ARTICLE IN PRESS
cortex xxx (2012) 1–15
Available online at www.sciencedirect.com
SciVerse ScienceDirect
Journal homepage: www.elsevier.com/locate/cortex

Research report

Melodic pitch expectation interacts with neural responses to syntactic but not semantic violations

Elisa Carrus [a,*], *Marcus T. Pearce* [b] and *Joydeep Bhattacharya* [a,*]

[a] *Department of Psychology, Goldsmiths, University of London, London, United Kingdom*
[b] *Center for Digital Music and Research Centre in Psychology, Queen Mary, University of London, London, United Kingdom*

ARTICLE INFO

Article history:
Received 29 March 2012
Reviewed 18 June 2012
Revised 17 July 2012
Accepted 26 August 2012
Action editor Stefano Cappa
Published online xxx

Keywords:
EEG
ERP
Melody
Language
Interaction
Syntax
Semantics

ABSTRACT

Current behavioural and electrophysiological evidence suggests that music and language syntactic processing depends on at least partly shared neural resources. Existing studies using a simultaneous presentation paradigm are limited to the effects of violations of harmonic structure in Western tonal music on processing of single syntactic or semantic violations. Because melody is a universal property of music as it is emphasized also by non-western musical traditions, it is fundamental to investigate interactions between melodic expectation and language processing. The present study investigates the effect of melodically unexpected notes on neural responses elicited by linguistic violations. Sentences with or without a violation in the last word were presented on screen simultaneously with melodies whose last note had a high- or low-probability, as estimated by a computational model of melodic expectation. Violations in language could be syntactic, semantic or combined. The electroencephalogram (EEG) was recorded while participants occasionally responded to language stimuli. Confirming previous studies, low-probability notes elicited an enhanced N1 compared to high-probability notes. Further, syntactic violations elicited a left anterior negativity (LAN) and P600 component, and semantic violations elicited an N400. Combined violations elicited components which resembled neural responses to both syntactic and semantic incongruities. The LAN amplitude was decreased when language syntactic violations were presented simultaneously with low-probability notes compared to when they were presented with high-probability notes. The N400 was not influenced by the note-probability. These findings show support for the neural interaction between language and music processing, including novel evidence for melodic processing which can be incorporated in a computational framework of melodic expectation.

1. Introduction

The brain automatically acquires statistical regularities in the environment, and it is through extrapolation of these regularities that perceivers form expectations about sequences of events unfolding over time (Huron, 2006). This extends to higher cognitive processes such as language and music, each of which is governed by sets of rules that allow the combination of

* *Corresponding authors.* Department of Psychology, Goldsmiths, University of London, New Cross, London SE14 6NW, United Kingdom.
E-mail addresses: e.carrus@gmail.com (E. Carrus), j.bhattacharya@gold.ac.uk (J. Bhattacharya).
0010-9452/$ – see front matter © 2012 Elsevier Srl. All rights reserved.
http://dx.doi.org/10.1016/j.cortex.2012.08.024

elements into complex structures (notes into melodies, words into sentences). Expectations in language may be disrupted as a result of a violation in the grammar or the meaning of a sentence; in a similar way, violating rules of musical syntax contravenes harmonic or melodic expectations formed by the perceiver (Meyer, 1956). For this reason, responses to music and language violations can be investigated together to gather an understanding of the mechanisms involved during processing of structures and expectations in the two domains. More specifically, studies using a simultaneous presentation of music and language can provide information regarding the extent to which violating expectations in music affects neural responses to linguistic violations.

A number of studies have examined neural responses to music and language violations in isolation (Besson and Faita, 1995; Friederici, 2004; Friederici et al., 1996; Gunter et al., 2000; Hagoort, 2003; Herrojo-Ruiz et al., 2009; Miranda and Ullman, 2007; Verleger, 1990). For example, in music, a recent electroencephalogram (EEG) study by Koelsch and Jentschke (2010) investigated differences in event-related-potential (ERP) components to melodic and harmonic violations. They showed that although both sequences elicited a clear negative deflection at frontal sites around 125 msec, chords also elicited a later negativity peaking at 180 msec, known as the early right anterior negativity (ERAN). This study showed that unexpected melodic elements, also contained in chord sequences, elicit earlier components compared to harmonic violations, further confirming previous findings by showing that both expected and unexpected notes produce a sharp negative peak at 100 msec latency (N1), with unexpected notes eliciting an enhanced negativity (Pearce et al., 2010). Other studies using the magnetoencephalogram (MEG) have observed early negativites following the presentation of unexpected notes (Herholz et al., 2008; Yasui et al., 2009). Further, harmonic violations have been shown to elicit late components, such as the P600 and the N5, possibly reflecting integration processes (Koelsch et al., 2005; Patel et al., 1998). Regarding language, studies have consistently reported the presence of two ERP components following syntactic violations, as compared to syntactically correct sentences: (i) an increased negative-going deflection around 300–450 msec at frontal sites, termed as the left anterior negativity (LAN), reflecting initial processing of the violation; (ii) a positivity peaking at 600 msec and maximal at posterior sites, termed as the P600, reflecting mechanisms of syntactic integration and reanalysis. Semantic violations consistently produce a larger negativity around 400 msec at centro-parietal sites compared to semantically correct sentences. This component was first reported by Kutas and Hillyard (1980) and termed the N400, reflecting semantic processing. A few studies have also investigated combined syntactic and semantic violations. Although the literature is somewhat inconsistent regarding interactions between syntax and semantics, most studies have reported that combined violations elicit components that reflect contributions from both syntactic and semantic aspects by showing that both LAN/N400 and P600 effects are elicited. Some studies have shown both N400 and LAN components being elicited at 350–450 msec (Gunter et al., 1997, 2000; Palolahti et al., 2005) and other studies have shown only an N400 (Ainsworth-Darnell et al., 1998; Hagoort, 2003; Osterhout and Nicol, 1999; Wicha et al., 2004) or a LAN (Friederici, 2004; Friederici et al., 1999; Hahne and Friederici, 2002; Ye et al., 2006). All studies except Ye et al. (2006) reported a P600 component following combined violations, though it is usually diminished compared to single syntactic violations (see Martin-Loeches et al., 2006).

As can be noticed from the above studies, structural violations of music and language elicit comparable ERP responses. For example, both music and grammatical language violations elicit early components with a frontal scalp distribution and with a negative polarity [(E)LAN for language and ERAN for music]. Also, a later component was found to be elicited following syntactic violations in music and language, namely the P600. Further theoretical and empirical work has led to suggest that music and language syntactic processing may use overlapping neural resources to process structural information (Patel, 2003), therefore predicting an interaction. Interestingly, Koelsch et al. (2005) reported a neural interaction between music and language showing that the presence of a harmonic violation, which produced an ERAN, attenuated the amplitude of the LAN when syntactic violations in language were presented simultaneously. Interestingly, the same attenuation was not reported for the N400 amplitude.

Research investigating interactions between music and language have accumulated in both behavioural and neuroimaging contexts. For example, behavioural studies (Fedorenko et al., 2009; Slevc et al., 2009) and ERP experiments (Koelsch et al., 2005; Steinbeis and Koelsch, 2008) have shown that both domains compete for resources as soon as syntactic errors occur simultaneously in music and language. Specifically, behavioural studies have shown that out-of-key chords impair processing of language violations, as evidenced in slower reading times and comprehension accuracies (Fedorenko et al., 2009; Slevc et al., 2009). Also, Hoch et al. (2011) reported a reduced language expectancy effect when sentences were presented on unexpected subdominant chords, compared to expected tonic chords. Further, an ERP study carried out by Koelsch et al. (2005) showed support for a neural interaction, as reflected in a decrease in the amplitude of the LAN whenever the violated word was presented simultaneously with a violation in the music domain. Further, deficits in language coincide with music processing impairment as revealed in Broca's aphasics and children with specific language impairment (SLI) (Jentschke et al., 2008; Patel et al., 2008). Specifically, Jentschke et al. (2008) reported that 5-year-old children with SLI, a developmental language disorder which severely impairs syntactic processing, exhibited no ERAN following music syntactic violations, whereas an ERAN was observed in age-matched healthy children. Related to this, Broca's aphasics have shown impairments in implicit and explicit processing of music syntax (Patel et al., 2008). Furthermore, musical training may enhance syntactic processing in language, as shown in the presence of an ELAN component observed in children with musical training but not in control children (Jentschke et al., 2005). Research on the anatomical overlap of music and language has also been carried out by using intracranial EEG (Sammler, 2009). Indeed, studies investigating the neural sources for the ELAN and ERAN separately revealed overlapping brain regions, specifically

Please cite this article in press as: Carrus E, et al., Melodic pitch expectation interacts with neural responses to syntactic but not semantic violations, Cortex (2012), http://dx.doi.org/10.1016/j.cortex.2012.08.024

within the left and right inferior frontal regions of the brain and the left and right anterior (LA and RA) part of the superior temporal gyrus (Friederici et al., 2000; Koelsch, 2006; Maess et al., 2001). In addition, studies using both chords and melodies have reported that music syntactic processing activates areas that are involved in language processing (Koelsch et al., 2002, 2005; Tillmann et al., 2003; but see also Rogalsky et al., 2011). Interestingly, studies reporting interactions between music and language syntactic processing have not been consistently reported for language semantic processing. In fact, several studies have reported evidence that music processing is independent from semantic processing in language (Fedorenko et al., 2009; Hoch et al., 2011; Koelsch et al., 2005; Slevc et al., 2009). The few occasions where interactions between language semantic and music were observed are restricted to those with music and language being presented in a single stream, like in vocal music, or when participants are required to pay attention to both music and language, like in a dual task (Poulin-Charronnat et al., 2005; Steinbeis and Koelsch, 2008). Interestingly, Steinbeis and Koelsch (2008)'s study reported the first evidence of an interaction between music syntax and language semantics, reporting a significant reduction of the N5 when participants were presented with semantic violations compared to correct sentences.

Research investigating neural interactions during simultaneous presentation of music and language has focused on violations of harmonic expectations[1] (Koelsch et al., 2005; Patel et al., 1998). However, besides harmony, there are other important structural aspects of musical syntax, like melodic, metric, rhythmic, and timbral structure, and the possible relationships between syntactic processing of these structural aspects and language syntactic processes have not been studied (Koelsch, 2012). Melodic processing is fundamental in the study of music perception as it embraces aspects that can be generalized to musical traditions beyond Western tonal music (Pearce et al., 2010). For this reason, the present study incorporates the use of melodic stimuli selected according to predictions of a computational model of melodic expectation, whereby high-probability (HP) notes are more expected than low-probability (LP) notes (Pearce, 2005). The rationale here is to use stimuli that violate perceptual expectations but which focus on aspects of music perception (melodic pitch expectation) that generalize widely across musical traditions. Further, studies exploring interactions between music and language have so far employed single syntactic or semantic violation (Fedorenko et al., 2009; Koelsch et al., 2005; Slevc et al., 2009; Steinbeis and Koelsch, 2008). For this reason, we decided to add a third language violation by combining a syntactic error and a semantic incongruity; this combined or double violation is useful to investigate in more depth the hypothesis of shared resources between music syntactic and language syntactic processes. In fact, the rationale behind the use of a combined violation could provide us with complementary information as to whether a syntactic violation paired with a semantic violation would produce interactive patterns that are comparable to those emerging between single syntactic violations and music processing, or whether the presence of a semantic violation would inhibit this interaction. The use of a combined violation has been employed before in the study of the interaction between syntax and semantics during language processing and sentence comprehension (Hagoort, 2003; Martin-Loeches et al., 2006). Specifically, the use of syntactic and semantic violations in isolation or in combination could provide information regarding the extent to which syntactic and semantic processes interact during sentence comprehension. Recent studies have suggested a prevailing role of semantic information in sentence processing. This has been particularly shown in the reduction of neural activity elicited by syntactic information in the presence of a semantic anomaly. In particular, some studies have shown that LAN/ELAN components are not elicited during combined violations, or the P600 component is reduced following combined violations compared to the one elicited following single syntactic violations (Ainsworth-Darnell et al., 1998; Gunter et al., 1997, 2000; Hagoort, 2003; Martin-Loeches et al., 2006; Osterhout and Nicol, 1999; Palolahti et al., 2005; Wicha et al., 2004). These findings are suggestive of an interaction between semantic and syntactic information at the LAN time window, with the possibility of a primacy of semantics over syntax. The present study follows up from the above findings by investigating the interaction between melodic processing and syntactic processing with or without a semantic incongruity.

In summary, the two novel aspects of the present study allow for an investigation of the effect of manipulating melodic expectations on neural responses elicited by linguistic violations (including syntactic, semantic and combined violations) as revealed by the study of the ERP components. Following previous literature, it was hypothesized that (a) unexpected (low-probability) notes would elicit a larger early negativity compared to expected (high-probability) notes; (b) syntactic and combined violations would elicit sizeable ERP responses such as the LAN and P600 and semantic violations would elicit an N400, compared to correct words; (c) the presence of an unexpected note would decrease the amplitude of the LAN but not the N400, when language violations are presented simultaneously with unexpected (low-probability) notes, compared to expected (high-probability) notes. Finally, no specific predictions were made with regards to interactions between melodic expectation and combined violations, as this condition has not been previously investigated in the literature. However, it could be suggested that interaction effects at combined violations may decrease compared to those at single syntactic violations due to inhibited effects of syntactic effects in the presence of additional semantic ambiguities.

[1] For the purposes of this article, harmony can be thought of as a collection of simultaneously sounding notes, forming a chord. When listening to music, listeners form harmonic expectations about the next chord in a sequence of harmonic movements. A melody is a sequence of non-overlapping notes, each with a pitch and duration. Listeners form melodic expectations about the next note in the melody, given the previous notes – here we focus specifically on the pitch of the notes.

2. Material and methods

2.1. Participants

Twenty-one individuals (aged 18–23 years, mean 20 years; 10 females) with normal hearing (self-reported) and normal or

Please cite this article in press as: Carrus E, et al., Melodic pitch expectation interacts with neural responses to syntactic but not semantic violations, Cortex (2012), http://dx.doi.org/10.1016/j.cortex.2012.08.024

corrected-to-normal vision participated in the experiment. They were Psychology undergraduates at Goldsmiths, University of London, and received course credits for their participation. All participants were native English speakers, right handed, and non-musicians. They reported normal hearing and were neurologically healthy. Written informed consent was received, and the study was approved by the local Ethics Committee of the Department of Psychology at Goldsmiths and conducted in accordance with the Declaration of Helsinki.

2.2. Stimuli

Two types of stimuli were used: musical stimuli presented aurally, and language stimuli presented visually.

Linguistic stimuli were 360 sentences (240 experimental sentences and 120 filler sentences) consisting of five words. The fifth word of each sentence could be a semantically incongruent or congruent word, a syntactically correct or incorrect word, or could contain both a semantic and a syntactic violation. Stimuli were distributed equally so that each language condition had 60 sentences. Examples of each type of sentence are given in Table 1. Additionally, 120 correct filler sentences were added to the experimental design, in order to have the same number of correct and incorrect sentences. Without using filler sentences, the experimental sentences would have contained three times more incorrect sentences than correct sentences (correct *vs* incorrect/incongruent/combined), and this could have biased participants' responses. Filler sentences were constructed in the same way as correct experimental sentences so that participants would not be able to distinguish between the two; they consisted of five words and ended with a correct/congruent word. EEG responses to these filler sentences were not analysed because they were only added to the experimental design to control for the number of correct and incorrect sentences, as mentioned above.

Each word was visually presented with the onset of a note; the presentation time for the first four words was 600 msec and for the final word was 1200 msec. Within each trial, words and notes were presented simultaneously with no breaks between them. Each sentence-melody presentation was separated from the next one by a fixation cross, which stayed on screen for 800 msec. Each sentence was repeated twice, once for high-probability and once for low-probability notes resulting in an overall number of 720 trials.

We used a computational model of musical processing (Pearce, 2005) to create melodies whose final notes have a low-probability of occurrence and, therefore, will violate expectations (Pearce and Wiggins, 2006; Pearce et al., 2010). The model is a variable-order *n*-gram model, which estimates the probability of the pitch of a note, given the preceding notes in the melody. It does so by learning the frequency counts of individual pitches appearing in similar contexts in a large corpus of Western tonal melodies, which is intended to represent the long-term musical experience of a typical Western listener. In the current study, we supplied our model of statistical sequence learning with representations of each note in terms of its scale degree (pitch relative to a notated tonic) and the preceding pitch interval. The model has been shown to predict listeners' melodic pitch expectations such that high-probability notes are perceived as expected and low-probability ones as unexpected (Pearce and Wiggins, 2006; Pearce et al., 2010). The model parameters used here are exactly the same as those used in Pearce et al. (2010).

The musical stimuli comprised 60 isochronous five-note phrases ending with a high-probability note (details of the corpus used can be found in the Supplementary material). For each of these phrases, the model was used to create a new, low-probability, final note. This was achieved by sampling from the conditional probability distribution the pitch of the final note subject to the constraint that the probability be lower than that of the actual continuation. Care was also taken to ensure that half of these notes were preceded by large intervals (six or more semitones) while the other half were preceded by small intervals (less than six semitones). The expectedness of the target notes may be expressed in units of information content (the negative logarithm, to the base 2, of the probability of an event occurring), which is a lower bound on the number of bits required to encode an event in context (MacKay, 2003) and may be thought of as the unexpectedness in context of a given note to the model. The mean information content of the final note of the low-probability melodies (mean = 11.75, standard deviation = 2.27) was higher than that of the high-probability melodies (mean = 1.98, standard deviation = 1.71). This procedure resulted in a set of 60 low-probability five-note melodies, corresponding to the 60 high-probability melodies. As previously mentioned, each of these melodies was paired with one of the following types of sentence: a correct sentence, an incorrect sentence, a semantically incongruent sentence, and a syntactically and semantically incorrect sentence.

In addition, a further 40 isochronous five-note phrases were added to the experimental design. Subsequently, 40 low-probability counterparts were created in exactly the same way as described above. These 80 melodies were repeated three times for pairing with the 240 filler sentences.

Corresponding to the linguistic stimuli, the presentation time for each of the first four notes was 600 msec, and for the final note was 1200 msec. Language stimuli were presented at the centre of the screen, one word after the other, and no blank screen was presented between two words. Sentences were presented on black background, and letters were in white. The font used for the sentences was Courier New, size 18. Melodies were aurally presented via two speakers (Creative Gigaworks, Creative Technology Ltd.). The volume was kept constant across participants and for the duration of the experiment. E-prime E-studio 1.1 was used to present the stimuli.

Table 1 – An example of the types of language conditions used in the experiment.

Language condition	Example
Correct	Julia was driving a car
Incongruent	Julia was driving a book
Incorrect	Julia was driving a cars
Double violation	Julia was driving a books

2.3. Procedure

Participants were seated in front of a computer in a dimly lit room. The experimenter placed an EEG cap on their head to record their brain's electrical activity during the task. Through written instructions, the participants were informed that they would be presented with a temporal sequence of five-word sentences on the screen. They were also informed that they would simultaneously hear a musical note for each word presented. Participants were only informed about the different sentence types, not about the unexpected and expected melodies. Participants were instructed to pay attention to the sentences on screen, and to respond by pressing response buttons labelled YES and NO, when prompted with the question, "was the last sentence acceptable?" Participants familiarized with the task by doing a few practice trials before the experimental trials where examples of all the possible conditions were presented. Participants were prompted on 10% of the trials. During the experiment, breaks were allowed after a block of 60 trials (about 6 min). Each block contained all types of sentences, whose order of presentation was randomized across participants. For each participant, each individual sentence was randomly paired with a melody. The experiment lasted approximately 1 h. An illustration of the experimental design is presented in Fig. 1 below.

2.4. EEG acquisition, data pre-processing, and data analysis

The EEG signals were recorded by placing Ag–AgCl electrodes on 64 scalp locations according to the 10–20 system (Jasper, 1958), using electrode AFz as ground. EEG signals were amplified (Synamps Amplifiers, NeuroScan Inc.), filtered (dc to 100 Hz), and digitized at 500 Hz. EEG data were re-referenced to the algebraic mean of the right and left earlobe electrodes (Essl and Rappelsberger, 1998). In order to monitor eye-movements and eye-blinks, horizontal and vertical electro-oculograms (EOGs) were recorded in bipolar fashion. All electrode impedances were kept below 5 KΩ.

Prior to data analysis, pre-processing steps included removal of noisy epochs (e.g., excessive muscular activity) by visual inspection and correction of eye-blink artefacts by independent component analysis using the EEGLAB toolbox (Delorme and Makeig, 2004). The data were filtered between .5 and 40 Hz, in order to remove both linear trends and alternating current (AC) power line noise. The data epochs representing single experimental trials time-locked to the onset of the last note/word were extracted from −500 msec to 1200 msec. ERPs were baseline corrected to 100 msec pre-stimulus period.

For statistical analysis, mean ERP amplitudes were computed for four spatial regions of interest (ROI): right anterior (RA) (F6, FC4, F4, F2 FC2, FC6), left anterior (LA) (F3, F5, F1, FC3, FC5, FC1), right posterior (RP) (P6, PC4, P4, P2, PC2, PC6), and left posterior (LP) (P5, PC5, PC1, P3, P1 PC3). See Fig. 2 for an illustration of these spatial ROIs. Further, we had three time windows of interest based on the previous literature: N1 (90–130 msec), LAN/N400 (300–450 msec), P600 (600–800 msec). Repeated measures analysis of variance tests (ANOVA) were used in the analysis. Possible factors entering the ANOVAs were *syntax* (correct, incorrect), *semantics* (congruent, incongruent), *note-probability* (high, low), *hemisphere* (right, left), *location* (anterior, posterior), at the time windows of interest and for anterior and posterior ROIs. Also, repeated measures ANOVAs were carried out to investigate differences between language conditions, independently of note-probability.

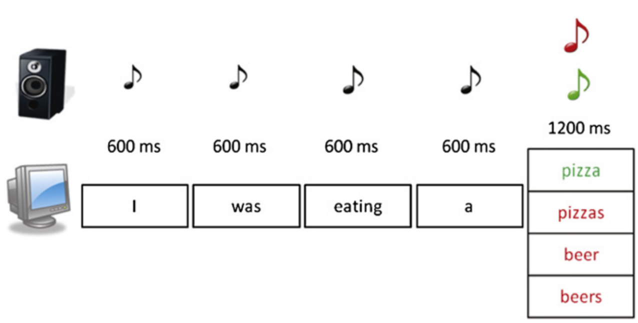

Fig. 1 – An illustration of the experimental design and procedure. Words and notes were presented simultaneously. Words were visually presented one after the other on screen, and notes were presented via speakers. The final word was the target word used in the analysis. Participants were shown five-word sentences in synch with five-note melodies. The linguistic stimuli ended with a syntactically and semantically correct word, a syntactically incorrect word, a semantically incongruent word or a word with a double violation (syntactic and semantic violation). Melodies ended with either a high-probability note or a low-probability note. The last word-note presentation lasted 1200 msec, while the previous four word-note presentations lasted 600 msec. A fixation cross in the centre of the screen was shown before each trial for 800 msec.

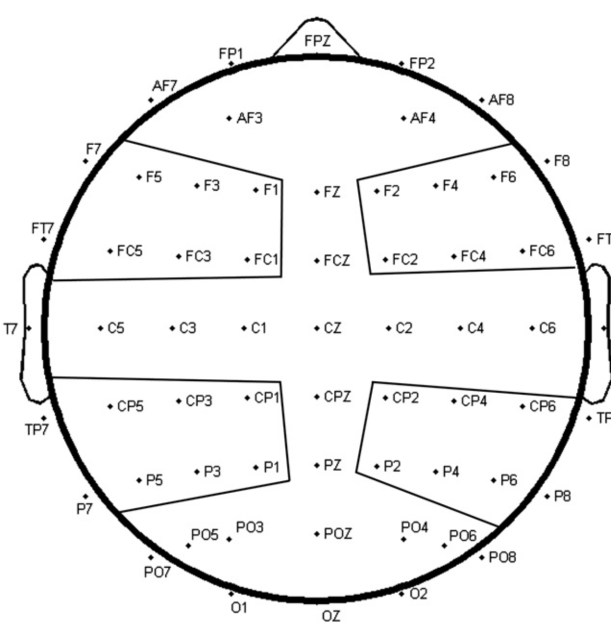

Fig. 2 – An illustration of the electrode layout and the four spatial ROIs (clockwise: LA (left anterior), RA (right anterior), RP (right posterior), LP (left posterior)).

Please cite this article in press as: Carrus E, et al., Melodic pitch expectation interacts with neural responses to syntactic but not semantic violations, Cortex (2012), http://dx.doi.org/10.1016/j.cortex.2012.08.024

In addition to these ROI-based analyses, we also performed exploratory analysis by performing cluster-based permutation tests (Maris and Oostenveld, 2007) for each ERP component in order to provide complimentary information regarding the locations and time windows at which the component was maximal. These tests are robust against the multiple comparison problem without constraining the analysis to specific time windows and ROIs, providing significant clusters in space and time [see Maris and Oostenveld (2007) for further details].

ERPs of the difference waves were low-pass filtered at 10 Hz for visual presentation only. All statistical tests were run on SPSS version 18, and cluster-based permutation tests were run using Fieldtrip (Oostenveld et al., 2011). The Greenhouse–Geisser correction (Winer, 1971) was applied for repeated measures ANOVAs and corrected *p* values are reported.

3. Results

3.1. Correct words, unexpected notes

As compared with the high-probability notes, low-probability notes were associated with a larger N1 component (more negative) around 100 msec with a predominantly fronto-central distribution (Fig. 3). In order to assess the statistical significance of this amplitude difference, a 2×2 repeated measures ANOVA was carried out at anterior ROIs for the N1 time window (90–130 msec) with within-subjects factors *note-probability* (high, low) and *hemisphere* (right, left). The analysis revealed a significant main effect of *note-probability*, $F(1, 20) = 4.23$, $p = .04$. This effect confirmed the presence of an enhanced negativity elicited at the N1 time window by low-probability notes, compared to high-probability notes. Additionally, cluster-based permutation tests run on the entire post-stimulus time window on all electrodes confirmed the presence of a significantly negative cluster covering the right fronto-central area at 100 msec ($p < .02$) (Fig. 4a). There was no significant main effect of *hemisphere*, nor an interaction between *note-probability* and *hemisphere* ($p > .1$). No significant effects were found for an analogous ANOVA carried out at posterior ROIs ($p > .1$).

3.2. Syntactically incorrect words, expected notes

As compared with the syntactically correct words, the syntactically incorrect words were associated with: (a) a negative deflection between 250 msec and 550 msec with a fronto-central distribution, resembling the LAN (b) a positive deflection between 600 msec and 800 msec, resembling the P600 (Fig. 5). In order to assess the statistical significance of this amplitude difference, a repeated measures ANOVA with within-subject factors *syntax* (correct, incorrect) and *hemisphere* (right, left) was carried out at anterior ROIs for the time window between 300 msec and 450 msec revealing a significant main effect of *syntax*, $F(1, 20) = 6.38$, $p = .02$. An analogous 2×2 repeated measures ANOVA carried out at posterior ROIs did not reveal any significant effects ($F < 1$). These results confirmed the presence of a LAN at anterior sites. A 2×2 repeated measures ANOVA carried out for the time window between 600 msec and 800 msec revealed a significant main effect of *syntax* at anterior and posterior ROIs, respectively, $F(1, 20) = 10.81$, $p = .002$, and $F(1, 20) = 17.33$, $p < .001$, confirming the presence of a P600 component. Similar to the analysis in Section 3.1, cluster-based permutation tests were run on the entire post-stimulus time window for all electrodes; this analysis confirmed the presence of a significantly negative cluster at frontal electrodes with a slight left lateralization at 380 msec, thus reflecting the presence of the LAN ($p < .001$), and a significantly positive cluster at centro-parietal electrodes at 640 msec, thus reflecting the presence of a P600 ($p < .001$) (Fig. 4b and c).

3.3. Semantically incongruent words, expected notes

As compared with the semantically congruent words, semantically incongruent words showed larger negative

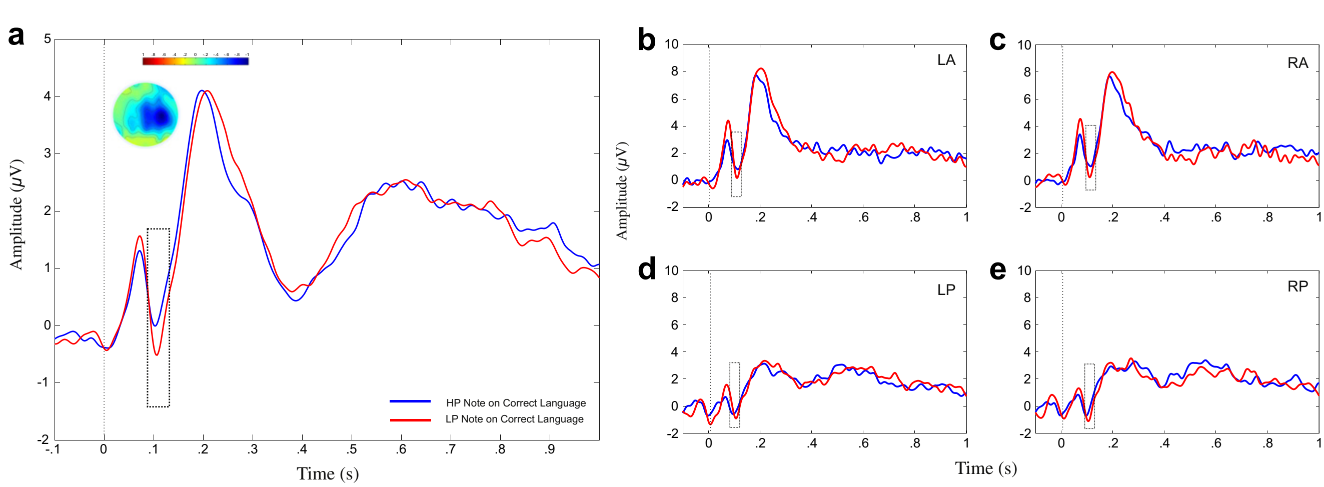

Fig. 3 – (a) Grand average ERPs following the onset of a low-probability note (red) and a high-probability note (blue), showing the anterior negativity (N1), indicated by a rectangle. The same information is displayed for the following ROIs: (b) LA, (c) RA, (d) LP, (e) RP. The scalp topography represents the difference between low-probability notes and high-probability notes at the N1 time window. These represent averages across participants and electrodes.

Please cite this article in press as: Carrus E, et al., Melodic pitch expectation interacts with neural responses to syntactic but not semantic violations, Cortex (2012), http://dx.doi.org/10.1016/j.cortex.2012.08.024

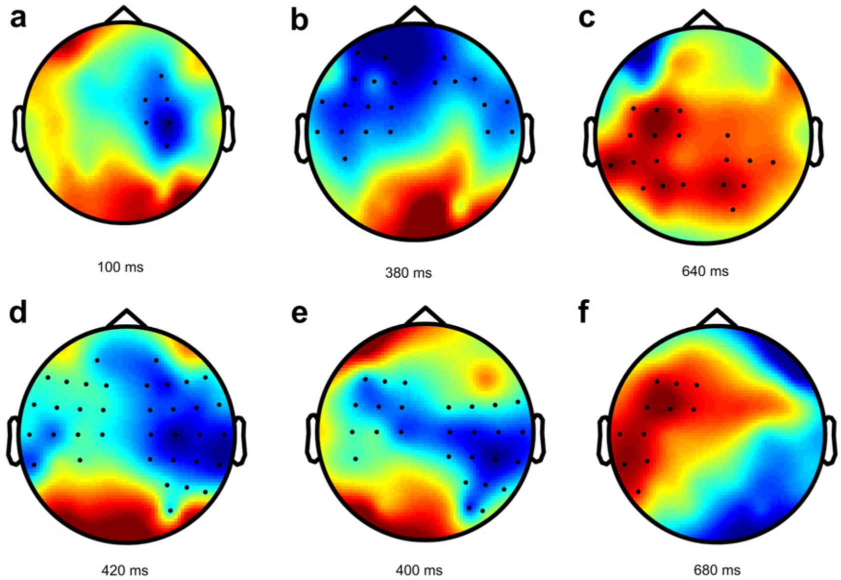

Fig. 4 – Difference scalp maps of ERP components averaged across participants showing significant clusters of activity: (a) scalp map of the ERP at 100 msec for high-probability notes subtracted from low-probability notes on correct language; (b) and (c) scalp maps of the ERP at 380 msec and 640 msec for correct syntax subtracted from incorrect syntax; (d) scalp map of the ERP at 420 msec for congruent semantics subtracted from incongruent semantics; (e) and (f) scalp maps of the ERP at 400 msec and 680 msec for correct language subtracted from combined violations.

responses between 300 msec and 500 msec, with a central distribution (Fig. 6), resembling the N400. In order to assess the statistical significance of this amplitude difference, a 2 × 2 repeated measures ANOVA with factors *semantics* (congruent, incongruent) and *hemisphere* (right, left) was carried out at anterior ROIs for the time window between 300 msec and 450 msec revealing a main effect of *semantics*, $F(1, 20) = 29.32$, $p < .001$. An analogous ANOVA carried out at posterior ROIs revealed a significant main effect of *semantics*, $F(1, 20) = 20.31$, $p < .001$, confirming the presence of an N400 component. Cluster-based permutation tests were run on the entire post-stimulus time window and confirmed the presence of a significantly negative cluster at central electrodes with a right lateralization at 420 msec ($p < .01$) (Fig. 4d).

3.4. *Combined (syntax and semantics) violations, expected notes*

As compared with correct words, words with a combined violation showed a larger negativity between 300 msec and

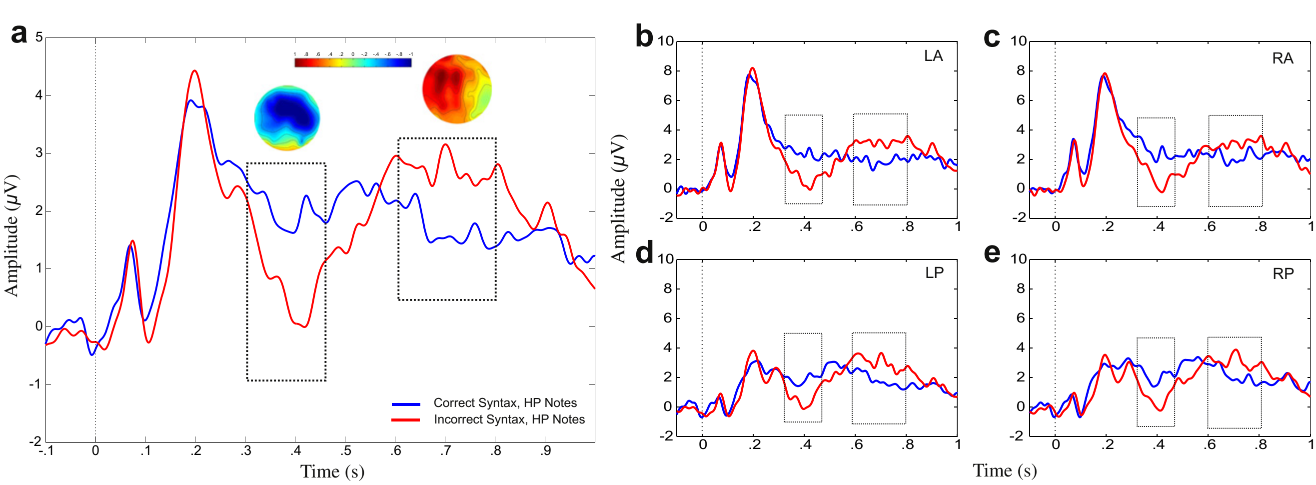

Fig. 5 – (a) Grand average ERPs following the onset of a syntactically incorrect word (red) and a syntactically correct word (blue), showing the LAN and P600 components, indicated by a rectangle. The same information is displayed for the following ROIs: (b) LA, (c) RA, (d) LP, (e) RP. The scalp topography corresponding to the difference between syntactically incorrect words and syntactically correct words is represented for each component. These represent averages across participants electrodes.

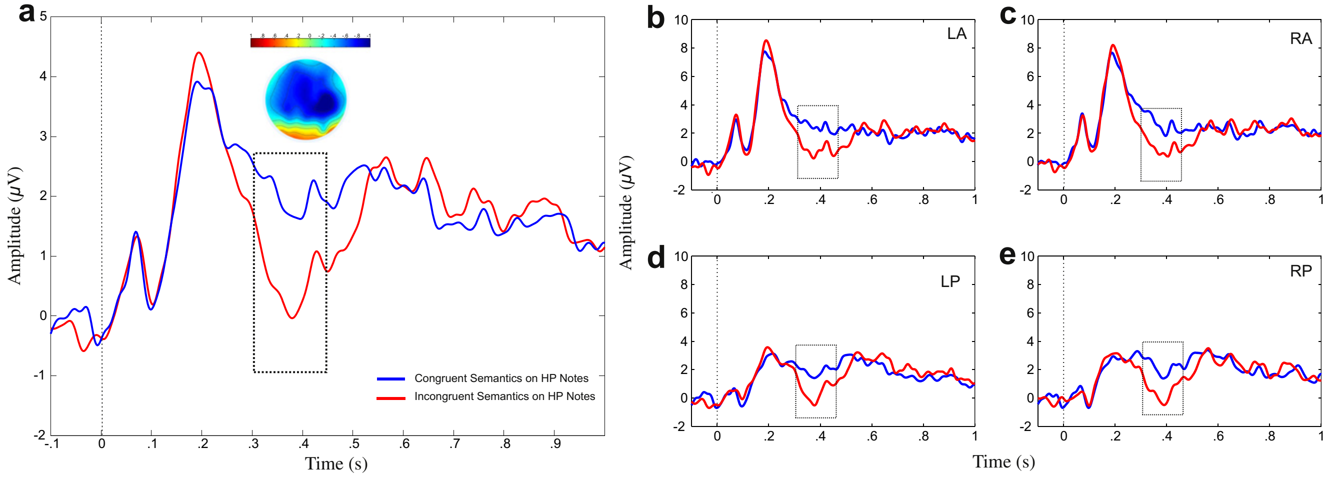

Fig. 6 – (a) Grand average ERPs following the onset of a semantically incongruent word (red) and a semantically congruent word (blue), showing the N400 indicated by a rectangle. The same information is displayed for the following ROIs: (b) LA, (c) RA, (d) LP, (e) RP. The scalp topography corresponding to the N400 time window shows the difference between semantically incongruent words and semantically congruent words. These represent averages across participants and electrodes.

500 msec, with a central scalp distribution and a larger positivity between 600 msec and 800 msec (see Fig. 7). In order to assess the statistical significance of this amplitude difference, a 2 × 2 repeated measures ANOVA with within-subject factors *combined violation* (yes, no) and *hemisphere* (right, left) was carried out at anterior ROIs for the time window between 300 msec and 450 msec, revealing a main effect of *combined violations*, $F(1, 20) = 9.07$, $p < .001$. An analogous ANOVA carried out at posterior ROIs revealed a main effect of *combined violation*, $F(1, 20) = 8.67$, $p = .002$. These results indicated a larger negativity elicited by combined violations compared to correct sentences, both presented on high-probability notes. In order to investigate differences in the time window between 600 msec and 800 msec, a 2 × 2 repeated measures ANOVA was carried out at both anterior and posterior ROIs, revealing a significant main effect of *combined violation* at posterior ROIs only, $F(1, 20) = 6.89$, $p = .03$. These ANOVAs showed the presence of a P600-like component following combined violations. Finally, these findings were corroborated by cluster-based permutation tests run on the entire post-stimulus time window; they confirmed the presence of a significantly negative cluster covering central electrodes with a right lateralization at 400 msec ($p < .003$), and a significantly positive cluster at central electrodes with a left lateralization at 680 msec ($p < .002$) (Fig. 4e and f).

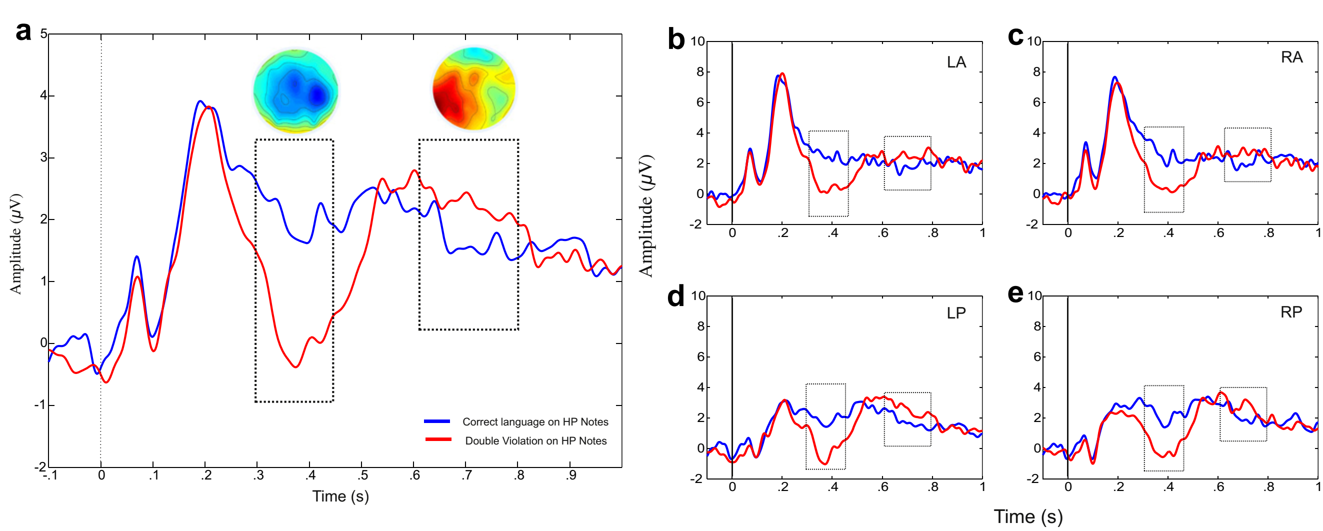

Fig. 7 – (a) Grand average ERPs following the onset of a syntactically incorrect and semantically incongruent word (red) and a correct word (blue), showing the LAN/N400 and the P600 indicated by a rectangle. The same information is displayed for the following ROIs: (b) LA, (c) RA, (d) LP, (e) RP. The scalp topography corresponding to the difference between the combined violation and the correct word is represented for each component. These represent averages across participants and electrodes.

Please cite this article in press as: Carrus E, et al., Melodic pitch expectation interacts with neural responses to syntactic but not semantic violations, Cortex (2012), http://dx.doi.org/10.1016/j.cortex.2012.08.024

3.5. *Language: syntax and semantics*

In order to understand the contribution of syntactic and semantic processing at each time window regardless of note-probability, further analysis was conducted. Fig. 8 shows the ERP profile for all language conditions across high- and low-probability notes. Firstly, in order to investigate the contribution of syntactic and semantic processes at an early stage of processing, a 2 × 2 repeated measures ANOVA with factors *syntax* and *semantics* was carried out for the time window between 300 msec and 450 msec for anterior ROIs revealing a significant main effect of *syntax*, $F(1, 20) = 6{,}78$, $p = .02$, and *semantics*, $F(1, 20) = 8.49$, $p = .01$. An analogous ANOVA was carried out at posterior ROIs, also revealing a significant main effect of *syntax*, $F(1, 20) = 7.16$, $p = .01$, and *semantics* $F(1, 20) = 8.41$, $p = .01$. Further, in order to assess whether both syntactic and semantic processes contributed to the generation of the P600, a 2 × 2 repeated measures ANOVA was carried out in the time window between 600 msec and 800 msec, revealing a significant main effect of *syntax* at posterior ROIs, $F(1, 20) = 4.52$, $p = .04$. These findings showed that both syntactic and semantic processes were involved at the time window 300–450 msec, but only syntactic processes emerge at later time windows, as suggested by the presence of a P600 only following syntactic violations or combined violations. Furthermore, in order to compare the LAN and P600 components elicited by the single syntactic violation and by the combined violations, we ran 2 × 2 repeated measures ANOVAs with within-subject factors *violation* (single, combined) and *hemisphere* (right, left). These ANOVAs did not reveal any differences ($F < 1$), showing that there was not a significant difference between these components at single and combined violations.

Further tests were carried out to investigate whether the component elicited at 300–450 msec by the combined violation was the result of an additive effect of the LAN and N400 elicited by the single violation. This was done by comparing the sum of the LAN for the single syntactic violation and the N400 for the single semantic violation with the ERP component elicited by the combined violation. In order to test this, 2 × 2 repeated measures ANOVAs at frontal and posterior ROIs were carried out for the time window between 300 msec and 450 msec with factors *violation* (sum, combined) and *hemisphere* (right, left). Both at frontal and posterior sites, the tests revelaed a main effect of violation, indicating that the ERP elicited by the combined violation was significantly smaller than the ERP elicited by the sum of the two single violations, $F(1, 20) = 4.7$, $p = .01$, and $F(1, 20) = 7.32$, $p = .003$, respectively. These results suggest non-additivity, therefore reflecting an interaction between syntax and semantics during language processing.

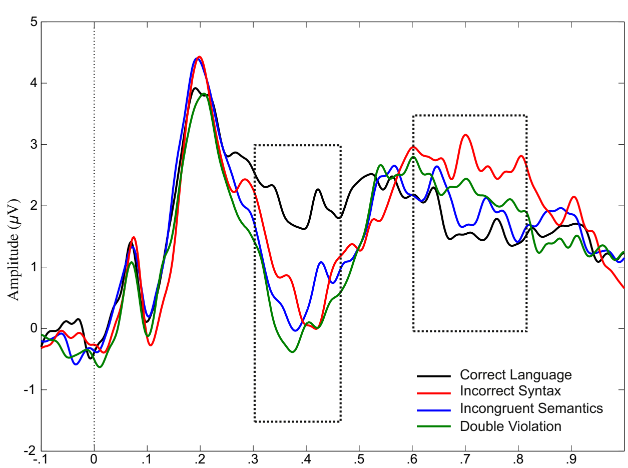

Fig. 8 – Grand average ERPs following the onset of the following language conditions: syntactically correct (black), syntactically incorrect (red), semantically incongruent (blue), combined violation (green).

3.6. *Interaction between syntax and note-probability*

Next we investigated whether the ERP components associated with syntactically incorrect words (compared to syntactically correct words) would interact with the effects of note-probability. We initially examined whether the LAN amplitude is influenced by the note-probability. In order to do this, we compared two difference waves: first, syntactically incorrect words presented on high-probability notes minus syntactically correct words presented on high-probability notes; and second, syntactically incorrect words presented on low-probability notes minus syntactically correct words presented on low-probability notes. The ERP profiles of the four conditions used in this comparison as well as the difference waves are represented in Fig. 9a and b, respectively. Fig. 9b shows that the LAN amplitude is smaller when incorrect sentences are presented on low-probability notes than on high-probability notes. Additionally, the supplementary Fig. S1 shows the interaction effect at each of the four ROIs. In order to explore the significant interaction between *note-probability* and *syntax* in the time window between 300 msec and 450 msec at anterior ROIs, a 2 × 2 ANOVA with within-subjects factors *note-probability* (high, low) and *syntax* (correct, incorrect) revealed a significant main effect of *syntax*, $F(1, 20) = 9.63$, $p < .001$, and a significant interaction between *syntax* and *note-probability*, $F(1, 20) = 6.61$, $p = .02$. An analogous ANOVA at posterior ROIs showed a main effect of *syntax*, $F(1, 20) = 19.54$, $p < .001$ but no significant interaction ($F < 1$). The significant interaction effect suggests that the LAN component is smaller when elicited on low-probability notes, compared to high-probability notes, and it is only significant at frontal sites. Further, an ANOVA for anterior ROIs was carried out to directly compare the ERPs elicited by syntactically incorrect words on a high-probability note with the ERPs elicited by syntactically incorrect words presented on a low-probability note; this comparison revealed a significant main effect of violation, confirming a significant difference between the two ERP profiles, $F(1, 20) = 9.35$, $p = .005$. An analogous ANOVA in the time window between 600 msec and 800 msec revealed a significant main effect of *syntax*, $F(1, 20) = 19.54$, $p < .001$ at posterior ROIs, but there was no interaction between *syntax* and *note-probability* ($F < 1$). This non-significant result suggests that interaction between note-probability and syntax does not emerge at later time windows. Analogous ANOVAs carried out in the time window between 90 msec and 130 msec did not show any interactions between syntax and note-probability. This suggests that the

Please cite this article in press as: Carrus E, et al., Melodic pitch expectation interacts with neural responses to syntactic but not semantic violations, Cortex (2012), http://dx.doi.org/10.1016/j.cortex.2012.08.024

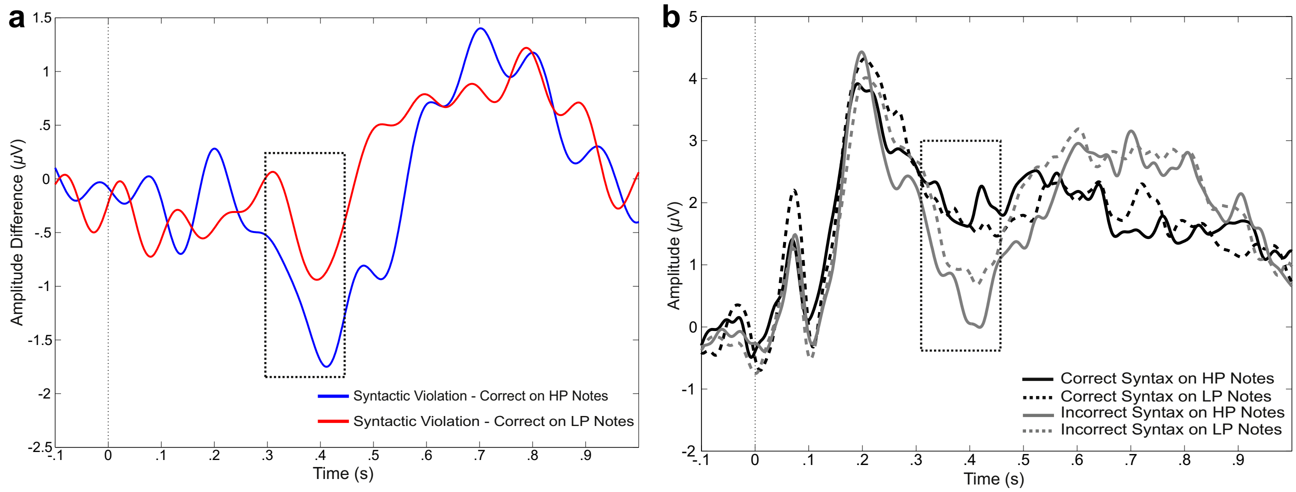

Fig. 9 – (a) Grand average difference ERPs for the interactions effects between syntactic violations in language and note-probability in music. The blue line represents the difference between syntactically incorrect and syntactically correct words both presented on high-probability notes and the red line represents the difference between syntactically incorrect and syntactically correct words both presented on low-probability notes. (b) Grand average ERPs for each condition used in the difference waves in a. The solid black line represents ERPs following presentation of correct sentences presented on high-probability notes, and the solid grey line represents ERPs elicited following presentation of single syntactic violations on high-probability notes. The solid black line was subtracted from the solid grey line to obtain the first difference wave (blue in a). The dashed black line represents ERPs elicited following presentation of correct sentences on low-probability notes, and the dashed grey line represented ERPs elicited following presentation of single syntactic violations on low-probability notes. The dashed black line was subtracted from the dashed grey line to obtain the second difference wave (red line in a).

presence of syntactic violations did not significantly affect the amplitude of the N1.

3.7. *Interaction between semantics and note-probability*

Next we investigated whether the ERP components associated with semantically incongruent words (compared to semantically congruent words) would interact with note-probability. Therefore we initially examined whether the N400 amplitude would be influenced by the note-probability. In order to do this, we compared two difference waves: first, semantically incongruent words presented on high-probability notes minus semantically congruent words presented on high-probability notes; and second, semantically incongruent words presented on low-probability notes minus semantically congruent words presented on low-probability notes. The ERP profiles of the four conditions used in this comparison as well as the difference waves are represented in Fig. 10a and b, respectively. Additionally, the supplementary Fig. s2 shows the interaction effect at each of the four ROIs. Fig. 10b shows that the N400 amplitude was larger when incongruent sentences were presented on low-probability notes than on high-probability notes. This difference was not statistically significant as revealed by the following tests. A 2 × 2 ANOVA carried out in the time window between 300 msec and 450 msec with within-subjects factors *semantics* (congruent, incongruent) and *note-probability* (high, low) revealed a significant main effect of *semantics*, $F(1, 20) = 42.40$, $p < .001$ at frontal ROIs but no significant interactions were found, $F(1, 20) = 4.52$, $p = .17$. An analogous ANOVA at posterior ROIs revealed a significant main effect of *semantics*, $F(1, 20) = 55.51$, $p < .001$, but no significant interaction between *semantics* and *note-probability* ($F < 1$). The lack of a significant interaction suggests an independence between processing of semantics in language and note-probability.

3.8. *Interaction between syntax–semantics and note-probability*

Next we repeated the entire analysis, but for the combined (syntax and semantics) violation condition. Although similar components were elicited following the presentation of a word with a combined violation elicited on a low-probability note and on a high-probability note, combined violations elicited a decreased negativity around 300–500 msec when presented on low-probability notes compared to high-probability notes. The ERP profiles of the four conditions used in this comparison as well as the difference waves are represented in Fig. 11 a and b, respectively. Additionally, the supplementary Fig. s3 shows the interaction effect at each of the four ROIs. ANOVAs were carried out to assess statistically the contribution of low-probability notes to the neural responses elicited by words with a combined violation. A 2 × 2 ANOVA with within-subjects factors *combined violation* (yes, no) and *note-probability* (high, low) in the time window between 300 msec and 450 msec for posterior ROIs revealed a significant main effect of *combined violation*, $F(1, 20) = 11.68$, $p < .001$, and a marginal interaction, $F(1, 20) = 3.81$, $p = .07$. The same ANOVA carried out for frontal ROIs revealed a significant main effect of

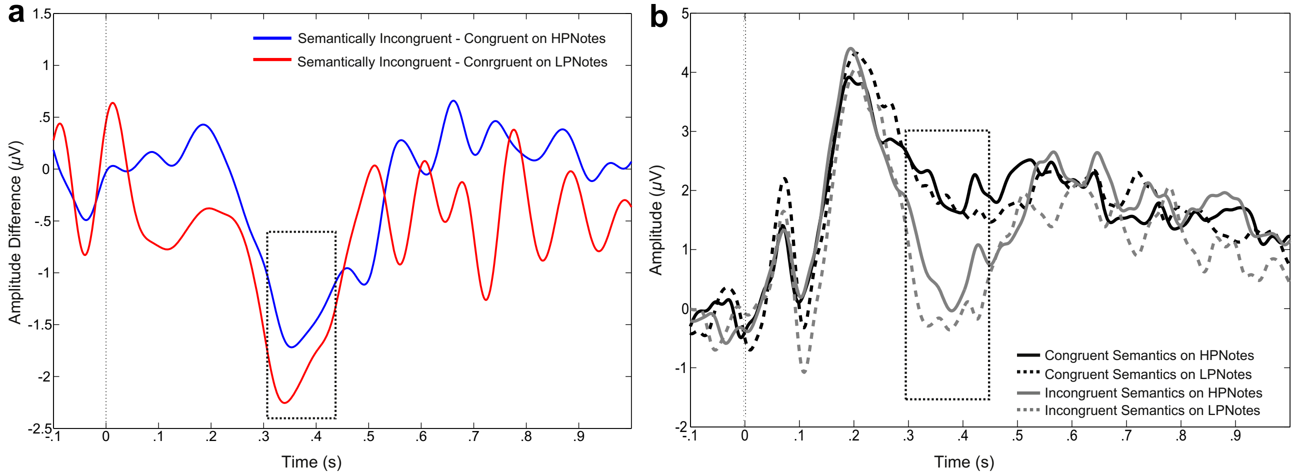

Fig. 10 – (a) Grand average difference ERPs for the interactions effects between semantic violations in language and note-probability in music. The blue line represents the difference between semantically incongruent and semantically congruent words both presented on high-probability notes and the red line represents the difference between semantically incongruent and semantically congruent words both presented on low-probability notes. (b) Grand average ERPs for each condition used in the difference waves in a. The solid black line represents ERPs following presentation of congruent sentences presented on high-probability notes, and the solid grey line represents ERPs elicited following presentation of single semantic violations on high-probability notes. The solid black line was subtracted from the solid grey line to obtain the first difference wave (blue line in a). The dashed black line represents ERPs elicited following presentation of congruent sentences on low-probability notes, and the dashed grey line represents ERPs elicited following presentation of single semantic violations on low-probability notes. The dashed black line was subtracted from the dashed grey line to obtain the second difference wave (red line in a).

combined violation, $F(1, 20) = 17.07$, $p < .001$, and a marginally non-significant interaction between *combined violation* and *note-probability*, $F(1, 20) = 3.65$, $p = .07$. These interactions may reflect a marginal difference in the amplitude of the neural component elicited by combined violations on high- and low-probability notes. Although these interactions are marginal, a repeated measures ANOVA directly compared the ERPs elicited by words with a combined violation on

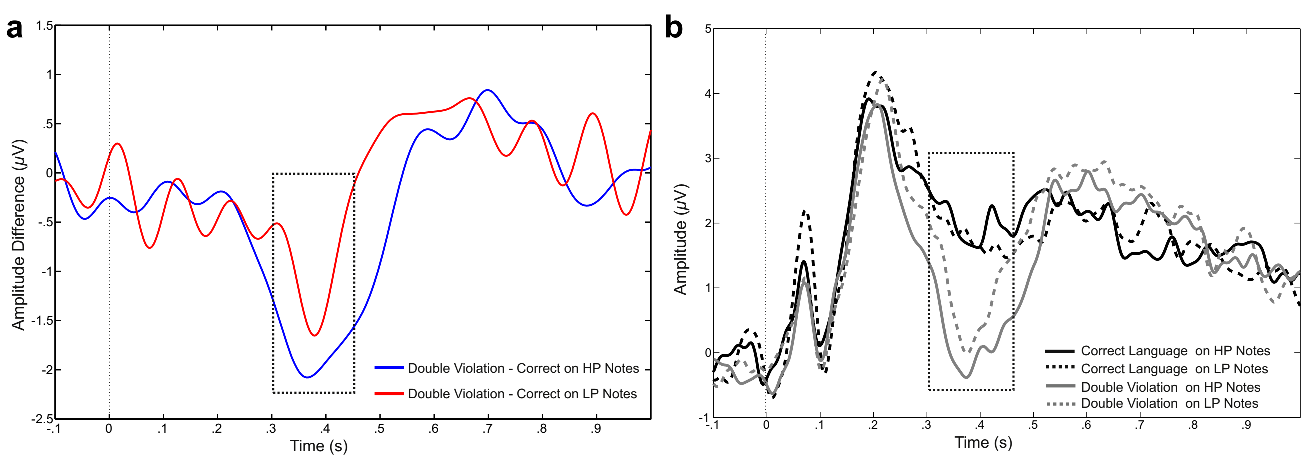

Fig. 11 – (a) Grand average difference ERPs for the interactions effects between combined violations in language and note-probability in music. The blue line represents the difference between combined violations and correct words, both presented on high-probability notes, and the red line represents the difference between combined violations and correct words, both presented on low-probability notes. (b) Grand average ERPs for each condition used in the difference waves in a. The solid black line represents ERPs following presentation of congruent sentences presented on high-probability notes, and the solid grey line represents ERPs elicited following presentation of single semantic violations on high-probability notes. The solid black line was subtracted from the solid grey line to obtain the first difference wave (blue line in a). The dashed black line represents ERPs elicited following presentation of congruent sentences on low-probability notes, and the dashed grey line represents ERPs elicited following presentation of single semantic violations on low-probability notes. The dashed black line was subtracted from the dashed grey line to obtain the second difference wave (red line in a).

Please cite this article in press as: Carrus E, et al., Melodic pitch expectation interacts with neural responses to syntactic but not semantic violations, Cortex (2012), http://dx.doi.org/10.1016/j.cortex.2012.08.024

a high-probability note with the ERPs elicited by words with a combined violation on a low-probability note revealing a significant difference between the two ERP profiles at posterior and frontal ROIs, $F(1, 20) = 4.56$, $p = .03$, and $F(1, 20) = 3.45$, $p = .04$, respectively. In order to investigate interactions at later time windows, a 2 × 2 repeated measures ANOVA with factors *combined violation* (yes, no) and *note-probability* (high, low) was carried out in the time window between 600 msec and 800 msec at posterior ROIs, revealing a significant main effect of *combined violation*, $F(1, 20) = 9.69$, $p < .001$, but no significant interaction. This confirmed that interactions between note-probability and combined violations did not emerge at later time windows.

A summary of the results for each time window can be found in Table 2.

3.9. Comparison of interaction effects

In order to compare the interaction effect at single syntactic violations with the interaction at combined violations we adopted a double differencing method by creating pseudo-factors to enter an ANOVA. More specifically, we created the following four pseudo-conditions:

Condition 1: Syntactically Incorrect on HP versus Correct on HP.
Condition 2: Syntactically Incorrect on LP versus Correct on LP.
Condition 3: Combined Violation on HP versus Correct on HP.
Condition 4: Combined Violation on LP versus Correct on LP.

The above procedure was also adopted for a second comparison between the interaction effect at single semantic violations and the interaction effect at combined violations.

Therefore, two pseudo-factors with two levels were created: *violation* (single, double) and *music* (HP, LP), to enter into two 2 × 2 repeated measures ANOVAs for frontal and posterior sites for the time between 300 msec and 450 msec. These two ANOVAs were run for both the first and the second comparison, revealing a significant interaction for the first comparison (interaction at single syntactic violations *vs* interaction at combined violations), $F(1, 20) = 10.93$, $p = .004$ and a non-significant interaction at frontal sites for the second comparison (interaction at single semantic violations *vs* interactions at double violations), $p > .1$. These effects suggest that the music–language interaction under combined violations is significantly smaller than the one emerging at single syntactic violations, but not at single semantic violations.

4. Discussion

This study investigated the effects of manipulating melodic expectation on the simultaneous processing of linguistic violations. The rationale behind this was to explore the extent to which processing of unexpected musical notes affected processing of unexpected words, as revealed by the EEG. Although studies have explored the relationship between processing of violations in music and language (Besson and Faita, 1995; Koelsch et al., 2005; Patel et al., 1998), no study has examined neural responses during simultaneous processing of melodic and linguistic processing. Furthermore, the use of a combined syntactic–semantic violation allows for a better understanding of the specific role of each type of violation in the context of the shared neural resources hypothesis.

An interesting aspect of this study was the use of melodies that embodied a definition of melodic expectation formulated in a computational model (Pearce, 2005; Pearce et al., 2010; Pearce and Wiggins, 2006). Previous studies have used the musicological theory of Western tonal music to create stimuli consisting of chord sequences that follow or violate the rules of harmonic movement (Koelsch et al., 2005; Patel et al., 1998). Our computational model allowed construction of stimuli where note-probability could be systematically estimated and manipulated, therefore enabling a more detailed and empirically well-founded notion of melodic syntax than that defined in music theory. Further, to a greater extent than tonal harmony, melodic movement constitutes an important part of other musical traditions beyond Western tonal music, leading to greater generality in the application of our results.

We used this model to distinguish between high-probability, or expected, and low-probability, or unexpected, phrase-final notes. As stated in our first hypothesis related to the music syntax, a significant difference between these two conditions emerged around 100 msec after presentation of the note, where unexpected notes elicited a larger N1 compared to expected notes. This effect was strongest at fronto-central sites. This is in line with previous findings of early brain responses to unexpected or violated musical elements (Herrojo-Ruiz et al., 2009; Koelsch et al., 2005; Pearce et al.,

Table 2 – A full list of statistical values for the main effects and interactions at each time window and region.

	Time windows					
	90–125 msec		300–450 msec		600–800 msec	
	Anterior	Posterior	Anterior	Posterior	Anterior	Posterior
LP versus HP notes	$p = .04$	*n.s.*				
Incorrect versus correct			$p = .02$	*n.s.*	$p = .002$	$p = .001$
Incongruent versus congruent			$p < .001$	$p < .001$		
Combined versus correct			$p < .001$	$p = .002$	*n.s.*	$p = .03$
Syntax × music	*n.s.*	*n.s.*	$p = .02$	*n.s.*	*n.s.*	*n.s.*
Semantics × music			*n.s.*	*n.s.*		
Combined × music			$p = .07$	$p = .07$	*n.s.*	*n.s.*

Please cite this article in press as: Carrus E, et al., Melodic pitch expectation interacts with neural responses to syntactic but not semantic violations, Cortex (2012), http://dx.doi.org/10.1016/j.cortex.2012.08.024

2010). For example, an N1 has been previously associated with processing unexpected notes in melodic sequences (Koelsch and Jentschke, 2010).

As surmised in our second hypothesis related to the language domain, we found distinct ERP components elicited by syntactic, semantic and combined violations. The LAN and P600 components, reflecting syntactic processing in language (Friederici, 2004; Koelsch et al., 2005), were elicited following presentation of syntactically incorrect words. Furthermore, an N400 was elicited following semantically incongruent words, as previously reported (Friederici, 2004; Gunter et al., 1997; Hagoort, 2003). Also most interestingly, the presence of a combined syntactic–semantic violation produced effects that resembled both syntactic and semantic processing. Following combined violations, we observed a LAN/N400 and a later component resembling the P600. Interestingly, these two components did not differ from the profiles and topographies of the components elicited by the single violations. Further, the LAN/N400 elicited by the combined violation did not reflect additive effects; non-additive effects of semantic and syntactic violations have been previously reported in studies investigating interactions between the two processes using a full factorial design (Ainsworth-Darnell et al., 1998; Gunter et al., 1997; Hagoort, 2003; Osterhout and Nicol, 1999). Finally, we showed that the P600 component is entirely generated by the contribution of syntactic processing, while both syntactic and semantic processing contributes to the generation of earlier components such as the LAN and the N400; this finding has been previously shown in studies investigating the interplay between syntactic and semantic processing in language (Hagoort, 2003).

Our third hypothesis was related to the principal goal of this study, to investigate the extent to which violations of melodic expectation affect the processing of linguistic violations at the neural level. The present study showed evidence for a neural interaction between processing of structure in music and language by demonstrating that melodically unexpected notes interfere with processing of syntactic violations supporting previous literature (Koelsch et al., 2005; Patel et al., 1998). More specifically, syntactically incorrect words presented simultaneously with low-probability notes elicited a smaller LAN compared to syntactically incorrect words presented on high-probability notes. This confirms previous theoretical proposals and empirical results suggesting the existence of a competition in the resources used for processing of syntax in music and language (Koelsch et al., 2005; Patel, 2003; Patel et al., 1998). Interestingly, this interaction only occurred at frontal electrodes, where both LAN and N1 are maximal. The same interaction only occurred at an early stage of processing, as no significant effect was shown at the P600 time window. It is therefore likely that the musical stimuli used in the present study elicit an influence on initial syntactic processing but have little or no effect at later stages of syntactic integration.

In line with most of the studies in the literature (Besson et al., 1998; Koelsch et al., 2005), the presence of low-probability notes did not significantly affect the amplitude of the N400 component, an index of semantic processing. Although the difference was not significant, the amplitude of the N400 elicited on low-probability notes was larger compared to the N400 elicited on high-probability notes. This is the opposite effect to that observed during syntactic processing (where low-probability notes elicited a smaller LAN), suggesting that melodic expectation could affect semantic processing in a qualitatively different way than syntactic processing. In fact, the pattern of interactions reported in the literature seems to be affected by whether participants are instructed to pay attention exclusively to language (see Koelsch et al., 2005 and Steinbeis and Koelsch, 2008). It could be suggested that semantic interactions concern later time windows compared to syntactic processes or rely highly on the attention to stimuli; these differences between the two processes could result in qualitatively different interactions with music. It would be interesting to test this hypothesis in future research, although the lack of a statistically significant difference in the present study suggests that music and linguistic semantics are processed independently. This is in line with previous findings reported by Koelsch et al. (2005) regarding an independence between semantics in language and syntax in music.

A novel condition in this experiment was the use of a combined violation of syntax and semantics. Although previous language research has examined this condition (Ainsworth-Darnell et al., 1998; Gunter et al., 1997; Hagoort, 2003), no studies have investigated the impact of musical expectation on this combined violation. This was useful to understand the extent to which the interaction between music and language syntax could be affected by an additional semantic ambiguity, therefore providing additional information regarding the hypothesis of shared neural resources between processing of music and language syntax. The combined violation produced effects that resembled both early and late effects of syntactic and semantic processing. Regarding interactions between note-probability and the processing of a combined violation, the presence of a low-probability note only interacted to a marginal extent with the processing of combined violations at frontal regions, where the presence of a low-probability note reduced the amplitude of the negative component elicited at the LAN/N400 time window. Interestingly, when a more direct comparison was made between the LAN/N400 components elicited by the combined violation on a high-probability note and on a low-probability note, the amplitude reduction was more evident. We speculate that the marginal interaction between combined violations and note-probability could be due to the presence of semantic processing inhibiting a stronger interaction effect, compared to that found between single syntactic violation and note-probability.[2] More specifically, the present findings suggest that the presence of a smaller

[2] Given that low-probability notes influence the neural response to syntactic and semantic violations in opposite directions (reducing the LAN to syntactic violations but enhancing, although non-significantly, the N400 to semantic violations), it is possible that the semantic violation "inhibited" or counterbalanced the effect of the unexpected note on the neural response to the syntactic violation in this time window. It could be speculated that melodic expectation may affect semantic processing in a qualitatively different manner than syntactic processing.

music–language interaction under combined violations compared to single syntactic violations could be due to syntactic processes being consumed by the presence of a simultaneous semantic incongruity; this is further supported by the findings of non-additivity in the interaction between syntax and semantics. This argument is also supported by previous findings in the language literature reporting suppression of syntactic neural components in the presence of an additional semantic violation, as found in combined violations (Ainsworth-Darnell et al., 1998; Gunter et al., 1997, 2000; Hagoort, 2003; Martin-Loeches et al., 2006; Osterhout and Nicol, 1999; Palolahti et al., 2005; Wicha et al., 2004). Further, the comparison between the interaction effect at single syntactic violations and the interaction at double violations is significant, suggesting a significant difference between the two interaction effects. However, the comparison between the interaction effect at single semantic violations and the interaction effect at combined violations was not significant, possibly suggesting the presence of an inhibition of semantic violations at the time window where the LAN/N400 is elicited.

In summary, we showed that an unexpected note in a melodic sequence interacts at the neural level with processing of syntactic violations, as evidenced by a decreased LAN amplitude at frontal electrodes. Our findings also suggest neural independence between pitch processing in melody and semantic processing in language. This study therefore enhances our understanding of neural interactions between music and language processing using a novel approach involving a probabilistic model of melodic pitch expectations, which generalizes naturally to musical traditions beyond Western tonal music.

Acknowledgements

The research is supported by the EPSRC (EP/H01294X/1). The authors are thankful to Prof. Geraint Wiggins for his useful comments. Author Contributions: EC designed the experiment, performed the data collection, analysed the data and wrote the paper; MTP invented the computational model; JB conceived the experimental design and supervised the research.

Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.cortex.2012.08.024.

REFERENCES

Ainsworth-Darnell K, Shulman HG, and Boland JE. Dissociating brain responses to syntactic and semantic anomalies: Evidence from event-related potentials. *Journal of Memory and Language*, 38(1): 112–130, 1998.

Besson M and Faita F. An event-related potential (ERP) study of musical expectancy: Comparison of musicians with non-musicians. *Journal of Experimental Psychology: Human Perception and Performance*, 21(6): 1278–1296, 1995.

Besson M, Faita F, Peretz I, Bonnel AM, and Requin J. Singing in the brain: Independence of lyrics and tunes. *Psychological Science*, 9(6): 494–498, 1998.

Delorme A and Makeig S. EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics. *Journal of Neuroscience Methods*, 134(1): 9–21, 2004.

Essl M and Rappelsberger P. EEG coherence and reference signals: Experimental results and mathematical explanations. *Medical and Biological Engineering and Computing*, 36(4): 399–406, 1998.

Fedorenko E, Patel AD, Casasanto D, Winawer J, and Gibson E. Structural integration in language and music: Evidence for a shared system. *Memory and Cognition*, 37(1): 1–9, 2009.

Friederici AD. Event-related brain potential studies in language. *Current Neurology and Neuroscience Reports*, 4(6): 466–470, 2004.

Friederici AD, Hahne A, and Mecklinger A. Temporal structure of syntactic parsing: Early and late event-related brain potential effects. *Journal of Memory and Language*, 43(3): 476–507, 1996.

Friederici AD, Steinhauer K, and Frisch S. Lexical integration: Sequential effects of syntactic and semantic information. *Memory and Cognition*, 27(3): 438–453, 1999.

Friederici AD, Meyer M, and von Cramon DY. Auditory language comprehension: An event-related fMRI study on the processing of syntactic and lexical Information. *Brain and Language*, 75(3): 289–300, 2000.

Gunter TC, Stowe LA, and Mulder G. When syntax meets semantics. *Psychophysiology*, 34(6): 660–676, 1997.

Gunter TC, Friederici AD, and Schriefers H. Syntactic gender and semantic expectancy: ERPs reveal early autonomy and late interaction. *Journal Cognitive of Neuroscience*, 12(4): 556–568, 2000.

Hagoort P. Interplay between syntax and semantics during sentence comprehension: ERP effects of combining syntactic and semantic violations. *Journal of Cognitive Neuroscience*, 15(6): 883–899, 2003.

Hahne A and Friederici AD. Differential task effects on semantic and syntactic processes as revealed by ERPs. *Cognitive Brain Research*, 13(3): 339–356, 2002.

Herholz SC, Lappe C, Knief A, and Pantev C. Neural basis of music imagery and the effect of musical expertise. *European Journal of Neuroscience*, 28(11): 2352–2360, 2008.

Herrojo-Ruiz M, Koelsch S, and Bhattacharya J. 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, 2009.

Hoch L, Poulin-Charronat B, and Tillman B. The influence of task-irrelevant music on language processing: Syntactic and semantic structures. *Frontiers in Auditory Cognitive Neuroscience*, 2(112), 2011. http://dx.doi.org/10.3389/fpsyg.2011.00112.

Huron D. *Sweet Anticipation: Music and the Psychology of Expectation*. Cambridge, MA: MIT Press, 2006.

Jasper HH. The ten-twenty electrode system of the International Federation. *Electroencephalography and Clinical Neurology*, 10: 371–375, 1958.

Jentschke S, Koelsch S, and Friederici AD. Investigating the relationship of music and language in children: Influences of musical training and language impairment. *Annals of the New York Academy of Sciences*, 1060: 231–242, 2005.

Jentschke S, Koelsch S, Sallat S, and Friederici AD. Children with specific language impairment also show impairment of music-syntactic processing. *Journal of Cognitive Neuroscience*, 20(11): 1940–1951, 2008.

Koelsch S. Significance of Broca's area and ventral premotor cortex for musics yntactic processing. *Cortex*, 42(4): 518–520, 2006.

Koelsch S. Language, music, and the brain: A resource sharing framework. In Rebuschat P, Rohrmeier M, Hawkins JA, and Cross I (Eds), *Language and Music as Cognitive Systems*. Oxford: Oxford University Press, 2012: 248–253.
Koelsch S and Jentschke S. Differences in electric brain responses to melodies and chords. *Journal of Cognitive Neuroscience*, 22(10): 2251–2262, 2010.
Koelsch S, Gunter TC, Cramon DY, Zysset S, Lohmann G, and Friederici AD. Bach speaks: A cortical "language-network" serves the processing of music. *NeuroImage*, 17(2): 956–966, 2002.
Koelsch S, Gunter TC, Wittfoth M, and Sammler D. Interaction between syntax processing in language and in music: An ERP Study. *Journal of Cognitive Neuroscience*, 17(10): 1565–1577, 2005.
Kutas M and Hillyard SA. Reading senseless sentences: Brain potentials reflect semantic incongruity. *Science*, 207(4427): 203–205, 1980.
MacKay DJC. *Information Theory, Inference, and Learning Algorithms*. Cambridge, UK: Cambridge University Press, 2003.
Maess B, Koelsch S, Gunter TC, and Friederici AD. "Musical syntax" is processed in the area of Broca: An MEG-study. *Nature Neuroscience*, 4(5): 540–545, 2001.
Maris E and Oostenveld R. Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods*, 164(1): 177–190, 2007.
Martin-Loeches M, Nigbur R, Casado P, Hohlfeld A, and Sommer W. Semantics prevalence over syntax during sentence processing: A brain potential study of noun-adjective agreement in Spanish. *Brain Research*, 1093(1): 178–189, 2006.
Meyer LB. *Emotion and Meaning in Music*. Chicago: University of Chicago, 1956.
Miranda RA and Ullman MT. Double dissociation between rules and memory in music: An event-related potential study. *NeuroImage*, 38(2): 331–345, 2007.
Oostenveld R, Fries P, Maris E, and Schoffelen JM. FieldTrip: Open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational Intelligence and Neuroscience*, 156869, 2011.
Osterhout L and Nicol J. On the distinctiveness, independence, and time course of the brain responses to syntactic and semantic anomalies. *Language and Cognitive Processes*, 14(3): 283–317, 1999.
Palolahti M, Leino S, Jokela M, Kopra K, and Paavilainen P. Event-related potentials suggest early interaction between syntax and semantics during on-line sentence comprehension. *Neuroscience Letters*, 384(3): 222–227, 2005.
Patel AD. Language, music, syntax and the brain. *Nature Neuroscience*, 6(7): 674–681, 2003.
Patel AD, Gibson E, Ratner J, Besson M, and Holcomb P. Processing syntactic relations in language and music: An event-related potential study. *Journal of Cognitive Neuroscience*, 10(6): 717–733, 1998.
Patel AD, Iversen JR, Wassenaar M, and Hagoort P. Musical syntax processing in agrammatic Broca's aphasia. *Aphasiology*, 22(7–8): 776–789, 2008.
Pearce MT. The Construction and Evaluation of Statistical Models of Melodic Structure in Music Perception and Composition. Doctoral Dissertation, , London, UK: Department of Computing, City University, 2005.
Pearce MT and Wiggins GA. Expectation in melody: The influence of context and learning. *Music Perception*, 23(5): 377–405, 2006.
Pearce MT, Herrojo-Ruiz M, Kapasi S, Wiggins GA, and Bhattacharya J. Unsupervised statistical learning underpins computational, behavioural and neural manifestations of musical expectation. *NeuroImage*, 50(1): 302–313, 2010.
Poulin-Charronnat B, Bigand E, Madurell F, and Peereman R. Musical structure modulates semantic priming in vocal music. *Cognition*, 94(3): B67–B78, 2005.
Rogalsky C, Rong F, Saberi K, and Hickok G. Functional anatomy of language and music perception: Temporal and structural factors investigated using functional magnetic resonance imaging. *Journal of Neuroscience*, 31(10): 3843–3852, 2011.
Sammler D. The neuroanatomical overlap of syntax processing in music and language: Evidence from lesion and intracranial ERP studies. *MPI Series in Human Cognitive and Brain Sciences*, 108 2009.
Slevc LR, Rosenberg JC, and Patel AD. Making psycholinguistics musical: Self-paced reading time evidence for shared processing of linguistic and musical syntax. *Psychonomic Bulletin Review*, 16(2): 74–381, 2009.
Steinbeis N and Koelsch S. Shared neural resources between music and language indicate semantic processing of musical tension-resolution patterns. *Cerebral Cortex*, 18(5): 1169–1178, 2008.
Tillmann B, Janata P, and Bharucha JJ. Activation of the inferior frontal cortex in musical priming. *Cognitive Brain Research*, 16(2): 145–161, 2003.
Verleger R. P3-evoking wrong notes: Unexpected, awaited, or arousing? *International Journal of Neuroscience*, 55(2–4): 171–179, 1990.
Wicha NYY, Moreno EM, and Kutas M. Anticipating words and their gender: An event-related brain potential study of semantic integration, gender expectancy, and gender agreement in Spanish sentence reading. *Journal of Cognitive Neuroscience*, 16(7): 1272–1288, 2004.
Winer BJ. *Statistical principles in experimental design*. 2nd ed. New York: McGraw-Hill, 1971.
Yasui T, Kaga K, and Sakai KL. Language and music: Differential hemispheric dominance in detecting unexpected errors in the lyrics and melody of memorized songs. *Human Brain Mapping*, 30(2): 588–601, 2009.
Ye Z, Luo Y, Friederici AD, and Zhou X. Semantic and syntactic processing in Chinese sentence comprehension: Evidence from event-related potentials. *Brain Research*, 1071(1): 186–196, 2006.