Listening to familiar music induces continuous inhibition of alpha and low-beta power

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[*] INTERACT: Brain-To-Sound Computer Interfaces: Neurofeedback of Music for Entrainment, Interaction and Neurorehabilitation" http://www.igsse.gs.tum.de/index.php?id=85

Abstract. How the brain responds temporally and spectrally when we listen to familiar versus unfamiliar musical sequences remains unclear. This study uses EEG techniques to investigate the continuous electrophysiological changes in the human brain during passive listening to familiar and unfamiliar musical excerpts. EEG activity was recorded in twenty participants while passively listening to 10 seconds of classical music, and they were then asked to indicate their self-assessment of familiarity. We analyzed the EEG data in two manners: familiarity based on the within-subject design, i.e., averaging trials for each condition and participant, and familiarity based on the same music excerpt, i.e., averaging trials for each condition and music excerpt. By comparing the familiar condition with the unfamiliar condition and local baseline, sustained low-beta power (12-16 Hz) suppression was observed in both analyses in frontocentral and left frontal electrodes after 800 ms. However, sustained alpha power (8-12 Hz) decreased in frontocentral and posterior electrodes after 850 ms only in the first type of analysis. Our study indicates that listening to familiar music elicits a late sustained spectral response (inhibition of alpha/low-beta power from 800 ms to 10 s). Moreover, the results showed alpha suppression reflects increased attention or arousal/engagement due to listening to familiar music; nevertheless, low-beta suppression exhibits the effect of familiarity.

Keywords: music, familiarity, dynamic brain response, alpha-beta power, EEG

New & Noteworthy

This study differentiates the dynamic temporal-spectral effects during listening to 10 s of familiar music compared to unfamiliar music. This study highlights listening to familiar music leads to continuous suppression in the alpha and low-beta bands. This suppression starts around 800 ms after the stimulus onset.

Introduction

People can discern a given musical sequence either as familiar (if they have heard it before and remember it) or as unfamiliar (if they listen to the sequence for the first time or do not remember it) under passive listening conditions. The concept of music familiarity thus refers to listening to known music that conveys a strong feeling of familiarity (Freitas et al., 2018). The feeling of familiarity relies on the subjective judgment of long-term memory content for the identification of items (e.g., auditory or musical sequences) based on their previous occurrence (Plailly et al., 2007). Moreover, listening to familiar or unfamiliar music requires the integration of auditory information over time (Green et al., 2018). Thus, the study of dynamic brain responses to familiar versus unfamiliar musical stimuli is one angle to obtain a better understanding of auditory sequence processing, because the process of familiarization with musical sequences involves brain mechanisms including memory formation, anticipation, and prediction (Leaver et al., 2009).

Related neuroimaging work

Brain responses to familiar versus unfamiliar musical stimuli have been studied mainly with neuroimaging techniques, such as functional magnetic resonance imaging (fMRI), in human volunteers (Freitas et al., 2018; Halpern, 1999), although the same techniques can also be applied to study the familiarity of sound sequences in animals' brains (Archakov et al., 2020). Due to the relatively high spatial resolution of fMRI, these studies allow pinpointing the involved brain regions during listening to familiar music, which includes the activation of the supplementary motor area (SMA), prefrontal cortex (PFC), and posterior parietal cortex (PPC). During listening to familiar music, SMA and PFC are responsible for predicting, anticipating, imaging, and processing upcoming sequential tones, while PPC is responsible for retrieving the stored information (Nan et al., 2008; Nyberg et al., 2000; Rauschecker, 2011). Previous findings highlighted the engagement of the SMA during perceptual listening to familiar music from native cultures (Nan et al., 2008), pop/rock song excerpts (Pereira et al., 2011), and familiar musical themes (Peretz et al., 2009) compared to unfamiliar ones. Moreover, some studies focused on the comparison between the perception and imagery of familiar music in the brain. The results of these studies demonstrated that SMA, pre-SMA, and PFC are activated under both conditions (Halpern, 1999; Herholz et al., 2012; Leaver et al., 2009; Rauschecker, 2011; Rauschecker & Scott, 2009), which indicates considerable overlap of brain activity during perception and imagery of familiar music due to memory retrieval (Zatorre et al., 1996). Hearing familiar sound sequences involves the recovery of stored information in the brain, which is referred to as memory retrieval (Nyberg et al., 2000). Studies have shown that the PPC, especially the precuneus, is associated with memory retrieval (Buckner et al., 1996; Klostermann et al., 2009; Nyberg, 1998) as well as episodic memory tasks (Wagner et al., 2005). Correspondingly, studies substantiated the engagement of posterior cortical regions (e.g., precuneus and posterior cingulate cortex) in representing responses to familiar pieces of music (Janata, 2009; Plailly et al., 2007). In comparison to their localization, the dynamic nature of brain responses to familiar versus unfamiliar music sequences over time has received less attention.

Related EEG-based work

With its high temporal resolution, electroencephalography (EEG) is utilized in many studies to feature the temporal and spectral responses related to the hearing of incoming auditory stimuli. These responses are analyzed via methods to extract time-frequency response (TFR) and the event-related potentials (ERPs) method to extract evoked responses upon stimulus onset. Analysis of the

TFR provides information about sustained spectral and temporal characteristics of neuronal activity in the brain. Measurement of the ERP in EEG signals allows accurate quantification of the temporal characteristics of neural activity (Friedman & Johnson Jr, 2000).

Several studies have indicated that music familiarity is related to the occurrence of large positive/negative ERP peaks around 400 ms, named P300/N400, in the fronto-central or posterior-central dimensions while listening to familiar but not to unfamiliar music (Calma-Roddin & Drury, 2020; Daltrozzo et al., 2010; Kemal Arikan et al., 1999; Zhu et al., 2008). Studies showed that P300 components following the effect of early right-anterior negativity (ERAN) component were modulated by the degree of predictability (Koelsch et al., 2019). However, as Koelsch (Koelsch et al., 2019) explained, the ERAN is linked to unexpected chords, errors, and irregularities in syntactic mechanisms in language and music, which located in the right frontal lobes and usually appears around 150ms after listening to stimuli (Koelsch, 2009; Koelsch et al., 2000; Sammler et al., 2013). This effect is not related to familiarity and unfamiliarity. Therefore, the examination of the ERAN is beyond the scope of the paper.

In addition to time-locked responses, previous studies mentioned that alpha modulation is related to aspects of music processing (Ross et al., 2022; Schaefer et al., 2011). This modulation of alpha power can increase or decrease depending on the task. For example, decreased alpha power was found in response to musical-syntactic irregularities between the right fronto-central and left temporal brain regions (Ruiz et al., 2009). Similarly, decreased alpha power was found at the left frontal electrode (F3) while listening to happy music (Tsang et al., 2001), whereas musical imagery generally elicited an increase of alpha power that is significantly stronger in posterior electrodes than alpha activation during perception of music (Schaefer et al., 2011).

Current study

Even though several studies have been conducted to localize the areas involved during passive listening to familiar and unfamiliar musical sequences, the specific characteristics (e.g., temporal and spectral dynamics) of brain activities remain understudied. For example, it is still unclear how alpha power, as well as other brainwave rhythms, are spectrally altered during listening to music as a function of familiarity. Moreover, although attempts have been made to explore temporal characteristics of gradual familiarization with novel music (Malekmohammadi et al., 2023), the temporal characteristics of the brain oscillations during listening to familiar versus unfamiliar music have not been a focus of past research. If we interpret an event-related attenuation of power compared to the local baseline in a specific frequency band as inhibition **(Takemi et al., 2013)** and an event-related intensification of power compared to the local baseline as excitation, it is not clear when the excitation or inhibition of the oscillations starts. More importantly, the sustainability of excitation or inhibition is not well understood. This information can be used for future connectivity analysis to explore the long-term connections between different areas of the brain as well as neural encoding based on the high-order processing of audio or music (Daly et al., 2014; Di Liberto et al., 2015). In other words, there is a lack of research that can confirm the consistency of oscillatory effects during listening to music. Thus, this paper focuses on the dynamic temporal-spectral effects of passive listening to excerpts in which participants determine the level of familiarity with musical sequences by indicating their self-assessment of familiarity. In this regard, we present an experimental paradigm exposing human volunteers to passive listening of 10-s-long familiar (i.e., previously heard) and unfamiliar (i.e., heard for the first time) music excerpts. The paradigm we designed, which is sometimes called the old-new recognition paradigm (Joordens et al., 2008), refers to the conscious retrieval of information or items that have been stored in memory for a long period (i.e., hours, months, and years) (Slotnick, 2017). We used

EEG techniques to explore the dynamics of brain activity, to identify the temporal-spectral characteristics, to investigate instantaneous variations of these frequencies related to hearing familiar and unfamiliar musical sequences, and to complement existing findings from neuroimaging studies. This study contributes to our knowledge in the following way:

1) We examined different spectral effects during listening to familiar versus unfamiliar music. We expect to observe the different oscillatory responses in at least the alpha band according to previous EEG studies which were based on the short (less than 2 s) passive listening to or imaging of musical sequences (Ross et al., 2022; Ruiz et al., 2009; Schaefer et al., 2011).

2) More importantly since our main goal was to determine the continuing changes of spectro-temporal responses, this study went beyond previous studies by determining whether or not different spectral modulation occurs continuously during the whole 10 s of listening to familiar versus unfamiliar music.

Materials and Methods

Participants

A homogeneous population of twenty healthy male volunteers (see SI, Figs S6-S7 for the justification of sample size), comprising staff and students from the Technical University of Munich and members of the public, between 21 and 39 years of age (mean = 29.10, SD = 4.40) with natural or corrected-to-normal vision (wearing glasses) and without any history of hearing impairment or psychiatric disorders (according to self-reports) were recruited for this study. They were right-handed and had no neurological problems. All of them were non-musicians. Non-musicians are defined in this study as having no more than 3 years of musical training and engaging in no current musical activity (Doelling & Poeppel, 2015). Seventeen out of 20 participants had no background in music theory/music education, nor were they playing any musical instruments. The other three had not played any instrumental music for more than seven years. This paper only focuses on the effect of familiarity with music on neural activity. Thus, we decided to remove all the possible parameters that might influence neural activity such as gender and musical background. Regarding selecting a single gender, previous studies mention that men and women show different brain responses to passive listening to music for syntactic, emotional, and structural processing (Goshvarpour & Goshvarpour, 2019; Koelsch et al., 2003; Nater et al., 2006; Sergeant & Himonides, 2014; Thorpe et al., 2012). Therefore, in the current study, we elected to focus on one single gender (i.e., men) since previous studies demonstrated that women tend to exhibit hypersensitivity to some music stimuli, and brain responses are raised during listening to arousing and unpleasant stimuli in women rather than men (Goshvarpour & Goshvarpour, 2019; Nater et al., 2006). Regarding musical background, previous studies have shown that changes in neural activity of musicians' brains are different compared to non-musicians (Liang et al., 2016; Sobierajewicz et al., 2018; Stupacher et al., 2017; Zhao et al., 2017). The reason is musicians are familiar with the musical instrument or music theory. In other words, musicians have prior knowledge during listening to any music, even novel ones, which contradicts the goal of this study i.e., being unfamiliar with music (listening to unknown music). Thus, we decided to only choose non-musicians.

The Ethics Committee at the Technical University of Munich approved the experimental research protocol (reference number 365/19 S). A consent form was signed by all individual participants before the experiment. All volunteers were given moderate monetary compensation for their participation.

Stimuli

Participants performed one experimental task by passively listening to 85 different excerpt pieces via a Sennheiser momentum 2 headphone (with a 3.5 mm Jack plug) while sitting in a comfortable chair and looking at the monitor located in front of them. Each excerpt took 10 s to cover a reasonable period of stimuli and to monitor the dynamic variation of frequencies over time (Popescu et al., 2004; Sridharan et al., 2007). To have a better quality of sound, an AVID MBOX 3 MINI was utilized as an interface to connect the headphone to the PC. All songs consisted chiefly of examples from the classical genre and covered a broad range of instruments (e.g., piano, violin, or drum) and composers (e.g., Beethoven, Mozart, Chopin, Bach, and Tchaikovsky). All songs included no human voices. Listening to human voices causes the paradigm more complicated because of involving specific speech-related information processing, such as semantics, phonetics, and phonemes. The beginning of music excerpts, which comprised only silent or slowly rising parts of the instrument, was removed. The loudness of all musical excerpts was normalized to -1 dB by matching the peaks in the signal, however, no other manipulation of the audio was performed, to keep it as close to the original music as possible. Moreover, since loudness is the subjectively perceived intensity of a sound (Waye, 2011), participants were allowed to adjust the volume of the music playback to a comfortable level while listening to six different classical excerpts before the start of the experiment.

Protocol

The experiment was started according to the protocol illustrated in Figure 1A. The duration of the resting period between each trial varied between 3000 ms and 4500 ms to avoid any habituation to the onset of the upcoming event. Then, one excerpt out of the 85 music excerpts was randomly played. After listening to each excerpt, participants were asked to indicate their familiarity by self-assessment using a Likert Scale from 1 (unfamiliar) to 7 (familiar). The question was: How familiar or unfamiliar is the excerpt to you? The participants were asked to choose "5, 6, or 7" when they knew the whole excerpt and could anticipate what tones come next; in contrast, when they were unfamiliar with the excerpt (i.e., they had not heard the excerpt before), participants were instructed to answer ''1, 2, or 3''. In other words, pressing a number higher than 4 denotes that they were more familiar with the melody. Pressing a number lower than 4 denotes that they felt the music was more unfamiliar. Pressing the number "4" means the participants did not pay attention to the excerpt or they were not sure about their familiarity with the excerpt. Before pressing any buttons, they mentioned the name of the composer, the title of the music, or the place/time they had heard the music. This information is helpful to make sure that the participants did not press random numbers and kept their attention on the music. We did not use this information (episodic information) in the analysis. A complete list of the music excerpts used in this study is provided in SI, Table S1[†]. The experiment was divided into 6 blocks of 15 excerpts each. Listening to fifteen music excerpts almost took five minutes depending on the time of participants' feedback. After each block, there was a break after listening to fifteen music excerpts to prevent exhaustion and body fatigue. Participants could take a short break for refreshment.

EEG Recording and Preprocessing

EEG data were acquired with a Brain Products actiChamp amplifier equipped with 52 gel-based electrodes (Fp1, Fp2, AF3, AF4, F7, F5, F3, F1, Fz, F2, F4, F6, F8, FT9, FT7, FC5, FC3, FC1, FCz, FC2, FC4, FC6, FT8, FT10, T7, C5, C3, C1, Cz, C2, C4, C6, T8, TP7, CP5, CP3 CP1, CPz, CP2, CP4, CP6, TP8, P7, P5, P3, Pz, P4, P6, P8, O1, Oz, O2). All electrodes were placed in accordance with the 10-10 international system, and a ground electrode was placed 1.5 cm in front

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[†] Supplementary Information link: https://figshare.com/s/015e3e3bfc1b091ea204

of the fronto-central area corresponding to the location of electrode Fpz. Two electrodes (TP9-TP10) were placed behind the ears (linked mastoids) as references. Three electrodes, utilized to capture the vertical and horizontal electrooculograms (EOG), were placed in the center of each participant's forehead and below the right and left outer canthi. Participants were asked to keep their heads still and avoid chewing on gum, mumbling to themselves, or any other movement. Furthermore, careful monitoring during recording was performed by the examiner to identify bad trials and artifacts. EEG was recorded at a sampling rate of 1000 Hz to have a superior temporal resolution. The impedance levels of all electrodes were kept below 15 KΩ throughout the experiment to make sure the signal-to-noise ratio was high enough. No filtering was applied during the recording. The data were transferred via USB to a separate recording PC (Intel® Core™ i5 CPU 750@2.67 GHz). All analyses were performed in the Matlab environment using FieldTrip (Oostenveld et al., 2011) (http://www.fieldtriptoolbox.org/). The continuous raw data were passed through a zero-phase (forward-reverse) low-pass Butterworth filter (the order was four) using a cut-off frequency of 90 Hz. A zero-phase high-pass Butterworth filter (fourth order) was then applied with a cut-off frequency of 0.5 Hz. In addition, a zero-phase notch filter at 50 Hz was applied to remove line noise. Then, after careful monitoring of all trials to select an appropriate baseline (i.e., not including any trace of artifact), we segmented data into stimulus time-locked epochs ranging from -2 s to 11.5 s.

Independent component analysis (ICA) was applied once to the all-segmented data, to identify artifacts (e.g., eye blink, eye movement, and muscle activity), which could not be eliminated by the filter procedures. In this study, the SOBI-ICA as implemented in Fieldtrip was chosen due to its superior performance. Since SOBI is a second-order blind source separation technique, it is more accurate to remove EOG and electromyography artifacts and to preserve more brain activity compared with higher-order statistical techniques such as INFOMAX, FastICA, and Jade (Joyce et al., 2004; Romero et al., 2008). Independent components that were visually assessed as artifacts were removed according to the basic summary statistics. All ICA components were monitored, and then the suspicious ones were removed (removed components across the participants: mean: 12.11, SD: 6.12). Moreover, epochs containing high variance (>250 μV^2) and high kurtosis (>14) were eliminated using the visual artifact rejection tool implemented in Fieldtrip. On average, less than 3 percent of the 85 trials were removed for each participant (mean = 2.72%, SD = 1.63). Trials with label 4 were removed from further processing since they indicate no attention to music or not being confident about their familiarity with the music. Overall, the standard deviation of all removed trials (noisy trials plus trials corresponding to label 4) was less than 7.5 percent across the participants. In the end, 72 percent of trials were kept on average. In other words, since the number of trials in each condition changes for each participant, on average, 30.43 trials are kept for further analysis per participant and condition.

ERP Analysis

As mentioned before, previous studies confirmed that listening to familiar music leads to an increased amplitude at 400 ms (i.e., P300) after listening in fronto-central areas. Although ERP analysis is not our focus in the paper, performing ERP analysis and comparing the similarity between our ERP results and previous studies suggest the reliability of the data. The results of the ERP analysis as well as the statistical analysis linked to ERP results are explained in the supplementary information.

Time-Frequency response (TFR) and Frequency response (FR): Within-subject design

We calculated the time-frequency response (TFR) for each trial to obtain spectral and temporal information on brain responses. Then, we averaged TFR over time, such as the listening period or the local baseline, and also over frequency bins to calculate the frequency response (FR) of each frequency band related to the conditions (i.e., familiar, and unfamiliar) and the baseline (see Figure 1B). The following explains the procedure of TRF and FR calculation in detail.

TFR: TFR was calculated using Fieldtrip's multi-taper convolution method (mtmconvol) (Kinney-Lang et al., 2019; Oostenveld et al., 2011) for each frequency (75 frequency bins; from 3 to 40 Hz with resolution of 0.5 Hz), each electrode (51 electrodes in total), and each sample time with a window display length of 0.5 s (221 samples in total from -1 to 10 s) using Hanning tapers after applying baseline correction on all trials by selecting a window in the range of -200 ms to -1 ms in the time domain ($X = X - \bar{X}_{(from-200\,to-\quad ms)}$). The extracted four-dimensional matrix (trials * channel * frequency * time) was averaged across the trials per each condition (i.e., familiar and unfamiliar) and participant to extract the three-dimensional Spatial-Spectro-Temporal data (channel * frequency * time). To have a balanced number of trials for averaging between two conditions (i.e., familiar and unfamiliar), we employed the under-sampling technique (Batista et al., 2004; Varotto et al., 2021) to balance the EEG dataset of two conditions per participant by reducing the size of the abundant condition. This method keeps all trials in the rare condition (e.g., if the familiar condition is a rare condition for one particular participant, it means that the participant rated a few trials as familiar rather than unfamiliar) and randomly selects an equal number of trials in the abundant condition (e.g., if the familiar condition is an abundant condition for one particular participant, it means that the participant rated more trials as familiar rather than unfamiliar) for each participant. On average, 49.65 percent of trials were rated unfamiliar while 41.94 percent of trials were rated as familiar (8.41 percent were labeled 4). We repeated this procedure 100 times. Each time, we averaged randomly selected trials of abundant condition (sub-average) and took a grand average across sub-averages. All trials of the rare condition are calculated to obtain a grand average. This would allow an equi-populated binarization into the two categories of familiar and unfamiliar. Then, baseline normalization (dB conversion) was applied for further statistical analysis according to the following equation:

$$power_{norm} = 10\ \log_{10}(\frac{power_{stimuli}}{power_{baseline}}) \qquad (1)$$

FR: To obtain the power of each frequency band as the frequency response (FR) during listening to stimulus, we simply averaged the TFR in the time and frequency domains. First, we averaged the TFR from 0.5 (not including the ERP effect) to 5 s across the time domain to calculate the power for each frequency bin. Since the resolution of the window length is 0.5 s, the frequency bin in the first 0.25 s also contains the baseline effect. Similarly, TFR is averaged from -1 to -0.25 s to obtain the frequency bin during the baseline. The frequency bins from -0.25 to 0 s contain both baseline and stimulus effects; therefore, it is not considered during averaging. Moreover, the low-frequency bins from -2 to -1 s suffer from the effects of edge artifacts after filtering. Thus, it is not also considered during averaging over time domain for calculating the FR of the baseline. Second, we averaged the frequency bins corresponding to frequency bands (i.e., theta [4-8 Hz], alpha [8-12 HA], low-beta [12-16 Hz], medium-beta [16-22 Hz], high beta [22-32 Hz], and gamma [32-40 Hz]) to calculate FR for each frequency bands.

It is essential to mention that statistical analysis, as mentioned in the following subsection, is applied to both FR and TFR in this study. FR analysis demonstrates whether there are any significant brain rhythms between familiar and unfamiliar conditions by comparing the conditions with each other and also with the baseline (i.e., familiar vs. unfamiliar; familiar vs. baseline;

unfamiliar vs. baseline). TFR analysis indicates the consistency of these brain rhythms, discovered in the FR analysis, between familiar vs. unfamiliar conditions over time.

Statistical Analysis: Within-subject design

TFR: To either reject or accept the null hypothesis (no statistical difference between TFRs of familiar versus TFRs of unfamiliar conditions), a non-parametric cluster-based permutation test (Maris & Oostenveld, 2007) (Montecarlo statistical analysis), implemented in the Fieldtrip toolbox (version 20191008) (Oostenveld et al., 2011), was applied on TFRs for all electrodes due to differentiate between two conditions i.e., unfamiliar vs. familiar (cfg.statistic = "*ft_statfun_depsampleT*"; within-subject t-test; degrees of freedom = 19). For TFR analysis, the latency of -0.7 to 5 s was selected with a temporal resolution of 0.05 s as well as a frequency range from 4 to 40 Hz with a resolution of 0.5 Hz. A clustering method was applied for multiple comparisons (cfg.correctm = "cluster") to reduce Type I errors. A cluster was defined as the sum of *t*-values in adjacent electrode-time-frequency bins. Adjacency in the electrode space was taken as a given if at least one neighboring electrode belonged to a cluster. The alpha level for the cluster analysis and the number of randomizations were set to 0.05 (cfg.alpha) and 1000 (cfg.numrandomization), respectively (Tagliabue et al., 2019). We used maxsize (cfg.clusterstatistic) (Oostenveld et al., 2011) as the parameter for the cluster statistics method. To report the strength of the significant effect between two conditions (effect size), Cohen's d is calculated via the Fieldtrip toolbox based on the analytic method ("*ft_statfun_cohensd*"), and the effect size above 0.2; 0.5; and 0.8 is considered as *small*; *medium*; and *large*, respectively (Bleichner et al., 2016; Oostenveld et al., 2011).

FR: To reject or accept the null hypothesis (no statistical difference in FRs), we performed a Montecarlo statistical analysis similar to TFR analysis (i.e., a two-tailed non-parametric cluster-based permutation test) between FRs of the familiar condition versus the unfamiliar condition, the familiar condition versus local baseline, and the unfamiliar condition versus local baseline for all 51 electrodes and all six frequency bands (i.e., theta, alpha, low-beta, medium-beta, high beta, and gamma). We applied a clustering method based on the maximum cluster to correct the p-values because of multiple comparisons to reduce Type I errors. Adjacency in the electrode domain was defined if at least two neighboring electrodes belonged to a cluster. The alpha and randomization levels were set to 0.05 and 4000, respectively. Cohen’s d is defined as the same as mentioned in the TFR analysis.

Post-hoc analysis: Familiarity judgment based on the same music excerpt design

To confirm that the results of within-subject design truly indicate the effect of familiarity, not the effects of other elements such as engagement, attention, or properties of stimuli sets, the EEG data were analyzed in another way named “familiarity judgment based on the music excerpt”. In this method, we analyzed data corresponding to those music excerpts which are mostly noncongruent with what participants considered familiar. In other words, we paired EEG data related to music excerpts that were judged unfamiliar by some participants and compared them against the same music excerpts that were judged familiar by other participants (i.e., familiarity judgments were fairly non-congruent). In this way, we could assess the pure effect of familiarity, all other things being equal. To select the noncongruent music excerpt, a two-tailed-paired t-test (degrees of freedom = 19) was performed on participants’ responses for each music excerpt. Familiarity with a music excerpt is considered congruent if it is statistically significant (alpha was 0.01). As shown in Figure 4, participants’ responses for 35 music excerpts were noncongruent.

TFR and FR: TFR was calculated like the previous method, i.e., we performed a multi-taper convolution method for 75 frequency bins (from 3 to 40 Hz with a resolution of 0.5 Hz), 51 electrodes, and 221 samples with a length of 0.5 s (from -1 to 10 s) using Hanning tapers after applying baseline correction on all trials corresponding to 35 music excerpts by selecting a window in the range of -200 ms to -1 ms in the time domain ($X = X - \bar{X}_{(from-200\, to-\ \ ms)}$). Then, we applied a baseline normalization for each trial individually according to the following equation:

$$TFR_{norm} = 10\ \log_{10}\left(\frac{TFR_{stimuli}}{TFR_{baseline}}\right) \qquad (2)$$

For each music excerpt, the trials considered unfamiliar (participants' answers of ''1, 2, or 3'') were averaged to obtain the grand averaged TFR for the unfamiliar condition. Similarly, the trials considered familiar (participants' answers of ''5, 6, or 7'') were averaged to obtain the grand averaged TFR for the familiar condition. Thus, we had 35 grand averaged TFRs for each condition in total. To obtain FR, we followed the same procedure mentioned in the previous subsection for within-subject analysis.

The same statistical analysis (e.g., the same alpha, number of randomization, clustering, and type of statistic methods) was also performed for new TFR and FR as mentioned in the previous subsection. It is important to notice that the degree of freedom for implementing paired t-test was 19 in the within-subject design because of 20 participants, while it is 34 for the new analysis because of 35 music excerpts.

Results

Time-Frequency Response (TFR) and Frequency response (FR): Within-subject design

FR and TFR analyses were performed on the dataset to differentiate familiarity and unfamiliarity in the time window of 0 to 10 s. Significant results were observed in the first 5 s after the stimulus onset, while no significant effects were found between 5 to 10 s. However, an effect similar to the first 5 s (0 - 5 s) could be tracked in the second 5 s (5 - 10 s) (see SI, Figs. S1-S2). The results of applying statistical analysis to FR and TFR are mentioned in the following.

FR: Figure 2A depicts the results of the statistical analysis of FR between these two conditions (unfamiliar vs. familiar) and two frequency bands (alpha band: $P = 0.020$, $2.83 > t_{19} > 1.88$; and low-beta band: $P = 0.046$, $2.83 > t_{19} > 1.97$) in the time window of 0 to 5 s. Other frequency bands were found not to be significant (high beta [20 32 Hz]: $P = 0.058$, $2.38 > t_{19}$; other frequency bands: $P > 0.100$, $2.17 > t_{19}$).

Statistical analysis shows that alpha power (8-12 Hz) is lower for familiar versus unfamiliar conditions in the frontal (e.g., Fz, F1, F2, F4, FC1, FCz, FC2, AF3, AF4) and posterior electrodes (Pz, P3, and CP1) ($P = 0.020$, $2.83 > t_{19} > 1.88$). Correspondingly, according to the statistical result ($P = 0.046$, $2.83 > t_{19} > 1.97$), it was found that listening to familiar music results in less beta power (12-16 Hz) compared to the unfamiliar condition in the fronto-central and left frontal electrodes of the brain (i.e., FCz, Fz, FC1, F1, FC3, F3, AF3, FC5, F5). Cohen's d was calculated for the significant electrodes in the time window of 0 to 5 s corresponding to both alpha and low-beta power between familiar and unfamiliar conditions to evaluate the strength of significant effects. Cohen's d was 0.748 for alpha power and 0.562 for low-beta power, indicating a *medium* effect size.

Figure 2A also shows the statistical comparison of FR between the alpha and low-beta powers of each condition individually versus the average local baseline (the rest period of each trial for each participant which started 1 s before the onset and continued until 250 ms before the onset) by frequency analysis to obtain exclusive alpha and low-beta band changes for each condition. According to these results, it was found that significant alpha suppression occurs in the left frontal (e.g., Fz, F1, FCz, FC1), left-central (e.g., Cz, C1, C3), and left posterior electrodes (e.g., Pz, CP1, P3, CP3) during listening to familiar music ($P = 0.023$, $|t_{19}| > 0.96$, Cohen's d = 0.622 [*medium*]). Similarly, low-beta suppression statistically occurs in left fronto-central electrodes (e.g., FCz, Cz, FC1, F1, C1, FC3, F3, C3, FC5, F5, CP1, CP3) during listening to familiar excerpts compared to the local baseline ($P = 0.008$, $|t_{19}| > 0.891$, Cohen's d = 0.824 [*large*]). On the other hand, no significant differences were observed during listening to unfamiliar music compared to the local baseline for both alpha and low-beta power ($P > 0.1$, Cohen's d = 0.198 [*small*] and 0.326 [*small*], respectively).

Figure 2B demonstrates the variation of alpha and low-beta power over time, which verifies that alpha and low-beta suppression effects are sustained during listening to familiar music compared to baseline, while little or no change could be observed during listening to unfamiliar music in comparison with baseline. The maps of spectral variations over time for signals recorded from the significant electrodes present a better perspective of instantaneous variations of these two frequency bands (alpha and low-beta) over time.

TFR: Figure 3 reveals TFR maps with a frequency range of 5 to 40 Hz from -700 ms to 5 s for four groups of channels ([Fz, F1], [CP1, Pz], [AF3, F3, F5, FC3, FC5], and [AF4, F4, F6, FC4, FC6]) based on the differences of familiarity (unfamiliar vs. familiar), familiar condition, and unfamiliar condition. Figure 3A represents the brain waves for the frontal channels (i.e., Fz, F1). In Figure 3A, continued significant alpha power differences were observed between the two conditions starting from 1.00 s to 5 s. In addition, continued low-beta (12-16 Hz) effects could be tracked from 800 ms to 5 s, illustrating a power reduction in low-beta during listening to familiar music compared to unfamiliar music ($P = 0.034$, $6.154 > t_{19} > 1.328$). Since total power was calculated, the effect of event-related potential (ERP) is easily observed in the low-frequency part of the onset responses, which is shown by a circle in both familiar and unfamiliar conditions. This effect is monitored over other pooled electrodes in Figure 3.

Figure 3B illustrates the oscillation of brain activity for the posterior channels (i.e., Pz, CP1), indicating continuously less alpha power in familiarity compared to unfamiliarity between 8 to 12 Hz from 850 ms to 4800 ms across all participants. TFR maps of individual conditions indicate a sustained alpha suppression over time for the familiar condition. Moreover, this alpha and low-beta suppression is sustained during the whole 10 s; nonetheless, it is only significant during the mentioned periods (see SI, Figs. S1-S2). The significant effects of high beta in TFR analysis are observed in both posterior (i.e., Pz, CP1) and frontal (i.e., Fz, F1) channels between 0.8 s to 5 s (see Figure 3A and Figure 3B); however, it is not significant in frequency analysis ($P = 0.058$, $2.38 > t_{19}$).

Figure 3C and Figure 3D present average TFR maps over two groups of electrodes (group1: AF3, F3, F5, FC3, and FC5; group2: AF4, F4, F6, FC4, and FC6) indicating left and right frontal electrodes, respectively. Although there are some small significant effects related to the alpha suppression during the time in both figures, significant permanent low-beta (12-16 Hz) suppression could be observed during listening to familiar music from around 800 ms after trial onset ($P = 0.034$, $6.154 > t_{19} > 1.328$). Some small significant parts in the alpha band could be observed in the TFR response for both group electrodes in Figure 3C and Figure 3D; however, this was not statistically significant in the frequency analysis ($P > 0.100$, $1.88 > t_{19}$). Like Figure 3A and Figure 3B, the low-beta suppression is sustained during the whole 10 s; nevertheless, it is only significant in the mentioned period (see SI, Figs. S1-S2). In general, the alpha and low-beta power in both frequency and TFR analysis are significant ($P < 0.05$) with a *medium/large* effect (Cohen's d) which indicates strong continuous effects in the familiar condition compared to the unfamiliar condition and baseline.

TFR and FR: Familiarity judgment based on the same music excerpt design

FR: Figure 5A demonstrates the FR results obtained by applying the statistical analysis to frequency bands between unfamiliar vs. familiar, familiar vs. baseline, and unfamiliar vs. baseline for two frequency bands in the time window of 0 to 5 s. The results indicate that nothing was found to be significant in the alpha band ($P > 0.1$, $1.93 > |t_{34}|$, Cohen's d < 0.470 [*small*]); however, significant low-beta changes were statistically found in the left frontal and the left temporal electrodes (i.e., AF3, F1, F3, F5, F7, FC1, FC3, FC5, FT7, C3, C5, T7, CP5, TP7, P5, P7) during listening to familiar music compared to unfamiliar music ($P = 0.020$, $2.85 > t_{34} > 0.21$, Cohen's d = 0.833 [*large*]). Moreover, significant low-beta changes were observed by comparing the familiar condition to the local baseline ($P = 0.017$, $3.48 > t_{34} > 1.23$, Cohen's d = 0.978 [*large*]) in the left frontal, central, temporal, and posterior electrodes (i.e., AF3, F1, F3, F5, F7, FC3, FC5, FT7, C1, C3, C5, T7, CP1, CP3, CP5, TP7, P3, P5, P7), indicating that listening to familiar music leads to low-beta suppression, especially in the left frontal and temporal electrodes. Nothing was statistically found significant between the local baseline and unfamiliar conditions in the low-beta band ($P > 0.1$, $1.70 > |t_{34}|$, Cohen's d = 0.431 [*small*]).

Figure 5B shows the variation of alpha and low-beta power over time confirming sustainable low-beta suppression effects during listening to familiar music compared to baseline in the left frontal electrodes. The low-beta suppression becomes stronger after 1 s, while little or no change could be observed during listening to unfamiliar music compared to the baseline.

TFR: Figure 5C exhibits average TFR maps over the groups of electrodes corresponding to the left frontal cortex (i.e., AF3, F3, F5, FC3, FC5). According to Figure 5C, significant continuous low-beta (12-16 Hz) suppression occurs during listening to familiar music from around 800 ms after trial onset. Although we observed permanent low-beta suppression during the whole 10 s; nevertheless, it is only significant in the mentioned period (see SI, Fig. S3).

Discussion

Previous EEG studies with non-musical stimuli (conducted by listening for less than 1 s) characterized two major components of memory recognition (i.e., familiarity and recollection) based on ERPs by illustrating that the old/new effect in the frontal ERP occurs within 300-500 ms, suggesting an effect of familiarity, whereas the old/new effect in the parietal ERP is found within 400/500-800 ms, suggesting an effect of memory retrieval (Curran, 2000, 2004; Curran & Doyle, 2011; Wais, 2013). However, passive listening to familiar/old/known music versus unfamiliar/new/unknown music also requires memory recognition engagement. The present study with the idea of listening for 10 s addresses a new perspective of brain responses to familiar versus unfamiliar music. Our results indicate listening to familiar music elicits late continuous spectral responses from ~0.8 s to 5 s. Moreover, our results are in agreement with previous studies that listening to familiar music leads to time-locked responses with latencies of 400-450 ms after trial onset (See SI, Figs. S4-S5 for ERP results and interpretation). The spectral results are interpreted in the following.

Alpha Suppression

Continuous suppression of alpha power and music familiarity:

Our results from FR analysis based on the within-subject design indicate that passively listening to familiar music leads to an amplitude reduction in the alpha band relative to the local baseline, whereas no significant differences were found during passive listening to unfamiliar music compared to the baseline. Thus, statistical alpha power suppression occurs during listening to familiar music compared to unfamiliar music. Moreover, the EEG TFR results show no differences based on the brain waves for these two conditions (compared to baseline) before 850 ms (existence of late spectral response for the familiar condition). Instead, TFR and spectral power (see Figure 2 and Figure 3) reveal a long-lasting reduction of alpha power in the above-mentioned regions for familiarity (compared to unfamiliarity and baseline) from 0.85 s to 5 s. Alpha suppression could be tracked for the whole 10 s, but the suppression was significant only during 0.85 s to 5 s (see SI, Figs. S1-S2).

Our results from FR analysis of the familiarity judgment based on the same music excerpt, however, demonstrate significant changes neither between the familiar and unfamiliar conditions nor between the familiar condition and the baseline. By comparing the results of the two analyses, one can conclude that the continuous alpha-band suppression obtained from the within-subject analysis does not reflect the effects of familiarity; however, this suppression might be due to other processes such as attention or arousal/engagement.

Moreover, no significant differences were found during passive listening to unfamiliar music compared to the baseline in both types of analysis. One reason for not detecting any significant responses between unfamiliar music and baseline might be related to the paradigm's design limitations, such as selecting a short baseline period (i.e., 750 ms) rather than several seconds of silence and a lack of employing scrambled music or other auditory stimuli. Since listening to any kind of music activates a myriad of processes, unfamiliar music probably elicits very specific and distinct processes. This might be due to the fact that the processing of unfamiliar music is associated with other areas of the cerebral cortex, such as the right insula, as has been reported by previous studies using functional imaging (Green et al., 2018; Nan et al., 2008; Plailly et al., 2007).

The role of alpha power suppression:

It has been shown previously that alpha band power suppression denotes superior engagement in the brain, which is related to perceptual judgment or increased attentiveness and correlates with memory performance in response to a visual or cognitive load (Bazanova & Vernon, 2014; Sutterer et al., 2019). Significant suppression of alpha power in fronto-central and posterior sites during passive listening to familiar music excerpts in the first analysis (i.e., within-subject design) but not in the second analysis (i.e., familiarity judgment based on the same music excerpt) indicates increased attention or arousal/engagement due to having prior knowledge of the music, which is verified by participants' self-assessment when judging familiar sequences. In other words, the dynamic temporal structure of alpha activity is strongly correlated with the dynamic structure of retrieving information that traces long-term memory. More precisely, since listening to familiar music leads to more engagement due to tracking what musical sequences are encoded *into* and retrieved *from* long-term memory, these findings suggest that the changes of decreased alpha power track long-term memory (Fellner et al., 2013; Hanslmayr et al., 2016; Hanslmayr & Staudigl, 2014). The strength of alpha suppression is related to the amount of information retrieved from memory (Woodman et al., 2021) since auditory recognition elicits event-related desynchronization (suppression) of alpha-band power (Karrasch et al., 2004; Pesonen et al., 2006). Thus, one can explain why the differences between familiar and unfamiliar conditions are not significant during the second half of music even though the alpha suppression can be tracked continuously during this period. It seems that the musical sequences are not completely retrieved during the second half of listening to the music, because the participants are either less familiar (less engaged) with this part or are exerting less attention (which is necessary as a mechanism embedded in the memory structure during encoding and retrieving) (Woodman et al., 2021).

The location of alpha power suppression:

Our results show that this alpha suppression is captured by fronto-central (e.g., Fz, F1, F2, FCz, FC1, FC2) and midline posterior (e.g., Pz, CP1) channels during listening to familiar compared to unfamiliar music and baseline, which is in line with previous functional imaging studies (Buckner et al., 1996; Halpern, 1999; Herholz et al., 2012; Klostermann et al., 2009; Leaver et al., 2009; Lima et al., 2016; Pereira et al., 2011; Plailly et al., 2007; Platel et al., 2003; Rauschecker, 2011; Rauschecker & Scott, 2009)**.** These studies indicate the role of fronto-central sites in predicting upcoming sequences based on previous sequences of tones as well as the role of midline posterior sites in the engagement with memory retrieval and association with recollection judgments while listening to familiar music (Halpern, 1999; Klostermann et al., 2009; Leaver et al., 2009; Lima et al., 2016; Pereira et al., 2011). It is important to notice that since EEG has a poor spatial resolution, no strong conclusions can be drawn regarding the precise location of these activities, although the electrode activity reported here is in agreement with previous fMRI results. In general, since participants' judgments indicate different levels of familiarity with music sequences, and passive listening to familiar sequences leads to retrieval of information, we suggest that alpha power suppression in posterior electrodes indicates arousal/engagement due to the retrieval of familiar sequences from memory.

Low-Beta Suppression

Continuous suppression of low-beta power and music familiarity:

The results in Figure 2 and Figure 5 show a dynamic superior reduction in the low-beta band (12-16 Hz) during listening to familiar music by comparison with both unfamiliar music and local baseline in electrodes FCz, Fz, FC1, and F1 (referring to the fronto-central sites); electrodes AF3, F3, F5, FC3, and FC5 (referring to the left frontal sites). Moreover, TFR maps, which are shown in Figure 3 and Figure 5, demonstrate this low-beta suppression in electrodes F1, Fz (frontal electrodes), electrodes AF3, F3, F5, FC3, and FC5 (left frontal sites) occurs permanently from 0.8 - 5.0 s while listening to familiar music. The beta suppression could be tracked for the whole 10 s; however, it was significant from 800 ms to 5 s (see SI, Figs. S1-S2-S3). On the other hand, power analysis and TFR maps show no statistical differences between the unfamiliar condition compared to the baseline condition. In other words, the continuous low-beta suppression in the familiar condition obtained from both types of analyses indicates another effect of music familiarity.

The role of low-beta power suppression:

Even though beta FR (around 20 Hz) mainly reflects motor activity (Bauer et al., 2015; Fujioka et al., 2009), it has been shown that beta power is also associated with cognitive processing such as visual short-term memory tasks or retrieval from working memory, and tasks related to the imagining and planning of movement (Karrasch et al., 2004; Kopp et al., 2004). It is illustrated that beta (20 Hz) started to decrease during performing, seeing, or hearing the tapping of a drum membrane (Caetano et al., 2007). Beta suppression is also reported in response to listening to learned melodies and transposed versions of them, which is related to the sequential aspects of auditory stimuli (Schalles & Pineda, 2015). It is important to notice that the beta band has a wide range from 12 Hz to 32 Hz. That is why researchers divided the beta band into three sub-bands (Rangaswamy et al., 2002). Each sub-band is related to specific concepts. For example, predictive timing and beat perception elicit medium beta oscillation (~ 20 Hz) (Chang et al., 2018; Fujioka et al., 2012; Merchant, et al., 2015; Merchant & Bartolo, 2018) since these effects are linked to the sensory-motor network; however, music familiarity elicited low-beta band (12-14 Hz) (Karrasch et al., 2004; Pesonen et al., 2006). Although musician-level expertise is not required to form auditory-motor integration (Chen et al., 2008), since even non-musicians can be trained in various ways (e.g., dancing) to couple motor activity to music, the paradigm of the present work lacks the ability to detect these effects and might partly be due to averaging across stimuli.

In agreement with our results, it is mentioned that not only memorization of auditory stimuli (e.g., speech) modulated low-beta power (13-18 Hz) at left frontal electrodes (F1, F7, F3, and Fz) (Weiss & Rappelsberger, 1998), but also auditory memory recognition elicited event-related desynchronization responses in alpha and beta rhythm (suppression of alpha and beta power) (Karrasch et al., 2004; Pesonen et al., 2006), indicating a role for beta (especially low-beta) in memory retrieval and recognition. Thus, the low-beta (12-16 Hz) suppression linked to listening to familiar music (compared to unfamiliar music and especially to baseline) in left frontal electrodes may point toward the fact that these regions are engaged in long-term memory (Blumenfeld & Ranganath, 2007). The reason for this hypothesis is the observed EEG effects related to changes in the level of familiarity with music sequences. The level of familiarity is determined by participants' self-assessment of whether they have heard the excerpts before or not, suggesting an engagement in long-term memory (Jagiello et al., 2019). More precisely, this significant low-beta suppression in the left frontal areas obtained from both analyses indicates the effect of familiarity due to the successful retrieval of encoded musical sequences (e.g., semantic information) from long-term memory (Hanslmayr et al., 2009, 2011). It is important to note that this retrieval of musical sequences occurs after 800 ms of listening to familiar music. The strength of the low-beta suppression points toward the quality of retrieving information from memory (Fellner et al., 2013; Hanslmayr & Staudigl, 2014). Our results show that the familiarity of the participants with the first half of musical sequences is stronger (more highly significant) than the second half of music (similar to alpha suppression). More importantly, comparing familiar music with baseline results in significant electrodes in the *left* rather than the *right* hemisphere, especially in the frontal areas. This shows that the low-beta suppression is stronger during listening to familiar music in the *left* frontal electrodes. Moreover, by comparing Figure 3C and Figure 3D, stronger continuous low-beta suppression is observed for the *left* frontal electrodes rather than the *right* site. It is worth mentioning that this significant low-beta suppression in the familiar condition occurs in the same areas compared to the baseline (left frontal, temporal, and central areas) and unfamiliar condition (left fronto-central areas). This indicates the role of low-beta suppression in memory formation due to having prior knowledge of the music, which is extensively reported in visual (semantic) paradigms (Fell et al., 2008; Fellner et al., 2013; Hanslmayr et al., 2009; Sederberg et al., 2006) but not (to the best of our knowledge) in auditory paradigms.

The location of low-beta power suppression:

The localization of this low-beta suppression is in line with previous findings. Functional imaging studies, for example, have shown that different regions of the left PFC successfully support memory recognition by presenting more activity for familiar or remembered stimuli (compared to unfamiliar or forgotten stimuli) (Braver et al., 2001; Wagner et al., 1998). The functional imaging results showed that left ventrolateral PFC was involved with long-term memory during the processing of familiar verbal items/words (Braver et al., 2001) and was linked to the strength of processes in memory (Wagner et al., 1998), which indicates a role of left ventrolateral PFC in selecting relevant item information and supporting the formation of long-term memory (Blumenfeld, 2006; Blumenfeld & Ranganath, 2007). Moreover, some functional imaging studies mentioned the role of long-term memory by establishing engagements among items that are active in memory in dorsolateral PFC (Blumenfeld, 2006). Our results are in line with previous studies related to the activity of left frontal electrodes in response to the familiar items and reveal the modulation of spectral characteristics of this late engagement (suppression of low-beta power after 800 ms of listening).

In general, the findings of this study indicate that listening to old-new sound sequences based on previous knowledge elicits a late (800 ms) spectral response in fronto-central and left frontal electrodes. Moreover, these dynamic involvements in response to familiar music are continuously reflected in the suppression of low-beta power.

Limitations

The present work is limited to exploring the brain activities of male non-musicians during listening to 10 s lengths of classical music. Therefore, to generalize the results of this study one could investigate the effect of music expertise and gender on familiarity. It is important to notice that naturalistic and complex music excerpts are used in this study which inevitably leads to limitations, such as the issue with time-locked ERP analysis. The present work can only speculate about the mechanistic relation between continuing suppression and specific musical features such as beat-based expectancy, melodic, harmonic, etc. Moreover, the present work (similar to previous studies (Madsen et al., 2019)) suffers from a lack of clear control stimuli (e.g., listening to noise), although efforts have been made to overcome this shortcoming by comparing the results of familiar and unfamiliar conditions with the baseline as well as analyzing in two ways (i.e., familiarity judgment across same participants and familiarity judgment across same the music excerpt) to extract the pure effect of familiarity.

Conclusions

The results of this study provide evidence that passive listening to familiar music elicits a late continuous spectral response. The late spectral response occurs after 800 ms by suppression of alpha and low-beta power in fronto-central (corresponding to both decreased alpha and low-beta power), posterior (corresponding to decreased alpha power only), and left frontal electrodes (corresponding to decreased low-beta power only). Moreover, our analyses indicate that low-beta suppression reflects the effect of familiarity, however, alpha suppression reflects the effect of attention or arousal/engagement due to listening to familiar music.

Supplementary Information link for the figures

https://figshare.com/s/015e3e3bfc1b091ea204
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Abbreviations

EEG: electroencephalography
EOG: electrooculograms
ERP: event-related potential
fMRI: functional magnetic resonance imaging
ICA: independent component analysis
PFC: prefrontal cortex
PPC: posterior parietal cortex
SMA: supplementary motor area
TFR: time-frequency response

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Author contributions statement

A.M.: designed the study, conducted the research, collected data, analyzed the data, interpreted the data, wrote the paper, and edited the manuscript; S.E.: designed the study, interpreted the data, and edited the manuscript; J.R.: supervised the research, and edited the manuscript; G.C.: conceptualized the study, provided resources, supervised the research, and edited the manuscript.

Figure Legends

Figure 1: Study protocol. A: Experimental design. A cross sign was shown in front of the participants before stimulus onset for an unknown duration (a random number with uniform probability distribution between 3 and 4.5 s). Then, a music excerpt was played through headphones for 10 s while participants were looking at the dark monitor. A familiarity question was asked 2 s after listening was completed. In case of familiarity, participants mentioned the name of the composer, title, or any other information related to the song. **B:** Calculating Time-frequency response (TFR) for the familiar condition and the unfamiliar condition as well as calculating Frequency response (FR) for the familiar condition, the unfamiliar condition, and baseline.

Figure 2: Frequency response (FR) of familiarity judgment based on the within-subject design. A: Topographic maps of FR differences between familiarity and unfamiliarity (unfamiliar minus familiar) for two frequency bands. Alpha power (8-12 Hz) differences are statistically significant in frontal (Fz, F1, FCz, FC1, FCz) and posterior (CP1, P3, and Pz) electrodes suggesting low power (effect size = 0.748) in unfamiliar compared to familiar conditions across all participants in the interval of 0.85-5.0 s ($P < 0.05$). Similarly, low-beta power (12-16 Hz) differences were statistically significant in the left frontal cortex and superior frontal gyrus in the interval of 0.8-5.0 s ($P < 0.05$). Additionally, statistical differences were calculated between the FR of baseline versus FR of both familiar and unfamiliar conditions for both alpha and low-beta bands. No significant differences were observed between the FR of the unfamiliar condition and the baseline in the alpha and beta bands. However, decreased power in the alpha band (channels Fz, F1, F3, FCz, FC1, FC3, Cz, C1, C3, C5, CPz, CP1, CP3, CP5, Pz, P3, and P5) and low-beta band (channels F1, F3, F5, FCz, FC1, FC3, FC5, FT7, Cz, C1, C3, C5, T7, CP1, CP3, CP5, TP7, P3, and P5) were observed in FR of familiar conditions compared to the baseline ($P < 0.05$). **B:** Variation of alpha and low-beta power before and after stimulation. The upper row indicates the differences between unfamiliar and familiar conditions (unfamiliar - familiar). The middle and lower rows refer to familiar and unfamiliar conditions, respectively. Sustained alpha and low-beta suppression effects were tracked for each stimulated interval while listening to familiar music.

Figure 3: Time-frequency response (TFR) maps of familiarity judgment based on the within-subject design for four groups of electrodes ([F1, Fz], [CP1, Pz], [AF3, F3, F5, FC3, FC5], and [AF4, F4, F6, FC4, FC6]) based on the differences between familiar and unfamiliar conditions (unfamiliar - familiar), familiarity, unfamiliarity, and quantified results for the grand-averaged TFR corresponded to the alpha and low-beta power across all participants. A: TFR maps for the frontal channel (F1, Fz) across all participants indicate both continued alpha and low-beta suppression during listening to familiar compared to unfamiliar music starting at 1.00 and 0.80 s ($P < 0.05$), respectively. **B:** TFR maps for the posterior channel (CP1, Pz) across all participants indicate sustained alpha suppression while listening to familiar compared to unfamiliar music starting from 0.85 s ($P < 0.05$). **C:** Averaged TFR maps over left frontal electrodes (AF3, F3, F5, FC3, FC5). These TFR maps indicate a statistically continued suppression in the low-beta band (12-16 Hz) during listening to familiar music compared to unfamiliar music ($P < 0.05$). **D:** Averaged TFR map over right frontal electrodes (AF4, F4, F6, FC4, FC6). These TFR maps point towards a statistically continued suppression in the low-beta band (12-16 Hz) during listening to familiar music compared to unfamiliar music ($P < 0.05$) starting from 0.8 s.

Figure 4: The distribution and congruence over what was considered familiar and non-familiar in 85 music excerpts. The red color indicates noncongruent responses of participants while the black color indicates congruent responses of participants over the familiarity with music ($P < 0.01$). Participants' responses for 35 music excerpts were noncongruent while participants' responses for 50 music excerpts were congruent. Left panel: the mean of rating scores. Right panel: the standard deviation (STD) of rating scores.

Figure 5: Results of familiarity judgment based on the same music excerpts related to noncongruent responses. A: Topographic maps of differences between familiarity and unfamiliarity (unfamiliar minus familiar) for two frequency bands. Nothing was found statistically significant in the alpha band ($P > 0.1$). However, low-beta power (12-16 Hz) differences were statistically significant in the left frontal and temporal cortex in the interval of 0.8-5.0 s ($P < 0.05$). Additionally, statistical differences were calculated between the local baseline versus both familiar and unfamiliar conditions for both alpha and low-beta bands. For the alpha band, no significant differences were observed. For the low-beta band, statistically decreased power was observed in the familiar condition compared to the local baseline ($p < 0.05$). **B:** Variation of alpha and low-beta power before and after onset. Sustained decreased low-beta effects were tracked for each stimulated interval while listening to familiar music. **C:** TFR for the groups of electrodes [AF3, F3, F5, FC3, FC5] corresponding to the left frontal cortex. The TFR maps demonstrate a statistically continued suppression in the low-beta band (12-16 Hz) during listening to familiar music compared to unfamiliar music.