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Fronto-temporal theta phase-synchronization underlies music-evoked pleasantness

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ABSTRACT

Listening to pleasant music engages a complex distributed network including pivotal areas for auditory, reward, emotional and memory processing. On the other hand, frontal theta rhythms appear to be relevant in the process of giving value to music. However, it is not clear to which extent this oscillatory mechanism underlies the brain interactions that characterize music-evoked pleasantness and its related processes. The goal of the present experiment was to study brain synchronization in this oscillatory band as a function of music-evoked pleasantness. EEG was recorded from 25 healthy subjects while they were listening to music and rating the experienced degree of induced pleasantness. By using a multilevel Bayesian approach we found that phase synchronization in the theta band between right temporal and frontal signals increased with the degree of pleasure experienced by participants. These results show that slow fronto-temporal loops play a key role in music-evoked pleasantness.

1. Introduction

Listening to music is a powerful source of pleasure for most human beings. This pleasurable experience is often associated with the activation of areas of the brain reward network (Blood and Zatorre, 2001), via dopaminergic activation of the dorsal and ventral striatum in the anticipation and realization of peak pleasurable musical events, respectively (Salimpoor et al., 2011). However, music-evoked pleasantness is not only explained by reward-related striatal activation, but engages a broader neural network, including perceptual, associative and emotional areas. Indeed, the temporal lobe is crucial in the processing of auditory inputs (Koelsch, 2014) and previous studies have found that the functional interaction of this area and the ventral striatum is pivotal in giving value to musical stimuli (Salimpoor et al., 2013) and in the pleasurable experience of listening to music (Martínez-Molina et al., 2016). In addition, the prefrontal cortex also plays a role in this mechanism. The ventromedial prefrontal cortex, orbitofrontal cortex and the inferior frontal gyrus have all been related to the processing of pleasant music listening (Blood and Zatorre, 2001; Brown et al., 2004; Menon and Levitin, 2005; Koelsch et al., 2006). It has also been found that people experiencing frissons with music present higher structural connectivity between the posterior portion of the supratemporal gyrus and medial prefrontal cortex than those people that do not experience them (Sachs et al., 2016). Furthermore, a recent study has linked the structural connectivity between supratemporal cortex and orbitofrontal cortex (OFC), as well as OFC and ventral striatum, with individual differences in music-evoked pleasantness sensitivity and the activation of the Nucleus Accumbens in response to pleasant music (Martínez-Molina et al., 2019). Limbic structures such as the amygdala, the hippocampus and the insula also appear to be involved in the processing of music-evoked pleasantness (Blood and Zatorre, 2001; Koelsch et al., 2006).

Within the broader topic of music-evoked emotions, it has been revealed that more complex psychological states and their associated brain correlates underlie pleasurable reactions to music. Familiarity, high emotional valence, as well as domain-specific emotions such as wonder and joy all appear to be related to activity in the striatum, although each construct relates to slightly different cortical and limbic structures, such as the OFC, the insula or the amygdala (Trost et al., 2012). The specific acoustic features and time-courses of music appear to be important in music-evoked emotions as well. Tightly related constructs to pleasantness, such as evoked valence or dissonance, correlate with the activity of the amygdala and the Nucleus Accumbens (Trost et al., 2015). Noteworthy is the proposal by Trost and Frühholz (2015) on the role of the temporal-limbic system, which includes the amygdala and the

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hippocampus, in orchestrating affective responses to music along personal preferences, memory associations and aesthetic evaluations.

The coordination of such distant brain areas involves a complex interplay of brain interactions. In order to coordinate all these distant structures the brain needs a mechanism to couple their respective activities efficiently. Neural oscillations have been proposed to fulfill such task (Buzsáki and Draguhn, 2004). By synchronizing to the same inputs, different brain areas are able to oscillate in one or several frequency ranges, thus facilitating coordination among those areas supporting a particular function. Allegedly, it has been proposed that slower rhythms would be a neural marker of more distant brain interactions, whilst faster rhythms would imply more local synchronization due to the natural constrains posed by structural connections (Buzsáki and Draguhn, 2004).

Despite the growing body of literature unraveling the anatomic interactions supporting music-evoked pleasantness, little is known about the temporal dynamics underlying these functional networks, and the consistence among the different results is limited. Among the few, Sammler et al. (2007) observed an increase in frontal theta power during consonant music listening as opposed to dissonant music in an EEG study. Other studies have consistently reported a positive relationship between theta power and positive valence (Lin et al., 2010; Mikutta et al., 2014; Rogenmoser et al., 2016). In addition, Omigie et al. (2015) found consonant chords to be related to greater power in the theta-alpha-low beta range in intracranial electrodes placed over the OFC. Both consonance and evoked valence were considered to be related to pleasantness by the respective authors.

In the present experiment we sought to study the temporal dynamics of the brain interactions underlying music-evoked pleasantness using EEG. To this purpose, we measured phase-synchronization between EEG signals. Many different indexes are available to study phase-synchronization in EEG research, all presenting advantages and disadvantages (Bastos and Schoffelen, 2016). We chose the inter-site phase clustering (also known as phase locking value in the literature) for being easily computed over time and maximally sensitive to phase synchronization (Cohen, 2014). We focused on the theta oscillatory band since it has previously been associated with music-evoked pleasantness in the power domain (Sammler et al., 2007; Rogenmoser et al., 2016; Lin et al., 2010; Omigie et al., 2015), and because given the far-off anatomic landmarks of music-evoked pleasantness, we assume that slower rhythms would be the ideal communication mechanism of such segregated network (Buzsáki and Draguhn, 2004). Previous studies have addressed the temporal dynamics of EEG when listening to music by computing the oscillatory power of different frequency bands over time in relation to musical and emotion attributes (Jäncke et al., 2015). Nevertheless, we consider the study of phase-synchronization appropriate in the context of the current experiment given our assumptions regarding neural rhythms and anatomic interactions.

In order to analyze the data, we propose a multilevel Bayesian approach to overcome the statistical challenges of the study of the brain synchronization using EEG, in particular dealing with non-normal multilevel-structured data and multiple testing. In experimental paradigms where each participant is exposed to and responds to different stimuli there are usually two levels of inference, at the individual and the group level. Doing the analysis separately or computing summary statistics for each participant may result in information loss (Bryk and Raudenbush, 1988). Multilevel modeling tackles this by estimating effects at all levels of inference, where individual effects inform group level effects and vice-versa (Baayen et al., 2008). In addition, different response distributions can easily be implemented in this modeling framework, which allows for more appropriate analyses when the data are not normally distributed (Stroup, 2012). Finally, Bayesian inference has gained popularity in this modeling framework, as it allows to quantify epistemic uncertainty and incorporate prior beliefs to the statistical problem at hand (Kruschke, 2015).

Particularly, Bayesian inference is useful in contexts where mass-univariate models must be run, such as in EEG research, because multiple testing does not inherently pose a problem in terms of type-I error inflation. This is the case because the same null hypothesis is not tested several times under the same theoretical distribution, thus inflating the probability of rejecting it by chance. Instead, the likelihood that a parameter of interest is relevant for explaining each data set is explored, with the prior believe that the contrary is more probable, and a decision is made on whether a null effect is excluded from the resulting posterior distributions (Han and Park, 2018). Hypothesis testing thus consists in deciding whether the parameter of interest has an effect in predicting each data set after Bayes' rule is applied, rather than checking several times whether a test statistic is extreme enough under the same theoretical null distribution (Kruschke, 2015). This procedure typically results in more conservative decisions as compared to using uncorrected frequentists threshold, but less than those yielded by standard p-value corrections (Han and Park, 2018).

Therefore, the goal of the present study was to determine the oscillatory neuronal connectivity underlying the pleasurable experience associated with listening to music. Based on previous literature, we hypothesized that oscillatory activity in the theta band would play a role in this process. In addition, we also introduce a modeling framework to deal with the problems associated with multilevel responses, non-normally distributed data and multiple testing in the study of EEG synchronization.

2. Material and methods

2.1. Participants

Twenty-five right-handed individuals ($M = 22.32$ years old, $SD = 2.66$, 19 women) participated in the experiment. All participants were chosen to roughly have similar music preferences toward indie, pop, electronic and folk music genres as assessed with the Short Test of Music Preferences revised (STOMP-R, Rentfrow and Gosling, 2003; cut-off ≥ 4) as well as similar profiles of music reward and physical anhedonia as assessed with the Barcelona Music Reward Questionnaire (BRMQ, Mas-Herrero et al., 2013, cut-off > 64) and the Physical Anhedonia Scale (PAS, Chapman et al., 1976, males cut-off < 28, females cut-off < 20), respectively. None of the participant had received formal training in music for more than three years. All participants gave written informed consent and were paid 10€ per hour. All procedures were approved by the local ethical committee.

2.2. Stimuli

Sixty musical fragments formed a pool of stimuli from which the experimental excerpts were taken. The stimuli consisted in fragments of 45 s from commercially available songs of several music genres including indie, pop, electronic, folk and experimental music (see Table A.1 in the supplementary materials for the complete list of songs). These stimuli were selected to be likely unfamiliar and to elicit variable degrees of pleasantness based on the results of a pilot study with a separate sample of individuals. The 45-s fragments were chosen to be representative of the whole musical pieces (e.g. that they included more than one theme, that variations took place and/or that several instruments were present).

2.3. Experimental procedure

Participants listened to 30 music excerpts randomly drawn from the pool of stimuli to avoid effects to be explained by common musical attributes of a fixed set of stimuli across subjects. Participants were asked to rate the degree of evoked pleasantness on a continuous basis while listening to each excerpt with as many responses as they wanted. Responses were given via the numeric keys of a computer keyboard with the following equivalences: 1: 'I don't like it'; 2: 'I like it a little'; 3: 'I like it moderately'; 4: 'I like it a lot'; and 5: 'I experience frissons'. Response keys had to be held for as long as a particular rating applied for the individual. Participants had to look to a fixation cross during the course of the excerpts. If no response was given after half the stimulus was presented, that trial was halted and automatically rejected. After each excerpt had finished participants responded to a series of 7-point likert scales: the overall liking for the musical fragment, its evoked valence and arousal, its perceived familiarity and the number and intensity of frissons, if experienced. Only the overall liking item is used in this study, where 1 meant ‘I despise this song’ and 7 ‘I love this song’. Exceptionally, one participant listened to all 60 excerpts. In order to make data from this participant comparable to the rest of the sample, only the first 30 excerpts were considered for this participants.

2.4. *Self-reported data*

In order to have a metric index of online evoked pleasantness we computed the average of every response given for each excerpt weighted by the amount of time each response was held. This index was compared to the overall liking likert scale in order to be validated.

2.5. *EEG data acquisition*

EEG was recorded from the scalp (0.01 Hz high-pass filter with a notch filter at 50 Hz; 250 Hz sampling rate) using a BrainAmp amplifier with tin electrodes mounted on an Easycap (Brain Products©), at 61 standard positions (Fp1/2, AF3/4, Fz, F7/8, F5/6 F3/4, F1/2, FCz, FT9/10, FT7/8, FC5/6, FC3/4, FC1/2, Cz, T7/8, C5/C6, C3/4, C1/2, CPz, TP9/10, TP7/8, CP5/6, CP3/4, CP1/2, Pz, P7/8, P5/6, P3/4, P2/1, POz, PO7/8, PO3/4, Oz, O1/2) and left and right mastoids. An electrode placed at the lateral outer canthus of the right eye served as an on-line reference and an electrode at the infraorbital ridge of the right eye was used to monitor vertical eye movements. Electrode impedances were kept below 10 kΩ during the whole session.

2.6. *EEG signal processing*

EEG was re-referenced off-line to the linked mastoids and band-pass filtered from 0.1 to 45 Hz. Subsequent processing steps are depicted in Fig. 1. Epochs consisted in the whole time frame of each listening and were baseline-corrected using the average of the whole time window. Artifacts in these epochs were identified and corrected using independent component analysis (ICA). Epochs with absolute mean amplitude higher than 100 μV after ICA correction were rejected. Three subjects were excluded from the analysis because of poor physiological data quality. The surface laplacian transform was applied to these data in order to reduce volume conduction and make the data reference-free (Perrin et al., 1989). To avoid effects of surprise at the beginning and end of the song, the first and last 2 s were removed from the epochs for subsequent analysis. Time-frequency decomposition was computed on each epoch using 5-cycle complex Morlet wavelets in the frequency band of interest (θ: 4–8 Hz). Phase values for each electrode and frequency were obtained over time from this decomposition.

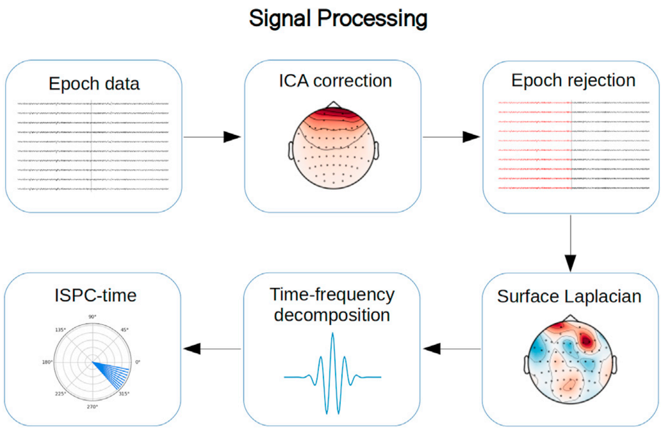

Fig. 1. Signal processing diagram.

The inter-site phase clustering (ISPC) over time was computed for each epoch as an index of phase synchronization between signals. This index describes the consistency in phase difference between two signals over time and is defined as:

$$ISPC_f = \left| n^{-1} \sum_{t=1}^{n} e^{i\left(\varphi_i - \varphi_j\right)} \right| \qquad 1)$$

where f is a given frequency, n is the number of time points and ϕ_{xt} and ϕ_{yt} are the phases of two given signals at a given time point (Cohen, 2014). This was done for every frequency and every combination of two electrodes. Finally, ISPCs were averaged across frequencies. We excluded from subsequent analysis connections involving peripheral electrodes (Fp1, Fp2, FT9, FT10, TP9 and TP10) and connections where the two electrodes were less than 6 cm apart from each other, since these most likely reflect residual artifactual activity and volume conduction, respectively. This reduced the number of analyzed connections from 1830 to 1289.

2.7. *Statistical analysis*

In order to validate the time-weighted reported pleasantness measure, a generalized Bayesian multilevel linear model with this index as response variable, overall liking as explanatory variable and varying intercepts and slopes per subject was performed. A student-t likelihood function was assumed to explain the data in order to accommodate outliers (μ: identity; prior on σ: student-t, $\mu = 0$, $\sigma = 10$, $\nu = 3$; prior on ν: gamma, $\alpha = 2$, $\beta = 0.1$). Weakly informative priors were placed over the intercept and slope (normal, $\mu = 0$, $\sigma = 1$), as well as over the varying effects (gamma, $\alpha = 2$, $\beta = 2$). To test the group-level slope to be non-zero a 95% highest density interval (HDI) was used to check the inclusion of the null hypothesis (H_0: $\beta_1 = 0$) in the posterior assuming a region of practical equivalence (ROPE) of ±0.01 (Kruschke, 2015). The reported point estimate (β_1) corresponds to the mode of the posterior. The Bayes factor for this parameter estimate (i.e Savage-Dickey density ratio; Dickey, 1971) is also reported.

In order to investigate the relationship between reported pleasantness and phase synchronization in θ, mass-univariate Bayesian multilevel beta regression models with ISPCs as response variables, (standardized) time-weighted reported pleasantness as explanatory variable and varying intercepts and slopes per subject were performed for every two-electrode combination. A beta likelihood function with the logit link function was assumed to explain the data (μ: logit(x); prior on ϕ: gamma, $\alpha = 0.01$,

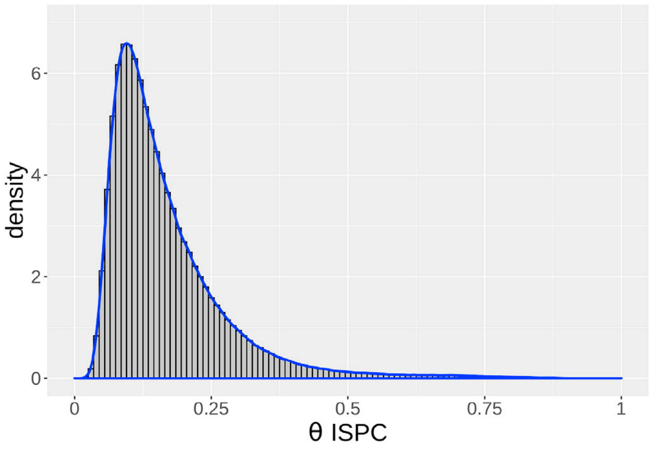

Fig. 2. Distribution of ISPC values in θ pooled across subjects and connections. The histogram and its overlying line represent the values’ densities.

$\beta = 0.01$), since ISPC values are non-normally distributed in the unit interval (Fig. 2). Weakly informative priors were placed over the overall intercepts and slopes (normal, $\mu = 0$, $\sigma = 1$), as well as over the varying effects (gamma, $\alpha = 2$, $\beta = 2$). Before the analysis was performed, bivariate outliers per connection and subject were identified and removed using bagplots (Rousseeuw et al., 1999). To test the group-level slopes to be non-zero a 95% HDI was used to check the inclusion of the null hypothesis (H_0: $\beta_1 = 0$) in the posteriors assuming a ROPE of ± 0.01. Reported point estimates correspond to the mode of the posteriors. Bayes factors for parameter estimates are also reported.

Posterior distributions were approximated using 5 markov chains of 1000 samples with no thinning, burning-in the first 200 samples. The No-U-turn sampler algorithm was used to draw samples. All chains were initialized at 0. All models converged as indicated by Gelman's split-R-hat equaling 1 (Gelman et al., 2013).

3. Results

3.1. Self-reported data

The distribution of the time-weighted reported pleasantness index per excerpt and subject is displayed in Fig. 3. Fig. 4 shows the relationship between time-weighted reported pleasantness and the overall liking likert scale for every individual (thin blue lines) as well as at the group level (thick black line). Time-weighted reported pleasantness was highly predicted by the overall liking scale at the group level ($\beta_1 = 0.52$, 95% HDI = 0.49–0.55, BF = $5.32 \cdot 10^{35}$). Thus, this on-line continuous index is consistent with an overall recall measurement of evoked pleasantness.

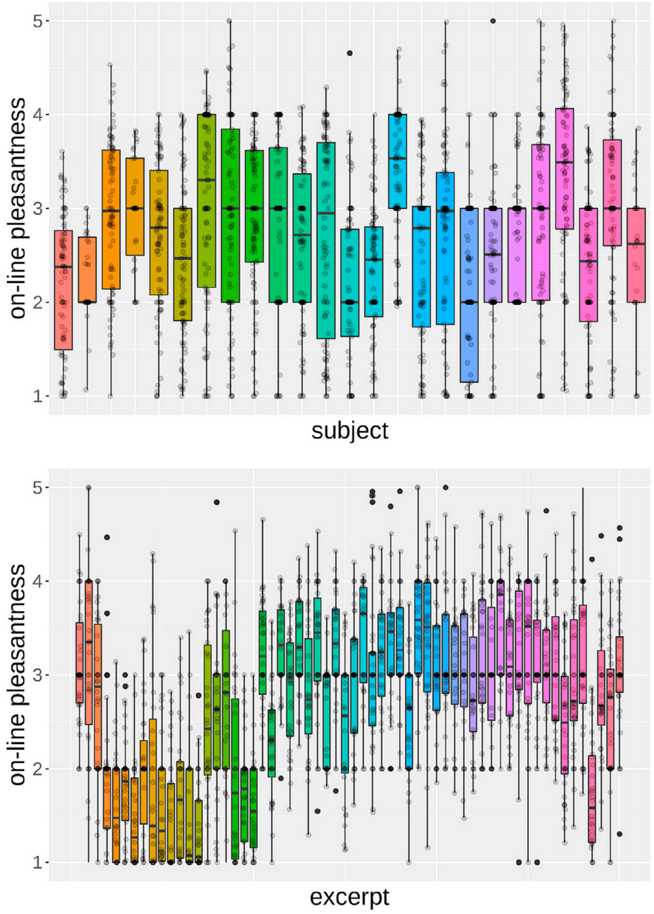

Fig. 3. Distribution of time-weighted self-reported pleasantness per subject (top) and excerpt (bottom).

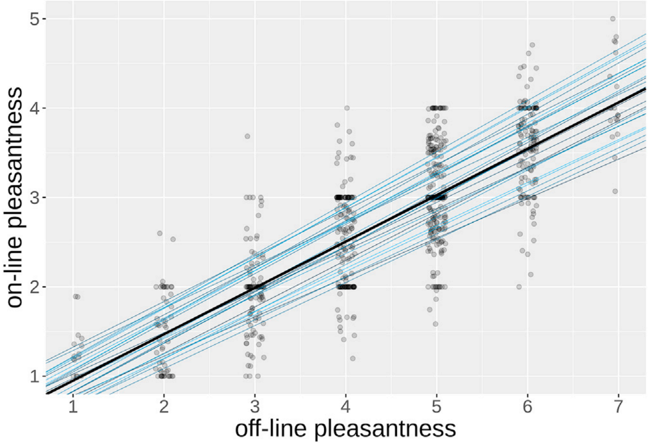

Fig. 4. Time-weighted (on-line) self-reported pleasantness regressed on likert scale (off-line) self-reported pleasantness. Thin blue lines represent each participant's regression line. The thick black line represents the group-level regression line. Observations (jittered) are shown for illustration purposes.

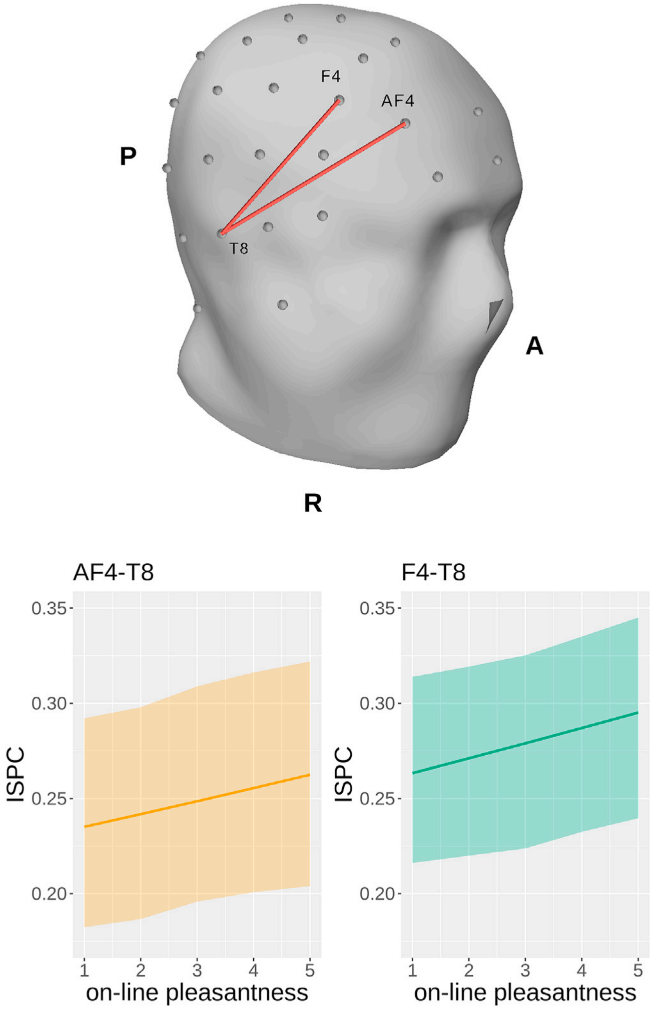

Fig. 5. Non-zero connections in θ (top) and their corresponding prediction plots (bottom). Straight lines and their ribbons represent predictions of the response variables at each value of the explanatory variable following parameter estimates and their 95% HDIs, respectively. Predictions are made on the original scale of the variables.

3.2. EEG phase synchronization

Fig. 5 shows the non-zero results of the phase-synchronization analysis in θ. Two non-zero right fronto-temporal connections showed an increase in synchronization with greater degrees of reported pleasantness at the group level (AF4-T8: $\beta_1 = 0.04$, 95% HDI = 0.02–0.06, BF = 3.42; F4-T8: $\beta_1 = 0.04$, 95% HDI = 0.02–0.06, BF = 11.01). Coefficients are expressed in log-odds.

In order to compare these results with standard frequentist approaches, we represented the results of the mass-univariate regressions using different frequentist alpha levels (see Figure A1 in the supplementary materials). As it can be seen, an uncorrected alpha level of 0.05 yields several connections, which are reduced if the alpha level is more restrictive. Only the rather arbitrary alpha level of 0.001 yields the same results as the proposed Bayesian approach. Importantly, none of the connections survived standard Family Wise or False Discovery Rate corrections, deemed too restrictive. Therefore, in contrast to the use of an arbitrary p-value or overly restrictive corrections to amilloriate the multiple testing problem, the proposed Bayesian approach yields non-inflated results with uncorrected inference standards.

4. Discussion

The goal of the present experiment was to study the temporal dynamics of the brain interactions underlying music-evoked pleasantness. To this purpose, we analyzed the relationship between phase synchronization of EEG signals in an oscillatory band of interest (theta) and reported pleasantness in a multilevel design where each participant listened to and rated several music stimuli.

We found increased synchronization between right temporal and right frontal nodes with higher degrees of reported pleasantness. These results are in agreement with previous findings showing the involvement of a cortical network associated with the process of giving value to music, which includes temporal and frontal areas (Salimpoor et al., 2013; Sachs et al., 2016; Martínez-Molina et al., 2019). In addition, frontal and parietal activations have been found in emotional control, both in reaction to music (Rogenmoser et al., 2016), and in general (Heller, 1993; Davidson, 2004). Interestingly, frontal and temporal areas have also been related to recognition processes during music listening, and to recognition of positively valenced music in particular (Altenmüller et al., 2014). Indeed, memory retrieval and working memory in musical contexts are tightly related to frontal function (Zatorre et al., 1994; Zatorre et al., 1996; Halpern and Zatorre, 1999; Zatorre and Halpern, 2005) and emotional processing (Eschrich et al., 2008). The results are also consistent with previous findings on the right hemispheric dominance in music processing (Zatorre and Gandour, 2008; Zatorre et al., 2002; Hyde et al., 2008; Ozdemir et al., 2006; Martínez-Molina et al., 2016). Nevertheless, it is important to note that there is also evidence showing that inter-hemispheric interactions are necessary for normal music processing (Schuppert et al., 2000), as well as research showing no hemispheric specialization (e.g. Jäncke and Alahmadi, 2016).

In a different line of research, phase synchronization between temporal and frontal nodes has also been found in theta during auditory working memory tasks (Kaiser, 2015). Working memory, in turn, has been hypothesized to play an important role in music-evoked pleasantness, as it would allow the formation of musical patterns and multi-modal structures that go beyond single auditory events (Zatorre and Salimpoor, 2013). Low-frequency synchronization between temporal and frontal nodes has also been related to auditory and musical prediction error computation (Recansens et al., 2018; Omigie et al., 2019). Different accounts have proposed a key role of expectancies and prediction errors in the pleasurable experience of listening to music. For example, Salimpoor et al. (2015) proposed that the process of listening to music involves the generation of expectancies. The resolution of such expectancies would induce prediction errors which would be coded by dopaminergic neurons in a similar way as reward prediction errors. Regarding this latter interpretation, however, it must be noted that not all studies report activation in reward core areas, at least when studying the broader construct of evoked valence (e.g. Trost et al., 2015).

Although in this study we focused on theta, it must be noted that other frequency bands have been related to music listening elsewhere. For instance, the alpha band has been found to increase in power during music perception (Sammler et al., 2007; Bumgartner et al., 2006). In addition, faster rhythms such as beta and gamma oscillations also exhibit an increase in power during music perception (Sammler et al., 2007; Martin et al., 2018). Future studies could be devoted to exploring these bands using appropriate settings (specially in the case of high-frequency analysis). On the other hand, frontal theta rhythms also appear to modulate evoked arousal, in addition to valence, suggesting a possible interaction between the two emotional dimensions (Sammler et al., 2007; Mikutta et al., 2012; Mikutta et al., 2014).

An important novelty of this study is the Bayesian multilevel models used to analyze the data. The application of this methodology had a double pursuit: first, the multilevel structure of the models allowed us to analyze the data taking into account both levels of inference (individual and group) simultaneously. This framework also allowed the adoption of appropriate assumptions about the distribution of the data (e.g. that ISPC values follow a beta distribution). Second, the use of this approach ameliorated the multiple testing problem by virtue of the statistical properties of Bayesian estimation.

Another methodological issue that we addressed is how music-evoked pleasantness was operationalized. In most previous related literature, music-evoked pleasantness is assumed to be related to the positive end of the valence dimension in a circumflex model of emotion (e.g., see Lin et al., 2010 or Rogenmoser et al., 2016). Whilst this holds true for most research in emotion, evoked pleasantness is sometimes found to be dissociated from valence in musical contexts (e.g. liking sad music, Sachs et al., 2015). This dissociation has often been attributed to the difference between perceived emotions (i.e. emotions identified by the listener) and evoked emotions (i.e. emotions evoked in the listener; Kawakami et al., 2014). According to this view, pleasant feelings to music belong to the realm of evoked emotions. This would justify paradigms using (evoked) valence to measure pleasantness. However, this dissociation can also be observed within evoked emotions themselves (e.g. liking music that makes one sad), which has motivated a different theoretical framework to resolve this confound. Schubert (2013) explains that in musical contexts evoked valence can be further broken down into two distinct dimensions, namely emotion valence (i.e. emotions felt by the listener) and affect valence (i.e. approach/avoidance toward these emotions). From this standpoint, if the researcher seeks to study pleasant/unpleasant responses to music independently of the emotions evoked, music-evoked pleasantness should be operationalized as affect valence. Sammler et al. (2007) and Omigie et al. (2015) did so in using consonant and dissonant music as proxies for pleasant and unpleasant music. Nonetheless, because of the previously mentioned idiosyncrasies, individual differences may arise in such paradigms, where some people may like or dislike the music employed to a different extent, or even dislike/like music thought to be pleasant/unpleasant by the researcher. We argue that continuous self-reported pleasantness ratings, albeit subjective and less controlled, are better suited to capture these nuances regardless of emotion valence and music preferences. Although continuous ratings have been demonstrated to influence the extent to which neural signals respond to music and its associated states (Markovic et al., 2017), they seem well suited to study evoked emotions in musical contexts, where these most likely vary as music dynamics unfold (Arjmand et al., 2017).

The present study also presents a number of limitations. One of the most important is the low spatial resolution of EEG and its incapacity to capture subcortical signals. Nonetheless, it is clear from the literature that the striatal and limbic systems are pivotal in the process of giving value to music. The techniques here employed thus offer an incomplete picture of the brain mechanisms involved in such function. Subsequent studies must address this by combining different technical modalities, such as simultaneous EEG-fMRI recordings. This approach would benefit from both the good temporal resolution of EEG and the good spatial resolution of fMRI, providing a more complete picture of the processes studied. Furthermore, the fact that subjects evaluated the stimuli while listening to them might have imposed an active listening strategy, which could have influenced our results and interpretations (Jäncke et al., 2018). Yet another limitation is the fact that we studied the overall temporal dynamics of the music fragments, being these portions of their complete counterparts, rather than their specific time-courses over the whole pieces. The related acoustics and emotional features and how they unfold over longer periods of time can offer a rich and complementary view on the study of music-evoked pleasantness (e.g. Arjmand et al., 2017; Sturm et al., 2014; Sturm et al., 2015; Jäncke et al., 2015; Martin et al., 2018).

5. Conclusions

In summary, the pleasurable experience associated with listening to music is associated with interactions between right temporal and frontal areas with theta rhythms as means of communication. This functional and anatomical interplay adds up to existing literature showing the involvement of frontal and temporal areas and theta rhythms in the process of giving value to music and its related neuropsychological mechanisms. The latter must be furthered researched using more controlled paradigms and finer grained operationalizations, as well as multimodal neuroimaging techniques.

CRediT authorship contribution statement

Alberto Ara: Conceptualization, Methodology, Investigation, Formal analysis, Software, Writing - original draft, Visualization. **Josep Marco-Pallarés:** Conceptualization, Methodology, Formal analysis, Writing - review & editing, Supervision, Funding acquisition.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuroimage.2020.116665.

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