for the same time–frequency ROIs as done earlier for the total oscillations. Most of the reported effects in the delta–theta band for total oscillations were not found to be statistically significant for evoked oscillations (see Supplementary Results, and Supplementary Figures 4, 5 for details).

2.7. Higher frequency bands

For reasons detailed in the Introduction, our hypotheses were focused on low frequency brain oscillations, i.e. delta–theta band. It may however seem overly restrictive as other frequency bands were not analysed. Therefore, we extended our analysis to three additional frequency bands: alpha (8–12 Hz), beta (12–30 Hz) and gamma (>30 Hz). A significant effect was found in the beta band during processing of semantic irregular words presented on regular chords. A repeated measure ANOVA in the N400 time window (350–450 ms) with factors *cloze-probability* and *hemisphere* revealed a significant main effect of *cloze-probability* at posterior ROIs ($F(1, 24) = 5.12$, $p < .05$) (See Supplementary Figure 6). Compared to semantically congruous words, less congruous words elicited an increase in beta band power. No other significant effects were observed in other time-windows/conditions/frequency-bands.

3. Discussion

The present study investigated oscillatory brain responses during simultaneous processing of music and language. As surmised in our first hypothesis related to the music domain, we found that theta power decreased during the ERAN time window (150–250 ms) for syntactically irregular chord sequences presented on syntactically correct sentences. This is in line with earlier findings by Ruiz et al. (2009) who reported a theta power decrease for isolated music syntactic violations. It should be noted that the Neapolitan chords used in the present study are both syntactically incorrect and acoustically irregular (due to the introduction of new pitches that were not contained in the previous chords; for a detailed explanation see also Koelsch (2009)). Importantly, however, Ruiz et al. (2009) used supertonics as irregular final chords, which did not introduce new pitches (see also Koelsch, Kilches, Steinbeis, & Schelinski, 2008). This indicates that the early theta power decrease, common across both types of irregular chords, reflects a response to music-syntactic irregularities, rather than to acoustical irregularities. The theta effect was found to be bilaterally distributed with a slight lateralization to the right. This right frontal distribution closely matches the ERAN scalp distribution described in ERP results (for a review see Koelsch, 2009). In addition, we also found a late delta and theta power increase in the P600 time window (350–700 ms) at parietal regions, which is a novel finding. Interestingly, it is similar in scalp distribution and latency to the power increase noticed in the language domain within the same time window in response to syntactic violations.

As expected in our second hypothesis related to the language domain, we found that low frequency bands including delta and theta were predominantly involved during language syntactic and semantic processing: Syntactically incorrect words in language presented on syntactically correct chords produced a delta–theta power increase in the LAN (300–450 ms) and P600 (450–700 ms) time windows at both frontal and centro-parietal regions. The same effect was found in the N400 time window (350–450 ms) when semantically irregular words occurred simultaneously with regular chords. This confirms previous findings regarding the involvement of theta band in language processing including syntactic and semantic violations (Bastiaansen et al., 2002a, 2002b; Bastiaansen et al., 2008; Bastiaansen et al., 2010; Davidson & Indefrey, 2007; Hald et al., 2006; Roehm et al., 2004).

Most importantly, our third hypothesis was related to possible interactions between syntactical processing in language and music. In line with previous ERP (Koelsch et al., 2005; Steinbeis & Koelsch, 2008b), and with behavioural studies (Fedorenko et al., 2009; Slevc et al., 2009), we observed an interaction in terms of low frequency oscillatory activity resulting from the simultaneous occurrence of music syntactic and language syntactic violations. Specifically, when the syntactic violations were present in both language and music, the delta–theta power was significantly reduced in the LAN and P600 time windows at parietal sites, compared to when the syntactical violation was only present in language. This result suggests the involvement of similar neuronal mechanisms

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mediated by overlapping networks of low frequency band oscillations (see also Patel, 2003): Simultaneous processing of structural information in both music and language resulted in an interaction at the oscillatory level (as apparent in the decrease in delta–theta power at posterior ROIs when syntactic violations occurred simultaneously in language and music). This is consistent with previous ERP findings from Patel et al. (1998), where both music-syntactic and language-syntactic irregularities evoked a P600 response. Our present findings might also be related to findings from Koelsch et al. (2005) and Steinbeis and Koelsch (2008b), where the simultaneous processing of music-syntactic and language-syntactic irregularities resulted in a decrease in the amplitude of the LAN; however, that amplitude decrease was observed at anterior sites, but the oscillatory interaction observed in the present study emerged only at posterior sites.

In terms of low frequency oscillatory activity, the presence of a syntactic violation in language did not interact with music syntactic processing (as evidenced by the presence of the theta decrease elicited by irregular chords, independent of the occurrence of a syntactic violation in language). This is analogous to the ERP results from Koelsch et al. (2005), where the ERAN amplitude was not affected by a simultaneous syntactic violation in language. However, note that participants ignored the music in the present study, and that, therefore, language processing might interfere with music syntactic processing if participants attend to both language and music (see also Steinbeis & Koelsch, 2008b).

Our last hypothesis was related to a possible independence between semantic processes in language and syntactical processes in music in the N400 time window. Like in previous ERP studies (Koelsch et al., 2005; Steinbeis & Koelsch, 2008a), we did not find an interaction between music syntactic processing and language semantic processing on the delta–theta band power during the N400 time window (350–450 ms). However, our results indicate a marginal interaction between music syntactic processing and semantic processing that is occurring at a later stage of processing between 450 and 700 ms. The specific contribution of this later interaction in terms of low frequency oscillations is not precisely known, and further research is needed in order to investigate the role that processing of meaning in language may have in the context of processing of syntactically unexpected musical events. Perhaps the processes related to the detection of the task-relevant incorrect words (and the decision to respond accordingly) evoked activity that interfered with the later stages of the processing of irregular chords such as structural re-integration (Patel et al., 1998) or processes related to the detection of the irregular chord functions. This prediction will need to be investigated at a behavioural level to confirm the presence of a cognitive/ behavioural interference.

Finally, we carried out additional analysis to understand the relative contribution of phase- vs. non-phase-locked oscillations to the reported effects. The overall pattern of results seems to suggest that the reported effects were predominantly contributed by the induced oscillations. Furthermore, by extending our analysis to higher frequency bands, we found that semantically incongruous words elicited a significant increase in the beta band power (12–30 Hz) compared to congruous words. Involvement of beta band oscillations has been previously reported in studies looking at sentence comprehension (Weiss et al., 2005) and syntactic operations (Bastiaansen et al., 2010).

The presence of an interaction between music and language syntactic processing occurring at later stages suggests the overlap of oscillatory networks involving shared neural resources. Although it will be necessary to investigate the above further, it is striking to see the shared recruitment of neural resources by both music and language. There is a qualitative and quantitative similarity in the oscillatory responses occurring across processing of music and language violations, at both syntactic and semantic levels, where such responses show a similar topography, latency and polarity. As described in the introduction, oscillatory power increases are related to an increase in locally synchronized firing of the neuronal populations; it is therefore probable that the same networks of neuronal populations are recruited during processing of both music and language. As Patel (2003) suggests that simultaneous occurrence of syntactic violations in both domains will produce interference at the neural level, we showed here that the increase in oscillatory power observed in low frequency bands after processing of syntactic violations in language decreased when also music syntactic violations were presented simultaneously.

Therefore, it is possible that common neuronal resources, here represented by the power increase in low frequency bands, are recruited for both music and language processes, and that such simultaneous activation causes neural interference, which is evidenced in the decrease of oscillatory power. It may also be that the size of the local network recruited decreases due to a competition of limited neural resources (e.g., neural resources used for language processing are taken away for processing of music violations). In simpler terms, it is possible that since oscillatory power decreases when a syntactic music violation is presented simultaneously with a syntactic language violation, both cognitive processes are sharing limited neural resources. Interestingly, such interaction at the neural level also emerges during simultaneous presentation of music violations and semantic ambiguities, where there is a marginally significant decrease in oscillatory power occurring after the N400 time window. However, due to poor time resolution of time–frequency analysis in the low frequency bands (Hagoort, Hald, Bastiaansen, & Petersson, 2004) and possible confounds resulting from acoustical deviants (Koelsch et al., 2005), the role of this later effect needs to be investigated in future research. Furthermore, due to the nature of the study, these results do not completely rule out alternative explanations for such interaction. For example, it should also be considered that perhaps the processes related to the detection of the task-relevant incorrect words (and the decision to respond accordingly) evoked activity that interfered with processes related to the processing of the (task-irrelevant) incorrect chords. In this sense, it is possible that interactions such as those observed in the present study would be elicited by any kinds of stimuli as long as they evoke detectional processes.

In summary, the current study shows that the large-scale oscillatory brain responses are complementary to the traditional ERP responses, and together they provide a comprehensive characterization of simultaneous processing of syntactic music and language processes.

4. Methods

4.1. Participants

Twenty-six right-handed non-musicians (19–30 years, mean 24.1 years; 15 women) with normal hearing (according to self-report) and normal or corrected-to-normal vision participated in the experiment.

4.2. Design

Sentences were presented visually, and were either (syntactically or semantically) correct or incorrect. They occurred simultaneously with auditorily presented chord-sequences which ended with either a tonic (regular) or a Neapolitan (irregular) chord. Each word was presented with the onset of a chord. Three different types of sentences were used: a syntactically correct sentence with a high-cloze

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probability noun as the last word; a syntactically correct sentence ending with a semantically low cloze probability noun; a syntactically incorrect sentence but ending with a semantically high cloze probability noun. Half of the sentences ended on a regular chord (tonic), and the other half on an irregular chord (Neapolitan). Sentences and chord sequences were combined in a 3×2 design to form 6 experimental conditions: syntactically correct sentences with syntactically incorrect music; syntactically correct sentences with syntactically correct music; syntactically incorrect sentences with syntactically correct music; syntactically incorrect sentences with syntactically incorrect music; semantically ambiguous sentences with syntactically correct music; semantically ambiguous sentences with syntactically incorrect music. Participants were asked to ignore the music and pay attention to the words.

4.3. Recording and pre-processing

The EEG was recorded from 60 Ag–AgCl electrodes placed on the head according to the extended 10–20 system. The reference electrode was placed on the tip of the nose. Sampling rate was 250 Hz and data were filtered with a 70-Hz anti-aliasing filter during data acquisition. Horizontal and vertical EOGs were recorded bipolarly. EEGLAB toolbox (Delorme & Makeig, 2004) was used for visualisation, pre-processing and rejection of blink-artefacts. Specifically, Independent Component Analysis was used to remove eye artefact components from the recorded EEG. Morlet wavelet-based time–frequency analysis was applied. Wavelets with a 7-cycle width were used. Power was analysed between 2 and 60 Hz in 1 Hz steps. The TFRs of the single trials were averaged for each of the six conditions (regular music with correct syntax, regular music with incorrect syntax, irregular music with correct syntax, irregular music with incorrect syntax, regular music with low-cloze probability words, irregular music with low-cloze probability words).

4.4. Statistical analysis

For the TFR data, the average power at each electrode was computed for the following time windows: ERAN (150–250 ms), LAN (300–450 ms), N400 (350–450 ms), and P600 (450–700 ms) in the delta–theta bands. These temporal regions of interest were strategically preselected after Koelsch et al. (2005); see also Introduction for additional reasons. Further, we also strategically focused on the low frequency brain oscillations, particularly delta and theta band, after previous studies

(Bastiaansen et al., 2002a, 2002b; Ruiz et al., 2009). For statistical evaluation, repeated measures ANOVAs were used. Possible factors entering the ANOVAs were: *Cloze probability* (high_low), *Syntax* (regular_irregular), *Hemisphere* (left_right ROIs), and *Chord type* (regular [tonic]_irregular [Neapolitan] chords). Four regions of interest (ROIs) were used: left anterior (F7, F3, FT7, FC3), right anterior (F4, F8, FC4, FT8), left posterior (P3, P5, CP3, TP7), and right posterior (P4, P6, CP4, TP8). The resulting values were averaged for the electrodes corresponding to the same ROI.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.bandl.2011.05.009.

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