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Modulation of theta and gamma oscillations during familiarization with previously unknown music

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A R T I C L E I N F O

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A B S T R A C T

Repeated listening to unknown music leads to gradual familiarization with musical sequences. Passively listening to musical sequences could involve an array of dynamic neural responses in reaching familiarization with the musical excerpts. This study elucidates the dynamic brain response and its variation over time by investigating the electrophysiological changes during the familiarization with initially unknown music. Twenty subjects were asked to familiarize themselves with previously unknown 10 s classical music excerpts over three repetitions while their electroencephalogram was recorded. Dynamic spectral changes in neural oscillations are monitored by time–frequency analyses for all frequency bands (theta: 5–9 Hz, alpha: 9–13 Hz, low-beta: 13–21 Hz, high beta: 21–32 Hz, and gamma: 32–50 Hz). Time-frequency analyses reveal sustained theta event-related desynchronization (ERD) in the frontal-midline and the left pre-frontal electrodes which decreased gradually from 1st to 3rd time repetition of the same excerpts (frontal-midline: 57.90 %, left-prefrontal: 75.93 %). Similarly, sustained gamma ERD decreased in the frontal-midline and bilaterally frontal/temporal areas (frontal-midline: 61.47 %, left-frontal: 90.88 %, right-frontal: 87.74 %). During familiarization, the decrease of theta ERD is superior in the first part (1–5 s) whereas the decrease of gamma ERD is superior in the second part (5–9 s) of music excerpts. The results suggest that decreased theta ERD is associated with successfully identifying familiar sequences, whereas decreased gamma ERD is related to forming unfamiliar sequences.

1. Introduction

Imagine a situation in which a person listens to an unfamiliar music excerpt. Then, the person decides to listen to the same music over and over without any interruption in between or with a small delay (i.e., a few minutes). Therefore, during this process, originally unfamiliar sequences of music become gradually familiar and memorable since the familiarity of music could be enhanced by repetitions (Russell, 1987). This suggests that brain responses change during the perception of each repetition of musical sequences. Previous studies employed music, as complex sound sequences, to elucidate the brain regions during sensory perception based on the feeling of familiarity (Plailly et al., 2007). However, the neural responses modulated by familiarization towards listening to new/unfamiliar music sequences are still not spectrally clear or consistent. Addressing this point could lead us to have a better understanding of the dynamic neural responses and illuminate the role of different rhythms of the brain during familiarization with the musical sequences.

Familiarity is defined as complete information derived from a close connection and acquaintance with previous experience (Son et al., 2002). The concept of familiarity is linked to the process of memory for recognition items, which depends on the explicit ratings of knowing or unknowing items (e.g., music) (Plailly et al., 2007). Previous studies mainly concentrated on the relationship between familiar music and physiological signals of the brain by employing various measurement tools in different contexts such as bottom-up and top-down processes (Ding et al., 2019), emotion (Pereira et al., 2011), tempo (Hahn & Hwang, 1999), self-consciousness in patients with Alzheimer's disease (Arroyo-Anlló et al., 2013), auditory-motor learning (Herholz et al., 2016), auditory imagery (Halpern and Zatorre, 1999), recognition tunes in songs (Hébert & Peretz, 2001), and performing a vigilance task (Fontaine & Schwalm, 1979). Similarly, a lot of effort has been made to identify the engagement of subcortical brain regions, or dynamic temporal/spectral characteristics between familiarity (old/known) versus unfamiliarity (new/unknown), which influence long-term memory (Wagner et al., 2005) during recognition of different items (Castro et al., 2020; Gruber et al., 2008; Stenberg et al., 2009). For example, one study investigated the differences in the neuronal processes involved in the

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familiarity or unfamiliarity of stimuli of two different sensory modalities, specifically odors and musical excerpts (Plailly et al., 2007). Besides, others distinguished the cortical activity between the feeling of listening to culturally familiar music (native) versus unfamiliar music (non-native) (Akrami & Moghimi, 2017; Arikan et al., 1999; Nan et al., 2008), or characterized the temporal features of the brain responses during the feeling of familiarity compared to unfamiliarity for musical excerpts (Daltrozzo et al., 2010). They observed considerable activities occurred predominantly in the left hemisphere in the prefrontal cortex (specifically the superior and inferior frontal gyri), the superior temporal gyrus, the bilateral middle frontal gyrus, and the precuneus during listening to familiar music (Leaver et al., 2009; Plailly et al., 2007; Platel et al., 1997; Platel et al., 2003).

In addition to long-term music familiarity (familiar vs unfamiliar), short-term familiarization with music influences brain responses. Repetition of items is one of the predominant ways to evaluate the effect of familiarization. For example, the effect of familiarization based on the implicit (pleasantness ratings) and explicit (yes–no recognition) memory task was shown by presenting previously unfamiliar tunes twice for two groups of old and young participants (Halpern & O'Connor, 2000). They found implicit memory involved in familiarization with unfamiliar melodies for both groups even though recognition memory for unfamiliar melodies was worse in older people compared to younger people. Moreover, previous studies related to the engagement of people in music showed that brain responses differ concerning the repetition of already familiar items as compared to unfamiliar ones (Madsen et al., 2019). They indicated that listeners' engagement tends to decrease with the repetition of familiar music; however, listening to unfamiliar music can sustain participants' interest. Likewise, neurophysiological studies highlighted that the effect of stimulus-related neuronal responses is different during the repetition of familiar and unfamiliar items. For example, it has been shown that decreased neuronal responses occurred during the repetition of familiar items (Fiebach et al., 2005). On the other hand, the repetition of unfamiliar items (e.g., faces and symbols) leads to an increase in neuronal responses during the representation of sensory input. Even though researchers found evidence that music familiarity influences the power spectra of brain waves (Thammasan et al., 2017), to our best knowledge, the electrophysiological activities related to the short-term familiarization with previously unknown auditory stimuli (e.g., music) have not been spectrally clarified, especially over repeatedly of listening to music. In this regard, a series of questions arise that this study intends to address: Which regions and rhythms of the brain are involved during familiarization with previously unfamiliar music? Does the brain show similar responses during prolonged listening? Does a non-phase-locked event-related synchronization or desynchronization (ERS or ERD) response occur during this prolonged listening? Which type of memory might be associated with the familiarization?

This paper concentrates on the familiarization with initially unknown music by employing a repetition task to evoke and evaluate human brain activity. In this regard, EEG is utilized in this work to track the dynamics of brain activity during passive listening to initially unfamiliar music excerpts. Thus, this study investigates the dynamic spectral changes in neural oscillations during the familiarization with unfamiliar music through three repetitions (short-term familiarization). We hypothesized that familiarization with music has a direct effect on the electrophysiological changes in the brain. Moreover, since participants are not previously familiar with the musical excerpts, we anticipate that being familiarized with music excerpts over three repetitions provokes neural activity related to the working memory (short-term memory) rather than long-term memory. Additionally, based on the previous studies on binary familiarization, it is expected electrophysiological changes occur in the frontal, and both sides of the prefrontal areas.

2. Results

2.1. Behavioral results

Subjective scores of music familiarity differ significantly between repetitions according to the result of one-way ANOVA ($F_{(2,\ 57)} = 18.92$, $P < 0.001$). Fig. 2 depicts the grand averages of participants' scores for each repetition of unfamiliar music excerpts. Increased subjective scores across participants are illustrated in Fig. 2 during repetitions of unfamiliar music excerpts. According to this figure, participants significantly indicate higher scores in the 2nd-rep and 3rd-rep compared to the 1st-rep based on the parametric two-sample *t*-test measurements ($t_{38} = 4.565$, $P < 0.001$ for comparing 2nd-rep versus 1st-rep; and $t_{38} = 6.039$, $P < 0.0001$ for comparing the 3rd-rep versus 1st rep). However, there were no significant differences observed between the 2nd-rep and 3rd-rep ($t_{38} = 1.539$, $P = 0.132$). The behavioral result shows that listening for the first time is insufficient to become familiarized with the music sequences (average rating is < 3.5 out of 7). Statistical analysis of behavioral results indicates that listening to music three times is sufficient to rate music familiarity higher than 5 out of 7 (become familiar).

2.2. Neural results

Fig. 3 demonstrates the results of repeated-measures multivariant ANOVA on TFRs of three repetitions. Fig. 3 indicates the significant differences between at least two repetitions in the theta band mainly in the left frontal and frontal central ($F_{(18,\ 2)} = 27.19$, $P = 0.015$). Moreover, Fig. 3 shows the significant differences between at least two repetitions in the gamma band, especially in the second part of listening (5 to 10 s) in the frontal central, bilateral frontal, and bilateral temporal electrodes ($F_{(18,\ 2)} = 35.32$, $P = 0.015$). Nothing was found significant for other frequency bands ($P > 0.738$). These results can be followed up by pair-wise comparisons between every-two repetitions to explore how neural activity statistically changes during familiarization in both theta and gamma bands.

Fig. 4 indicates the statistical results of Post-hoc analysis of every-two repetitions (3rd rep vs 1st rep, 3rd rep vs 2nd rep, and 2nd rep vs 1st rep) for the theta and gamma bands, respectively. It is important to note that nothing was found significant for other frequency bands ($P > 0.1$). Moreover, according to Fig. 4, nothing significant was found between the 3rd rep versus the 2nd rep and between the 2nd rep versus the 1st rep from 1 s to 10 s in both theta and gamma bands ($P > 0.1$). However, Fig. 4 illustrates the theta power (5–9 Hz) significantly changes in the 3rd rep compared to the 1st rep from 1 s to 6 s and from 8 s to 10 s ($P = 0.002$, $4.300 > t_{19} > 2.115$) in the frontal midline and left prefrontal electrodes. In addition, Fig. 4 illustrates that the gamma power (32–50 Hz) significantly changes in 3rd rep compared to 1st-rep from 2 s to 10 s in the frontal midline, bilateral frontal, and bilateral temporal electrodes ($P = 0.002$, $5.573 > t_{19} > 2.095$).

Fig. 5 visualizes the time–frequency of these three TFR-ROIs, respectively, to compare the significant frequency bands with other frequencies, and to quantify the corresponding significant power changes during the repetitions. It is important to note that Fig. 5 is entirely descriptive and is not tested for generalization. Our observations show neural oscillations related to the alpha and beta bands decreased in comparison with the baseline in all three TFR-ROIs during listening to the music excerpts regardless of the repetitions. However, increased gamma and theta power, in the frontal midline (TFR-ROI1) and both sides of the prefrontal areas (TFR-ROI2 and TFR-ROI3), are observed over the entire stimulated time, which is immediately started after the stimuli. Since the total power was calculated, the early increase power around 5 Hz in the interval of 0 to 0.5 s is overt for all three TFR-ROIs and each repetition, which is related to the auditory ERP occurring immediately after the onset of the stimuli (Koelsch et al., 2007; Koelsch & Jentschke, 2008). Fig. 5 also illustrates the intensity of grand averaged

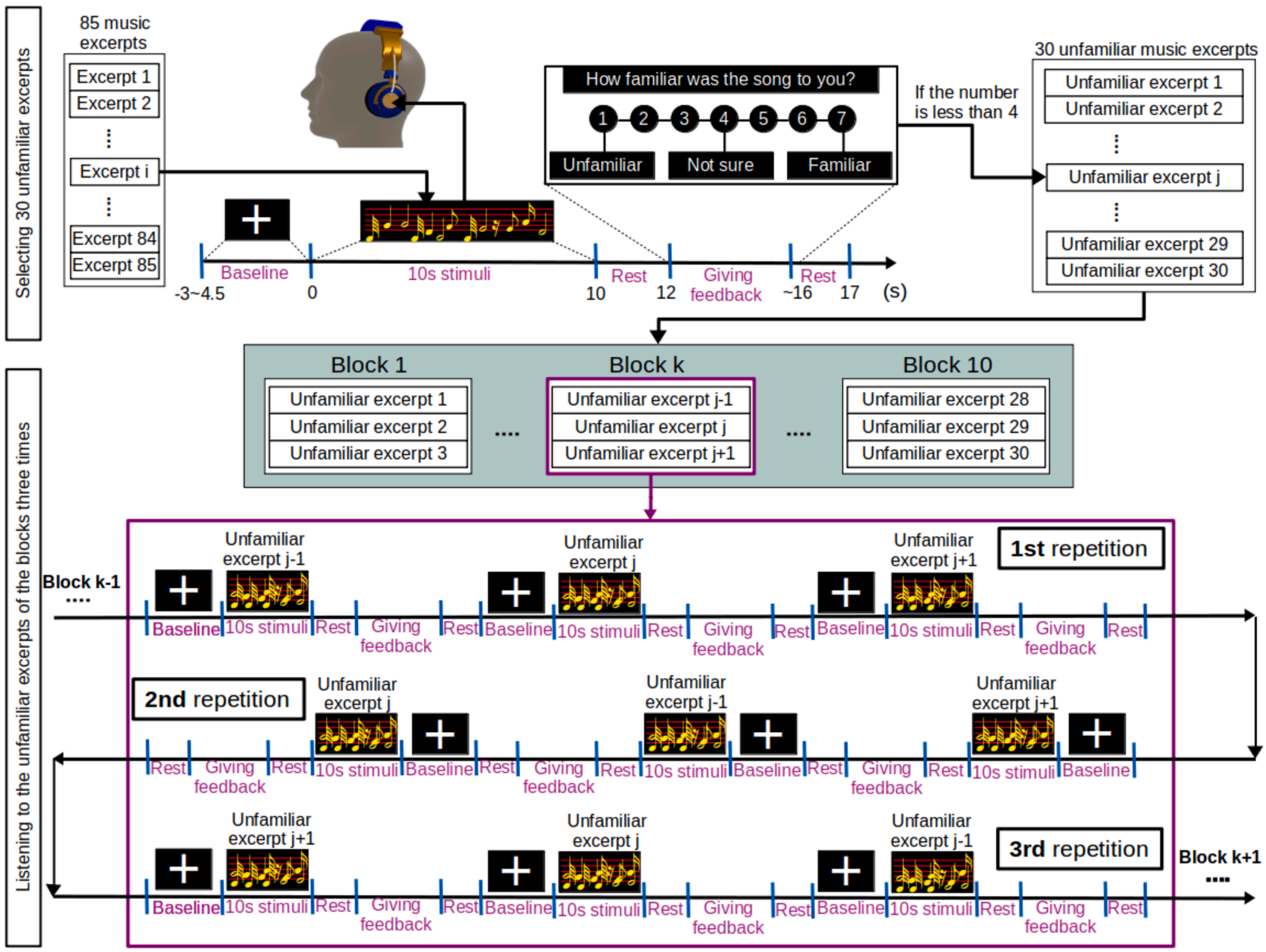

Fig. 1. Experimental protocol: A cross sign appeared on the display placed in front of subjects before stimulus onset for an unknown duration (a random number with uniform probability distribution between 3 and 4.5 s). Then, a song was played through the earphones for 10 s while subjects were looking at the black monitor. A familiarity question was asked 2 s after the completion of listening. In the case of familiarity, they mentioned the name of the composer, title, or any information related to the song. Unfamiliar songs were extracted for the familiarization task. Then, ten blocks of three songs were created in this phase. Finally, participants were asked to perform the music familiarization task by listening to the unfamiliar music excerpts of each block via 3-times repetition.

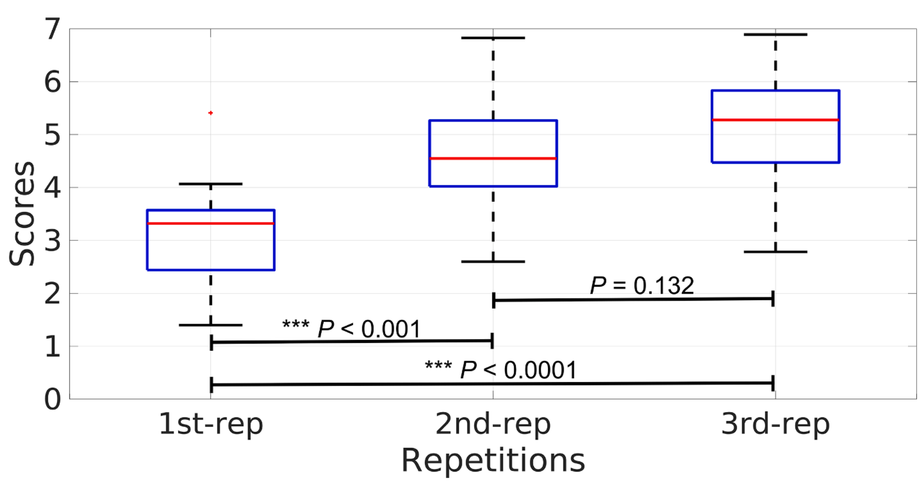

Fig. 2. Participants' feedback: Grand averages of participants' cognitive ability while playing unfamiliar music excerpts three times with the p-value between each pair repetition obtained by *t*-test measurement.

for these oscillations corresponding to these three TFR-ROIs per repetition, respectively. These results are shown in the second row of each sub-figure to highlight the variation of both theta and gamma frequency bands between each repetition. As it is illustrated in Fig. 5A, both theta and gamma power gradually increased (theta power: 27.69 % for the 2nd repetition and 57.90 % for 3rd repetition, gamma power: 46.65 %

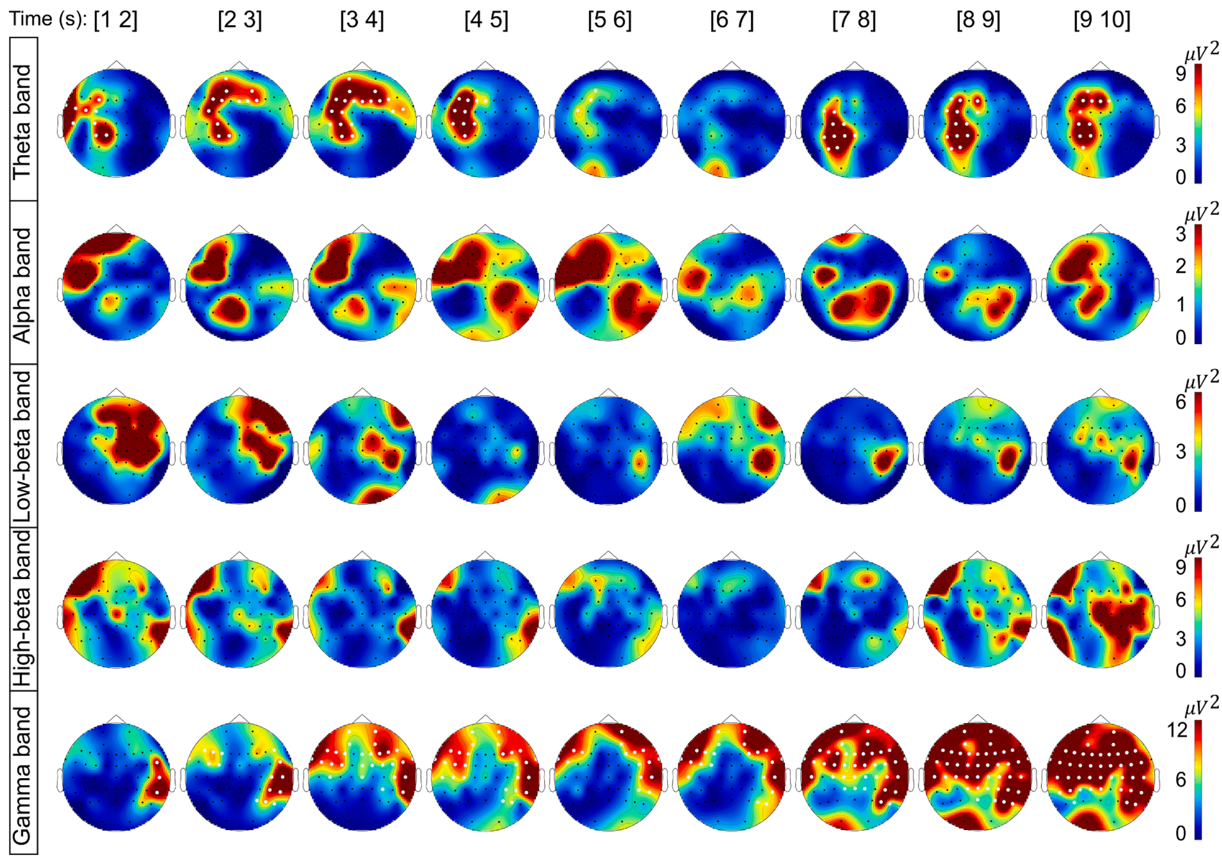

Fig. 3. The results of repeated-measures multivariant ANOVA in a 3-D space (channels * frequency bands * time points). The significant electrodes are highlighted in white color. Significant clusters are only observed in the theta and gamma bands.

for the 2nd repetition and 61.47 % for 3rd repetition) in frontal-midline areas (TFR-ROI1) over the whole stimulated time (disinhibition). Similarly, Fig. 5B indicates that theta power is increased by 23.60 % and 75.93 % for the 2nd repetition and the 3rd repetition in comparison with the 1st repetition in the left prefrontal area (TFR-ROI2). Fig. 5B also indicates a 73.24 % and 90.88 % increase of gamma power in the 2nd and 3rd repetition in comparison with the 1st repetition. Likewise, weak increase theta, but not significant, is observed in the right prefrontal area (TFR-ROI3) compared to the left side in Fig. 5C (35.76 % and 32.29 % for the 2nd and 3rd repetition compared to the 1st repetition). However, a significant increase in gamma power occurs in TFR-ROI3 (45.60 % in the 2nd repetition and 87.74 % in the 3rd repetition). In all three regions, both theta and gamma power decreased during hearing unfamiliar excerpts for the first time (i.e., inhibition); then, increased power in theta occurs when the excerpts become familiar and memorable throughout performing the repetition task (i.e., disinhibition; see Fig. 5A, Fig. 5B, and Fig. 5C). The increase of power immediately after the onset (0 to 0.7 s) is compared to other intervals (0.7 to 10 s) regardless of repetitions. This increase in power is associated with the ERP since the total power is calculated in this work without removing ERP effects. The quantified results show that the changes of theta/gamma power for the 3rd repetition compared to the 2nd repetition are 1.72 greater than changes of theta/gamma power for the 2nd repetition compared to the 1st repetition even though behavioral results do not show significant differences in participants' scores between the 3rd and the 2nd repetition. The quantified results in Fig. 5 show the grand-averaged power for the 1st and 3rd repetition is almost consistent over time; however, the grand-averaged power for the 2nd repetition differs during listening to the first half of music excerpts with the second half of music excerpts for all three regions.

Fig. 6 which is entirely a descriptive analysis/comparison illustrates two different states to investigate the differences of the grand-averaged power during listening to the "first part" (1 to 5 s) and "second part" (5 to 9 s) of music excerpts for all three repetitions. Fig. 6A indicates that theta power is increased by 34.30 % and 55.17 % during listening to the "first part" while is increased by 21.95 % and 49.57 % during listening to the "second part" for the 2nd and 3rd repetition in comparison with the 1st repetition in the frontal midline area (TFR-ROI1), respectively. Fig. 6B shows theta power is increased by 39.33 % and 74.03 % during listening to the "first part" while is increased by 16.64 % and 58.92 % during listening to the "second part" for the 2nd and 3rd repetition in comparison with the 1st repetition in the left prefrontal area (TFR-ROI2), respectively. Fig. 6C illustrates the increase of theta power by 44.44 % and 34.78 % during listening to the "first part", and the increase of theta power by 18.41 % and 31.17 % during listening to the "second part" for the 2nd and 3rd repetition in comparison with the 1st repetition in the right prefrontal area (TFR-ROI3), respectively. Fig. 6D, E, and F shows a comparable increase of gamma power for the 3rd time compared to the 1st time repetition during listening to the "first part" (TFR-ROI1: 50.80 %, TFR-ROI2: 78.86 %, TFR-ROI3: 76.29 %) in comparison with the "second part" (TFR-ROI1: 69.36 %, TFR-ROI2: 104.80 %, TFR-ROI3: 99.67 %). Finally, Fig. 6 illustrates that theta power is decreased by 25.57 %, 27.51 %, and 44.45 % while gamma power is increased by 22.07 %, 34.58 %, and −2.02 % during listening to the "second part" for the 2nd repetition compared to listening to the "first part" for the 2nd repetition in TFR-ROI1, TFR-ROI2, and TFR-ROI3, respectively.

2.3. Results of the general linear model (GLM)

Table 2 indicates the statistical results obtained by applying GLM to affirm any potential links between increased familiarization and power

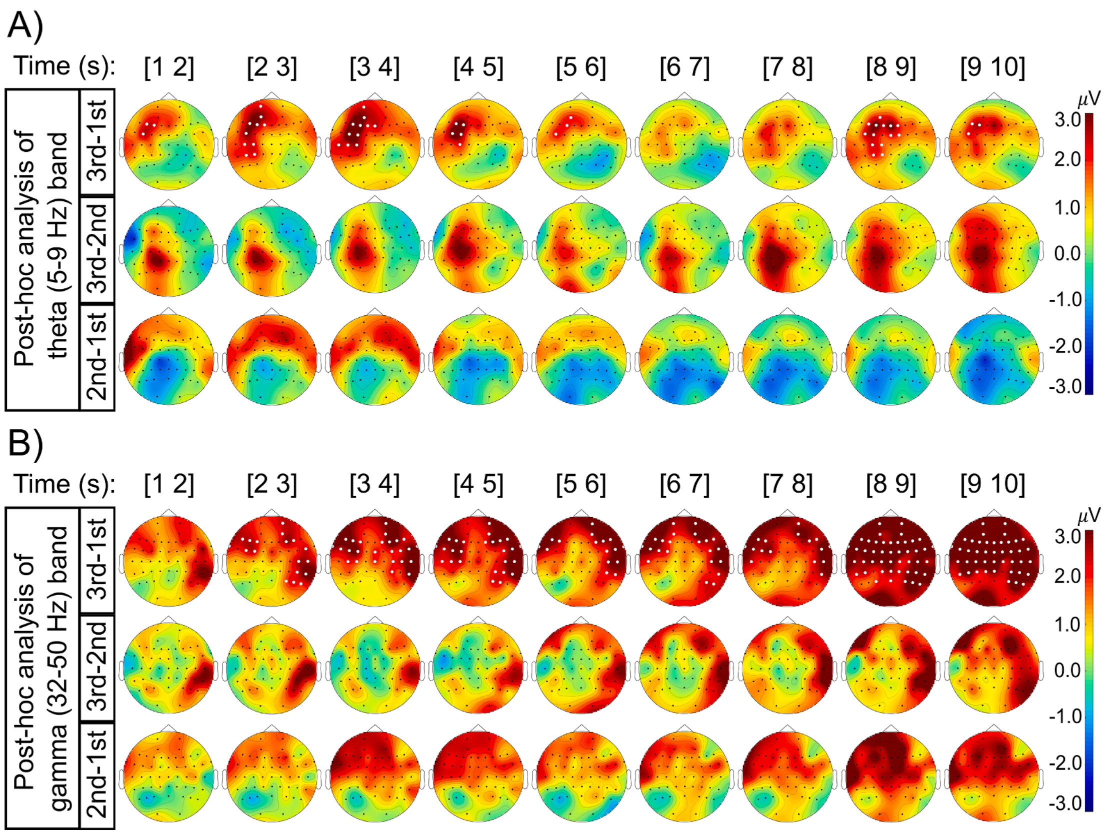

Fig. 4. The results of pairwise Post-hoc analyses: Topographic maps of statistical differences between every-two repetitions (3rd rep vs 1st rep, 3rd rep vs 2nd rep, and 2nd rep vs 1st rep) are visualized for each 1 s slot from 1 to 10 s. The significant electrodes are highlighted in white color. A: Post-hoc analysis of theta band (5–9 Hz) B: Post-hoc analysis of gamma band (32–50 Hz).

changes in every-two conditions (3rd rep vs 1st rep, 3rd rep vs 2nd rep, and 2nd rep vs 1st rep). The results indicate a statistical relationship between behavioral changes (participants' feedback) and power changes in the theta band (5–9 Hz) related to the comparison of the 3rd with the 1st repetition in the left prefrontal electrodes (ROI2: $P = 0.003$). In addition, the results show that the behavioral changes and power changes in the gamma band (32–50 Hz) related to the comparison of the 3rd with the 1st repetition are statistically linked together in bilateral prefrontal electrodes (ROI2: $P = 0.004$ and ROI3: $P = 0.001$).

3. Discussion

Our findings elucidate a characterization of the oscillatory brain dynamics, notably of theta power inhibition compared to the baseline in all repetitions (theta ERD) and decrease in theta ERD in the 2nd and 3rd repetitions in the frontal midline and left side of the prefrontal areas. Similarly, our finding indicates gamma ERD decreases during familiarization with previously unfamiliar music excerpts in the bilateral frontal, prefrontal, and temporal area. The locations of these electrophysiological changes are in line with the changes in cortical activities based on the binary familiarization in the previous studies (Leaver et al., 2009; Plailly et al., 2007; Platel et al., 1997; Platel et al., 2003). The dynamic spectral characterization indicates sustained responses (decrease in theta/gamma ERD) during familiarization with initially unknown music over the whole stimulating period. Additionally, decreased alpha and beta power are observed compared with the baseline in all three repetitions of music excerpts in the superior frontal gyrus, which suggests successfully memorizing during listening to unfamiliar music excerpts, especially in the left prefrontal electrodes (Hanslmayr et al., 2012). Suppression of alpha and beta oscillation for each repetition also suggests the enhancement of information processing due to successfully engaging in a cognitive task (Griffiths et al., 2019). In general, the results demonstrate inhibition of theta [5–9 Hz] and gamma [32–50 Hz] power in the first repetition compared to the baseline and disinhibition in the next repetitions of unfamiliar music excerpts.

3.1. *Theta in the frontal midline, and left prefrontal areas*

Our results indicate sustained decreased theta (5–9 Hz) ERD in F1, F2, Fz, and FC1 over a stimulating period during repetitions of unfamiliar music sequences. The activity in these channels can be associated with activations within the frontal midline areas (Gärtner et al., 2014). In addition, the results show a sustained decrease in theta ERD in the left prefrontal electrodes (AF3, F3, F5, FC3, FC5).

Theta power indicates the identification of familiar sequences: Theta synchronization is associated with memory retrieval and encoding (Bakker et al., 2015). This could support theta changes in the repetition of music since the familiarization process of unfamiliar music with 10 s length includes encoding sequences in the 1st repetition and retrieving learned/memorized sequences in the 2nd and 3rd repetition. In other words, decreased theta ERD over the repetitions (less desynchronization in the 3rd repetition compared to the 1st repetition) during listening to both the "first part" (1 to 5 s) and "second part" (5 to 9 s) of music excerpts indicates successful familiarization/memorization with music. This assumption is supported by previous studies which indicated two following major points: first, successful encoding reflects changes in theta and gamma power (Düzel et al., 2010); second, successfully encoded words that are recalled in a later elicit lower amplitudes of theta (less desynchronization) compared to forgotten or novel words (Bakker et al., 2015; Düzel et al., 2010; Osipova et al., 2006). Therefore, fewer changes in theta ERD (more disinhibition) in the 2nd repetition for the "second part" compared to the "first part" in the frontal and left

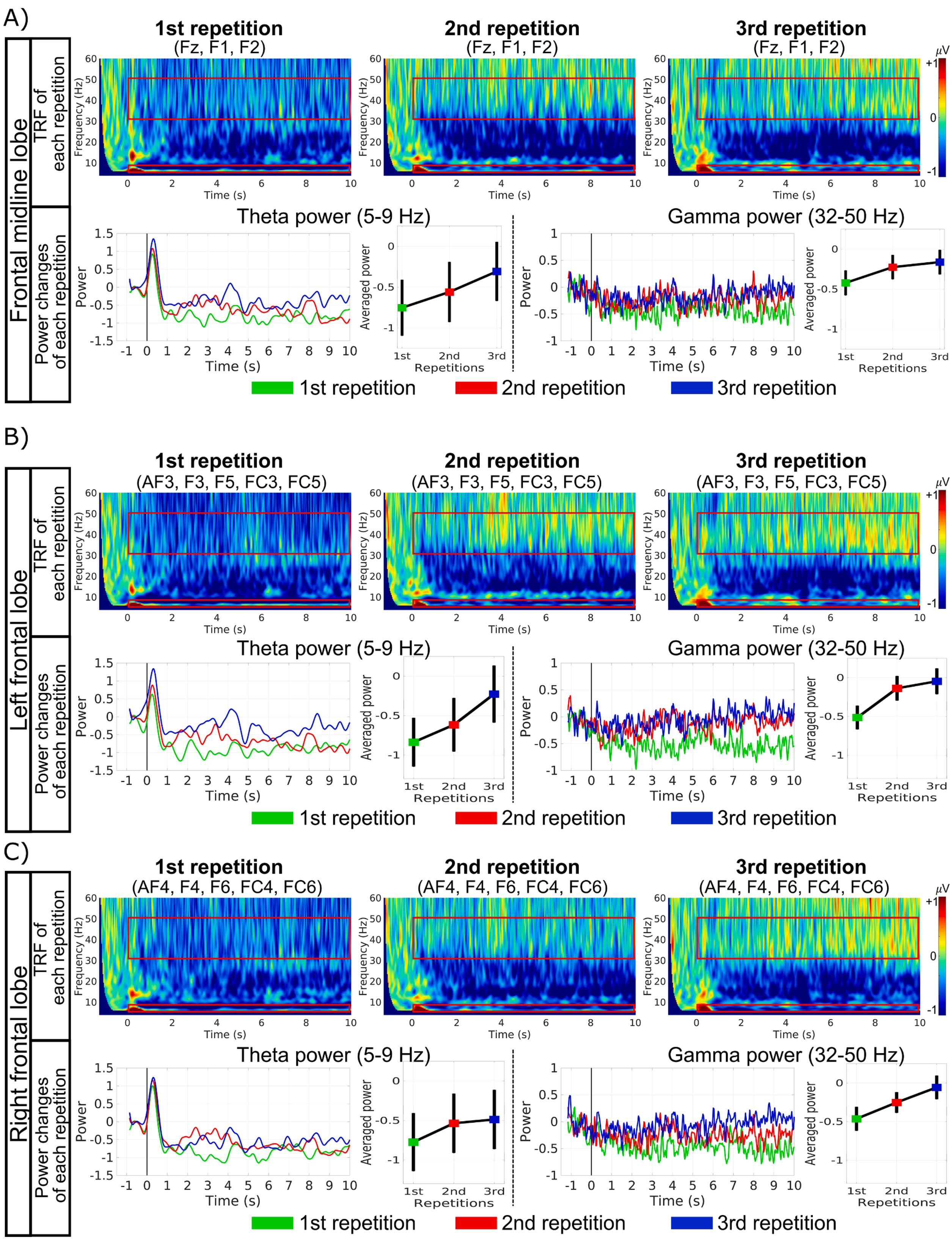

Fig. 5. TFR maps across all subjects for each repetition of previously unfamiliar music excerpts for three groups of electrodes, which corresponded to the midline frontal, left prefrontal, and right prefrontal areas, respectively. The second row is related to the variation of grand-averaged power changes over the entire listening period per each repetition for theta [5–9 Hz] and gamma [32–50 Hz] power indicating both theta and gamma power is increased for the 2nd and 3rd repetition compared to the 1st repetition. A: TFR maps for the frontal midline channels [Fz, F1, F2, FCz, FC1, FC2], and the grand-averaged power of frontal midline areas of the brain over time per each repetition. B: TFR maps for the left prefrontal channels [AF3, F3, FC3, F5, FC5] across all subjects per each repetition, and the variation of grand-averaged power of left prefrontal areas of the brain over time per each repetition. C: TFR maps for the right prefrontal channels [AF4, F4, FC4, F6, FC6] across all subjects per each repetition, and the variation of grand-averaged power of right prefrontal areas of the brain over time per each repetition.

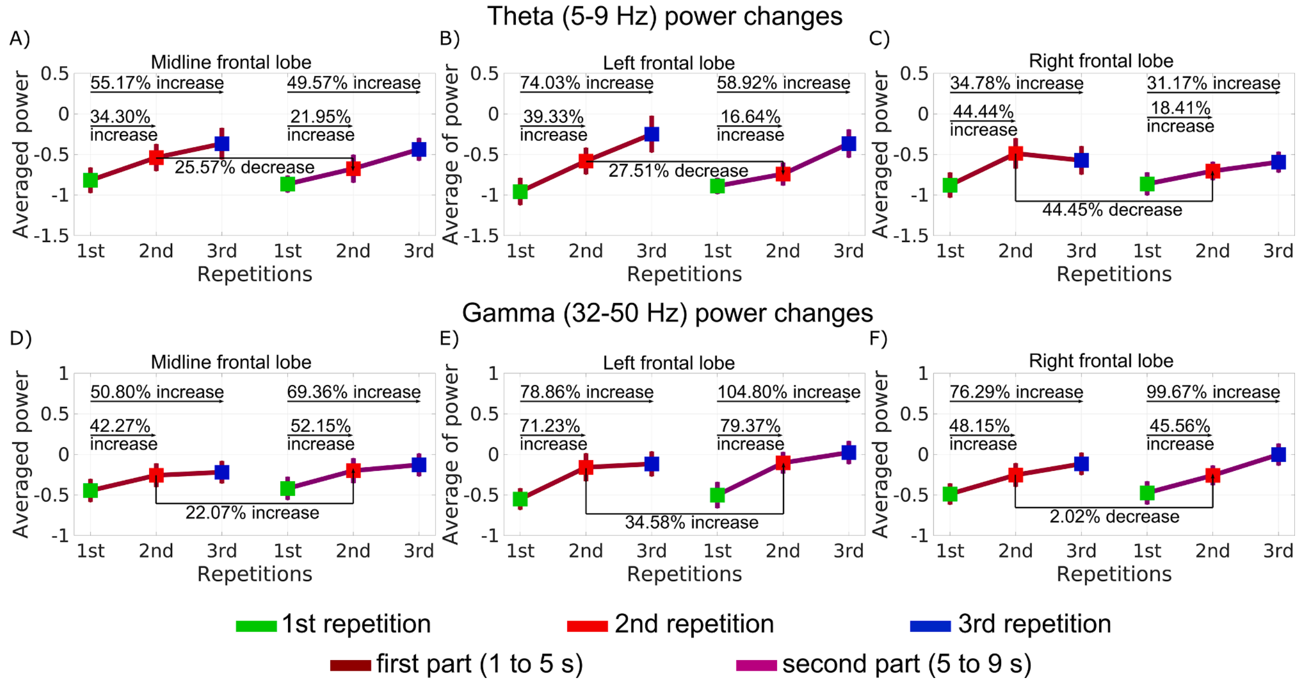

Fig. 6. Power differences between the first and second parts: The grand-averaged power of three significant areas of the brain (midline frontal, left prefrontal, and right prefrontal areas) over time per each repetition corresponded to the significant frequency bands (theta power [5–9 Hz], gamma power [32–50 Hz]) for two states: 1- "first part" which is related to the first half part of listening to the music excerpts (1 to 5 s). The error bar is shown on the left side of each subfigure. 2- "second part" which is related to the second half part of listening to the music excerpts (5 to 9 s). This error bar is shown on the right side of each sub-figure.

prefrontal area show superior familiarization with the "first part" of music excerpts (1 to 5 s) compared to the "second part" (5 to 9 s). This shows that participants were more familiar with the beginning of music sequences compared to the end of music sequences during listening for the 2nd time. Thus, the results suggest that the decrease in theta ERD is related to the identification of familiar sequences. In other words, the frontal midline and left prefrontal electrodes are continuously responsible for the identification of familiar sequences.

3.2. Gamma in bilaterally prefrontal, frontal, and temporal areas

Validity of the results of gamma power: Our findings illustrate sustained increased gamma ERD in the bilateral temporal and frontal areas of the brain corresponding to the electrodes [Fz, F1, F2, FC2, FCz, AF3, F3, F5, FC3, FC5, AF4, F4, F6, FC4, FC6, FT9, FT10, FT7, FT8, TP8] during repetitions of the music excerpts. These results illustrate changes in neuronal oscillation rather than muscle activity. In addition to the mentioned special care for processing EEG data and designing protocol, the results show a steady-state high-frequency response, especially around 40 Hz, which is a characteristic of high-frequency neural activity in EEG data (Muthukumaraswamy, 2013). Moreover, gamma power differences should not be observed in the baseline during the repetitions since participants performed no activation in this period. This point is vividly illustrated in Fig. 4 and Fig. 5 by employing both topographic maps and plotting the grand average of gamma changes, respectively. Finally, even though muscle artifacts usually occur in frontal-temporal areas (Muthukumaraswamy, 2013), the activity related to the frontal and temporal muscles is salient in the frequency of 20–30 Hz and 40–80 Hz, respectively (Goncharova et al., 2003). However, the results indicate the predominant broadband of gamma power in the frequency of 32 to 40 Hz. Therefore, these results are devoid of the effect of muscle contamination.

Gamma power indicates the formation of unfamiliar sequences: Increased gamma-band response during the repetition of unfamiliar objects is reported in previous studies under the concept of repetition priming, indicating neural activity reflects the reactivation of cortical items' representation (Hassler et al., 2013). In general, previous studies highlighted the opposite effect of object/item representations based on familiarity. In particular, the repetition of familiar items (i.e., pictures) leads to a reduction in gamma-band response amplitudes (Friese et al., 2012; Hassler et al., 2013). On the other hand, the repetition of unfamiliar items increases gamma power (Fiebach et al., 2005). The results of this study (inhibition of gamma power in the 1st repetition and disinhibition of gamma power in the 3rd repetition) are compatible with the previous studies based on the representation of the unfamiliar items. It is important to notice that since previous studies employed visual stimuli, this effect was observed in the occipital and parietal/temporal cortex, indicating visual object identification (Fiebach et al., 2005; Supp et al., 2007). However, decreased gamma ERD is observed in the bilateral temporal (Cohen's d is *very large*), prefrontal (Cohen's d is *medium*), and frontal areas (Cohen's d is *medium*) in this study because of employing auditory stimuli. As previous studies mentioned for the representation of unfamiliar visual objects (Gruber & Müller, 2006), we suggest that the decreased gamma ERD is relevant to the formation of unknown sequences of music representation during the whole 10 s of listening. Like the theta power changes, decreased gamma ERD over the three repetitions during listening to both the "first part" and "second part" of music excerpts indicates successful familiarization with unknown music. On the other side, in contradiction to the theta power changes, less desynchronization of gamma power occurs during listening to the "second part" (more unfamiliar) in comparison with the "first part" (less unfamiliar) for the 3rd repetition in comparison with the 1st repetition (see Fig. 4). Moreover, gamma ERD is decreased during the 2nd repetition for the "second part" compared to the "first part". The reason is participants were more unfamiliar with the end of music sequences (5 to 9 s) compared to the beginning of music sequences (1 to 5 s). Therefore, less inhibition of gamma power is observed for the "second part" or more unfamiliar part rather than the "first part" or less unfamiliar part. In other words, more disinhibition of gamma power in the "second part" suggests the predominant role of gamma power in the processing of unfamiliar sequences compared to the familiar ones. Thus, although theta power is related to the successful identification of

Table 1

List of all music excerpts with composers and the average of familiarity grade across 15 subjects. "N0." indicates the number of music; "Excerpt from" points to the title of music; "Composer" means the name of the person who created the music; "Avg-Fam." indicates the average familiarity grades across all 15 participants.

No.	Excerpt from	Composer	Avg-Fam.	No.	Excerpt from	Composer	Avg-Fam.
1	Symphony #5 in C minor, Op.67	Beethoven	6.93	44	L'Arlesienne suite #1: Prelude	Bizet	3.33
2	Fur Elise	Beethoven	6.93	45	Minuetto	Boccherini	3.20
3	In the Hall of the mountain king	Grieg	6.87	46	Four Mazurkas #3 in A flat major	Chopin	3.13
4	The pink panther	Mancini	6.87	47	Dream is collapsing	Zimmer	3.13
5	Buono brutto cattivo	Morricone	6.80	48	Palladio (second part)	Jnekins	3.13
6	Eine kleine Nachtmusi	Mozart	6.80	49	Violin concerto #3 in G major k.216	Mozart	3.00
7	Sonata #11 in a major, K. 331 - III. Alla Turca	Mozart	6.53	50	Flute concerto #2 in D Major K.314	Mozart	3.00
8	Suite #2 in B minor, BWV 1067, Badinerie	Bach	6.40	51	Clarinet concerto in A major k. 622 adagio	Mozart	3.00
9	Toccata and Fugue in D minor BWV 565	Bach	6.40	52	Divertimento #17 K. 334 in D major, III Menuetto	Mozart	3.00
10	Carmen Suite #1 Les Toreadors	Bizet	6.33	53	Wind Serenade #11	Mozart	2.93
11	Hungarian dance #5 in G minor	Brahms	6.27	54	Horn concerto #3 K 447	Mozart	2.93
12	He's a pirate	Zimmer	6.27	55	Impromptu in E flat major	Schubert	2.93
13	Star Wars: Main title and escape	J. Williams	6.27	56	Symphony #6B minor unfinished	Schubert	2.80
14	Symphony #40 in G minor, K 550-1. Molto Allegro	Mozart	6.13	57	The Gypsy Baron Einzugsmarsch	Strauss	2.80
15	Chariots of fire	Vangelis	6.00	58	Die fledermaus overture	Strauss	2.80
16	Spring	Vivaldi	5.80	59	Piano concerto #1 Allegro	Tchaikovsky	2.73
17	Peer Gynt - morning mood	Grieg	5.40	60	The sleeping beauty ballet	Tchaikovsky	2.73
18	The Battle	Zimmer	5.27	61	1812 Overture Op.49	Tchaikovsky	2.73
19	Swan lake ballet #10	Tchaikovsky	5.00	62	Overture to tannhauser	Wagner	2.67
20	Dance of the Sugar Plum Fairy	Tchaikovsky	4.93	63	November sky	Yanni	2.67
21	Libiamo, ne' lieti calici	Verdi	4.87	64	Standing in motion	Yanni	2.53
22	The Four Seasons, Concerto #3 in F Major	Vivaldi	4.73	65	Orchestral suite #2 in B minor, BWV 1067: Sarabande	Bach	2.40
23	Orchestral suite #2 in B Minor BWV 1067: Minuet	Bach	4.47	66	Symphony #9, in E Minor the new world: Scherzo	Dvorak	2.40
24	Symphony #6 in F major	Beethoven	4.40	67	Coriolan overture Op.62	Beethoven	2.40
25	Nocturne in C sharp minor	Chopin	4.33	68	Scherzo #1 in B minor Op.20	Chopin	2.33
26	Symphony #9 in E minor	Dvorak	4.20	69	Nocturnes Op.9 #3 in B major	Chopin	2.33
27	The end?	Zimmer	4.20	70	12 Etudes Op.25 #10 in B minor	Chopin	2.27
28	Cornfield chase	Zimmer	4.20	71	24 Preludes Op.28 #18 in F minor	Chopin	2.27
29	Modern warfare 2 credits	Zimmer	4.07	72	Claudion arrau	Balakirev	2.20
30	Cassation in b flat	Mozart	4.07	73	Palladio (first part)	Jnekins	2.20
31	An der schoenen, blauen Donau	Strauss	3.93	74	Moment musical in A flat major	Schubert	2.20
32	The christmas tree - March	Tchaikovsky	3.93	75	Ballet Music #2 Rosamunde	Schubert	2.20
33	Divertissement: Trepak	Tchaikovsky	3.87	76	24 Preludes, Op.34 in D minor	Shostakovich	2.13
34	Alpha	Vangelis	3.80	77	Der zigeunerbaron (ouverture)	Strauss	2.00
35	Conquest of paradise	Vangelis	3.80	78	String serenade waltz	Tchaikovsky	2.00
36	La petite fille de la mer	Vangelis	3.80	79	Capriccio italien Op.45	Tchaikovsky	1.93
37	One man's dream	Yanni	3.70	80	Eugene onegin polonaise	Tchaikovsky	1.93
38	Within attraction	Yanni	3.67	81	Memories of green	Vangelis	1.87
39	A love for life	Yanni	3.60	82	To take to hold	Yanni	1.67
40	Orchestral Suite #4 in D major, BWV 1069	Bach	3.47	83	Piano concerto in G, II. Adagio assai	ravel	1.60
41	Kommst du nun, BWV 650,	Bach	3.40	84	Trout quintet tema con variazioni	Schubert	1.40
42	Piano Concerto #2: Adagio	Beethoven	3.33	85	Missing: Main theme	Vangelis	1.40
43	Symphony #5 Op.67: Allegro	Beethoven	3.33	86			

Table 2

Statistical analysis of GLM between neural and behavioral data.

ROI1: Frontal midline lobe: Fz, F1, F2

	Theta (5–9 Hz)	Alpha (9–13 Hz)	Low-beta (13–21 Hz)	High-beta (21–32 Hz)	Gamma (32–50 Hz)
3rd rep – 1st rep	$P = 0.051$	$P = 0.564$	$P = 0.092$	$P = 0.658$	$P = 0.021$
3rd rep – 2nd rep	$P = 0.424$	$P = 0.961$	$P = 0.934$	$P = 0.173$	$P = 0.264$
2nd rep – 1st rep	$P = 0.614$	$P = 0.573$	$P = 0.127$	$P = 0.016$	$P = 0.029$

ROI2: Left frontal lobe: AF3, F3, F5, FC3, FC5

	Theta (5–9 Hz)	Alpha (9–13 Hz)	Low-beta (13–21 Hz)	High-beta (21–32 Hz)	Gamma (32–50 Hz)
3rd rep – 1st rep	**$P = 0.003$**	$P = 0.222$	$P = 0.548$	$P = 0.804$	**$P = 0.004$**
3rd rep – 2nd rep	$P = 0.101$	$P = 0.646$	$P = 0.926$	$P = 0.320$	$P = 0.402$
2nd rep – 1st rep	$P = 0.216$	$P = 0.112$	$P = 0.274$	$P = 0.395$	$P = 0.013$

ROI3: Right frontal lobe: AF4, F4, F6, FC4, FC6

	Theta (5–9 Hz)	Alpha (9–13 Hz)	Low-beta (13–21 Hz)	High-beta (21–32 Hz)	Gamma (32–50 Hz)
3rd rep – 1st rep	$P = 0.\ 566$	$P = 0.706$	$P = 0.141$	$P = 0.187$	**$P = 0.001$**
3rd rep – 2nd rep	$P = 0.\ 886$	$P = 0.883$	$P = 0.608$	$P = 0.024$	$P = 0.015$
2nd rep – 1st rep	$P = 0.\ 806$	$P = 0.770$	$P = 0.087$	$P = 0.035$	$P = 0.037$

familiar sequences, gamma power changes are more related to the formation of unfamiliar sequences.

3.3. Familiarization with music elicits working memory

WM is considered temporary storage whose contents are permanently updated, scanned, and manipulated in response to immediate information processing demands necessary for complex tasks (Baddeley & Hitch, 1974; Manoach et al., 1997; Wianda & Ross, 2019). Since short-term familiarization with unfamiliar music via three times listening requires updating and manipulating new information during the repetition of music excerpts, one may argue that the process of music familiarization engages neural resources associated with WM (Leeser, 2007). This idea can be promoted since studies have demonstrated that music training (familiarization in both action and perception) is highly associated with enhancement and development in WM (Bergman Nutley et al., 2014; Yurgil et al., 2020) and that familiar music might facilitate the recollection compared with unfamiliar music since it does take much space in working memory storage (Silverman, 2010). Moreover, the familiarization process (i.e., three repetitions) for each unfamiliar excerpt lasted 20 s to 80 s, so it is expected that neural activity related to the WM rather than long-term memory is elicited during listening to the excerpt. Similar to the results of this work, previous studies highlighted the association between increased frontal midline theta power (Hsieh & Ranganath, 2014; Jensen & Tesche, 2002; Maurer et al., 2015; Meltzer et al., 2008) and increased gamma power in bilateral temporal, prefrontal, and frontal areas (Jacobs & Kahana, 2009; Lundqvist et al., 2016; Mainy et al., 2007; Pesaran et al., 2002; van Vugt et al., 2010) in WM tasks. Besides, increased activity is observed in the left prefrontal area compared to the right prefrontal area (Mull & Seyal, 2001) during working memory as it occurs in the process of familiarization with music. This engagement of the left prefrontal area might associate with the identification of melodies (Groussard et al., 2010). This is coming from the idea that this oscillation in the prefrontal area is mnemonic, and increased theta could reflect the storage of past sequential information (Curtis & D'Esposito, 2003). Thus, we suggest that familiarization elicits neural activity related to the WM, which indicates common neural sources being engaged in processing both tasks.

4. Limitations and future work

Our work is limited to 10 s lengths of classical music, male non-musicians. Therefore, to generalize the results of this study, it would be interesting to extend this research to differentiate the effect of familiarization with music based on the different types of music, both genders (male and female), and different backgrounds in music (musicians and non-musicians). A various range of musical features (i.e., instruments, melodies, pitches, timbres, rhythms, and grammatical structures) are employed in this study, and participants were asked to rate their familiarization with music (i.e., how well or poor they can play the music itself in their mind). However, it is still unclear what is stored in memory and why. It is recommended for future studies to use controlling stimuli (e.g., different timbre, tempo, rhythm, keys, and so on) to address what participants remember of the music (e.g., the melody, the chords, the timbre). In addition, this research is limited to three repetitions of playing music excerpts. The experiment took one hour of carefully listening to non-meaningful sounds (i.e., music). More repetitions might lead to tiredness and less involvement of participants in the task, although the behavioral results show that three repetitions are sufficient to familiarize participants with the music. Avoiding long recording was the reason for not including control stimuli and being contented with the baseline (-1 to 0 s) although techniques such as block-playing along with correlations of behavior ratings with the neural change were employed to ensure that the effects are not due to the experimental protocol.

This research provides the opportunity for future studies to increase the number of repetitions and monitor changes in neural activities from short-term familiarization to long-term familiarization. More importantly, these results are promising to explore the pattern of a neural network during familiarization with initially unknown music at the sensor level for future studies, since it has been shown that at least 6 s of listening to music is needed to achieve stable connectivity patterns (Fraschini et al., 2016).

5. Conclusions

Our findings indicate the sustained significant differences between listening to familiar and unfamiliar music during repetition indicating the effect of short-term familiarization in the successful identification of familiar sequences (corresponding to the increased theta power) and the formation of unfamiliar sequences (corresponding to increased gamma power). These effects are reflected in the bilateral prefrontal, and midline frontal electrodes. The understanding of the neural activity during familiarization with music could be beneficial for neuro-rehabilitation due to its therapeutic support for patients suffering from Alzheimer's disease, Down syndrome, verbal memory and motor deficits, and language impairments (Freitas et al., 2018); the results of this paper (i.e., dynamic neural responses during familiarization with music) could inspire other researchers to use familiarization with music as a criterion to monitor the healing process of the mentioned diseases in patients as well as the progress of memorization in healthy people.

6. Experimental procedure

6.1. Participants

Twenty healthy male volunteers in the age range of 21–39 years (mean = 29.10, SD = 4.40) participated in this experiment which sounds reasonable and sufficient compared to previous studies (Haenschel et al., 2000; Halpern and Zatorre, 1999; Thammasan et al., 2017; Zhang et al., 2017) and based on post hoc power analysis (power > 94 %). Participants were staff and students from the Technical University of Munich and members of the public from different nations (e.g., Germany, Lebanon, Austria, Japan, Iran, and Brazil). All participants were asked to fill out a self-report questionnaire before starting the experiment. According to their answers, all of them had normal or corrected-to-normal vision, and none had any history of hearing impairment or psychiatric disorders. All of them were right-handed and non-musicians. Non-musicians are defined in this study as having no>3 years of musical training and engaging in no current musical activity (Doelling & Poeppel, 2015). Seventeen out of twenty participants had also no background in music theory/music education, and the other three have not played any instrumental music for more than seven years.

The study (reference number is 365/19 S) was approved by the Ethics Committee of the Technical University of Munich. All participants signed a consent form before the start of the experiment. Monetary compensation of 8 EUR/h was given to all the volunteers as a reward for their participation after completing the experimental task.

6.2. Stimuli and apparatus

All the music excerpts are listed in Table 1, indicating that a various range of instruments and twenty-six different composers (e.g., Chopin, Bach, Beethoven, Mozart, and Tchaikovsky) were utilized in this study. These music excerpts were played back via earphones (Samsung 3.5 mm sound stereo in-ear headphone with remote and mic), which was connected to the PC through an AVID MBOX 3 MINI device to ensure high standards of sound quality. All the music excerpts were chiefly selected from the classical genre with purely instrumental sounds. Each excerpt lasted 10 s to cover a reasonable period of stimulus and to monitor the dynamic variation of frequencies during passive listening over time (Popescu et al., 2004; Sridharan et al., 2007). Moreover, the beginning of each excerpt was removed if it comprised a silent or solely gradually rising part of the instrument (e.g., piano, violin, or drum). A normalization of loudness to −1 dB was applied to all the excerpts based on matching the peaks in signals. To detect familiar music with minimum effort, other manipulations of the audio signals were avoided to keep the music excerpts as close as possible to the original ones. Participants also had the opportunity to individually adjust the volume of the music by listening to the six different classical songs at the beginning of the experiment.

EEG data were recorded from 51 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, *C*2, C4, C6, T8, TP7, CP5, CP3 CP1, CPz, CP2, CP4, CP6, TP8, P7, P5, *P*3, Pz, *P*4, *P*6, P8, O1, O2) which were arranged according to the 10–10 international system using the Brain Products actiChamp amplifier. One electrode (FPz) was located as a ground, and two electrodes (TP9 and TP10) were attached behind the ears as references (averaged mastoid channels). Besides, three electrodes were located in the center of each participant's forehead and below both eyes to record the vertical and horizontal electrooculogram (EOG) for posthoc EOG artifact reduction. Even though participants were asked to avoid chewing on gum, mumbling to themselves, or making any movement, careful monitoring during the recording of EEG data was applied by the examiner to identify bad trials and artifacts due to any possible movement or other things which could be induced artifacts. EEG signals were recorded at a sampling rate of 1000 Hz. The experimenter checked the impedance levels of all electrodes to keep them below 15 KΩ throughout the experiment to have a high signal-to-noise ratio. No filtering was performed during the recording of EEG data. The data were transferred via USB to a separate recording PC (Intel® Core™ i5 CPU 750@2.67 GHz).

6.3. Protocol

Participants were asked to perform one experimental familiarization task by passively listening to different excerpt pieces that lasted 10 s for three times. Each participant sat on a comfortable and non-movable chair while a monitor was placed in front of them on a table. Then, the experiment began, according to the protocol illustrated in Fig. 1 when the volunteers expressed their readiness.

- **Selecting 30 unfamiliar excerpts out of 85 excerpts:** Participants listened to all 85 excerpts, and they were asked to provide feedback related to their self-assessment familiarity by using the Likert Scale from one (unfamiliar) to seven (familiar) after listening to each excerpt (Daltrozzo et al., 2010). The question was: is this excerpt familiar or unfamiliar to you? They were asked to choose "5, 6, or 7" when they were familiar with the whole excerpt; in contrast, when they were not familiar with the excerpt at all, participants were instructed to choose "1, 2, or 3''. 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. The intertrial rest period varied between 3000 ms and 4500 ms for each excerpt to avoid any habituation to the onset of the coming event. There was a break after listening to fifteen music excerpts (which almost took five minutes, depending on the time of participants' feedback) to prevent exhaustion and body fatigue. When playing each excerpt was finished, they pressed their desired number on the keyboard with their right hand. Excerpts that corresponded with the feedback of the lower than four were considered unfamiliar music. Finally, only 30 excerpts with the lowest feedback number (i.e., "1, 2, and 3") were selected as unfamiliar excerpts. After finishing listening to all the excerpts, participants took a long break (at least 30 min) before starting the main task.
- **Playing each of 30 unfamiliar excerpts three times:** These 30 unfamiliar excerpts were shuffled and divided into ten blocks of three excerpts each. Then, each block was selected, and its excerpts were played to the participants. After playing each unfamiliar excerpt, they were asked to indicate their ability to play the same excerpt in their head by self-assessment using the Likert Scale from one (could not play in their mind–or–poor remembering) to seven (playing correctly in their mind–or–perfect remembering). In other words, they were supposed to determine how well they learned and memorize the excerpt, and how much information related to the excerpt was stored in their head. When all excerpts of the block were played, they were shuffled (to avoid participants predicting the onset of the coming event) and played again. The excerpts of each block were played three times in total. After playing all excerpts of each block three times, participants could take a break in which they could move or take a refreshment. Furthermore, the breaks were used to assess the electrode impedance before continuing the experiment. Then, the next block was considered, and all the mentioned procedures were repeated until playing all three excerpts of the last block three times.

If we defined the retention interval as a time interval of playing one specific music excerpt twice; Then, it could be realized that the retention interval was a random number between 20 s (the last excerpt of a block is the same as the first excerpt of the next block) to 80 s (the first excerpt of a block is the same as the last excerpt of next block) since playing each excerpt took almost 20 s. The experimental protocol ensures that contrasted measures of brain activity are not affected by variations of music structural factors (e.g., rhythm, harmonics, pitch, intensity, spatial, and timbre), because the data corresponding to the first repetition of unfamiliar excerpts is compared with the data corresponding to the second and third repetition of the same unfamiliar excerpts for each participant. Hence, the outcomes of comparison between different repetitions are only associated with familiarization with the unfamiliar music excerpts. Since the excerpts were played three times; then, we have three repetitions. And each repetition is considered as one condition.

6.4. Subjective ratings

Participants were asked to listen to unfamiliar excerpts three times and then subjectively rate their ability to memorize the music and repeat the music in their minds. All participants completed the familiarization task. To assess their cognitive ability, their scores were measured after listening to the excerpts. Then, the average scores were calculated for each repetition and each participant.

6.5. Statistical analysis of behavioral data

Two statistical analysis was applied to the behavioral data. First, we performed a one-way ANOVA implemented in Matlab on all behavioral data corresponding to the repetitions to discover any significant differences in general. Second, the parametric test (two independent sample *t*-test statistical analysis) was applied to the participants' feedback (subjective rating) to highlight exactly where the significant progress occurs during familiarization with music ($P < 0.05$).

6.6. Data analysis

All analysis was applied in the Matlab environment using Brainstorm (Tadel et al., 2011) (https://neuroimage.usc.edu/brainstorm/) and FieldTrip (Oostenveld et al., 2011) (https://www.fieldtriptoolbox.org/). The continuous raw data were passed through a 4th order Butterworth IIR band-pass filter (zero-phase) with a low cutoff frequency of 0.5 Hz and a high cutoff frequency of 80 Hz. Moreover, a 2nd order IIR notch filter (zero-phase) at the frequency of 50 Hz was performed to remove any possible line noise. In this study, implemented logistic infomax independent component analysis (ICA) in Brainstorm was employed to identify and remove any possible artifacts (e.g., eye-blink, eye-movement, and muscle activity) in the continuous data which could not be eliminated by the filter procedures. Independent components were removed if they were visually evaluated as artifacts (mean = 5.80, SD = 1.93). Finally, the continuous data were segmented from −1250 ms to 11250 ms based on the stimulus time-locked i.e., listening to each excerpt was considered as one trial. Therefore, the number of trials for each condition (repetition) is 30. The baseline (resting state) correction was applied for each channel and each trial with the pre-stimulus interval of −200 to −2 ms ($X_{new\_i\in(-1.25to11.25s)} = X_{i\in(-1.25to11.25s)} - \overline{X}_{(from-200to-2ms)}$) (Jagiello et al., 2019; Kirschner et al., 2015). The baseline correction only changes the DC component (f = 0) and does not influence other frequency components. Then, all epochs were re-sampled from 1000 Hz to 500 Hz. In the end, all data corresponding to each repetition of unfamiliar music were processed for further analysis without considering the participants' feedback. The average number of trials across all participants after cleaning was 28.4 with a standard deviation of 6.38 per condition.

6.7. Gamma and artifacts

Since beta and gamma frequency bands could be contaminated by artifacts such as cranial muscles (facial and neck muscles) and ocular muscles (Goncharova et al., 2003), special attention was considered during processing and designing protocol based on the recommendations of previous studies. First, the data were carefully inspected by employing ICA to remove any components representing cranial and ocular muscle artifacts (mean = 5.80, SD = 1.93) (Hipp & Siegel, 2013; May et al., 2019), and EEG data were transferred to the averaged references and not to a single reference electrode to suppress the chance of activation mislocalizations (Michels et al., 2010). Second, any epochs were manually removed if they contained saccadic spike artifacts (Hipp & Siegel, 2013). Third, the situation for each repetition was equal. For example, the same music excerpts were played for each repetition; therefore, the results are not affected by any features of the music like intensity. Moreover, a block-playing strategy was used in this work to avoid the effect of unwanted experimental elements such as possible tiredness or excitement. Playing all the music at once and repeating the playing for the next time might influence the results of the gamma band between the 1st repetition and the 3rd repetition since participants become tired or excited over time. However, we divided the music excerpts into ten blocks of three excerpts. Then, we played each block three times first, and we played the next block. Therefore, the results are not influenced by the musical excerpts or experimental protocol.

6.8. Time-frequency analysis

All the data were considered in analyzing time–frequency response (TFR) without removing the event-related potential (ERP) effect to obtain the total power. TFR was calculated using Fieldtrip's multi-taper method convolution (mtmconvol) (Kinney-Lang et al., 2019; Oostenveld et al., 2011) for each frequency (started at 4 Hz to 60 Hz to cover all brain waves with a reasonable resolution of 0.5 Hz), each electrode, and each sample time (resolution of 0.03 s) with a 7-cycle width to detect sustained effects rather than transient effects using Hanning tapers. Since the total length of each music excerpt is 10 s, a fixed 7-cycle wavelet is suitable even for low frequencies to detect the dynamic spectral responses of neural activity. Then, the extracted four-dimensional TFR representations (trials × channel × frequency × time) were averaged in the next step over trials for each subject, separately for each condition. Then, a baseline normalization (dB conversion) was performed on the average power values by the following equation by selecting an interval window in the range of −1000 ms to −2 ms (rest period or baseline):

$$power_{norm} = 10\log_{10}\left(\frac{power_{stimuli}}{power_{baseline}}\right) \quad (1)$$

Finally, the average TFR for each participant was applied across the whole stimulated time (0 to 10 s), and frequency bands (theta: 5–9 Hz, alpha: 9–13 Hz, low-beta: 13–21 Hz, high beta: 21–32 Hz, and gamma: 32–50 Hz) to calculate topographic mapping of each band for further statistical analysis. Moreover, the averaged TFR of eleven-time slots with an interval of 1 s was calculated across the mentioned frequency bands to obtain continuous topographic maps during listening.

6.9. Statistical analysis of TFR: Spatio-Spectro-Temporal analysis

Sample-wise repeated measures multivariate ANOVA using the cluster-based permutation test, implemented in the Fieldtrip toolbox (Oostenveld et al., 2011), was performed on the TFRs of all three conditions in one single analysis to highlight the existence of significant Spatio-Spectro-Temporal clusters. Thus, the 3-D space of data is analyzed in a single test (i.e., rm-ANOVA using the cluster-based permutation test as multiple comparisons problem (MCP)) which is more sensitive than performing statistical tests on marginalized data (averaging in one or two dimensions). This approach avoids increasing the risk of false positives (noise falsely detected as a signal) and precisely controls the family-wise error rate. TFR is used for statistical analysis to certify that the effect is widespread during the listening period rather than strongly existing in a very short period and disappearing in other moments. In this regard, we used Montecarlo as the method, parametric cluster threshold, 0.05 as the alpha value (P value), permutation with 1000 randomizations (Tagliabue et al., 2019), weighted cluster mass (WCM) (Oostenveld et al., 2011) with the weight of 2 as the parameters for re-sampling, cluster method as MCP. A cluster is defined as the sum of t-values in adjacent electrode-time–frequency bins. A cluster is significant if the p-value is<0.05 ($P < 0.05$). Adjacency in the electrode space is considered a given if at least one neighboring electrode belonged to one cluster. This statistic is applied to all conditions together between dependent variables (i.e., 51 electrodes, 5 frequency bands [theta, alpha, low-beta, high beta, and gamma], and 18 time-points [1 to 10 s]) on one independent variable with three levels (three repetitions) to detect any overall significant differences. The temporal resolution is 0.5 s ((10 s – 1 s) / 0.5 s = 18 time-points) with a time smoothing of 0.5 s (0.5 s smoothing means plus-minus 0.5 s). The first second (0 to 1 s) of listening to music is excluded since this epoch reflects the evoked responses to sound onsets in low-frequency bands (e.g., theta and delta bands).

6.10. Post-hoc analysis: Pairwise statistical analysis on a 3D space of TRF

Performing statistical analysis (i.e., rm-ANOVA) over a 3-D space of TRF reveals the existence of significant differences between at least two repetitions on specific frequency bands, electrodes, and time points. Performing the following Post-hoc analyses (3rd-1st, 3rd-2nd, 2nd-1st) in the same 3-D space of TRF explores which of these pairwise analyses are statistically different. To either reject or accept the null hypothesis (no statistical difference between two specified conditions), a non-parametric statistical cluster-based permutation test (Maris & Oostenveld, 2007) (Montecarlo statistical analysis), implemented in the Fieldtrip toolbox (Oostenveld et al., 2011), was applied between every-two repetitions (3rd rep vs 1st rep, 3rd rep vs 2nd rep, and 2nd rep vs 1st rep). We exclude the first second (0 to 1 s) of listening to music because it reflects evoked responses to music onsets. We employed the following parameters to apply the statistical analysis: paired t-test (two tails) is used for the statistics, Montecarlo methodology is used to estimate significant probabilities, cluster method is used for MCP, WCM with the weight of 2 is used for cluster statistics methods, adjacency in the electrode is one, permutation with 10,000 randomizations is used for resampling, and alpha is set to 0.05 (P < 0.05). The statistical analysis is applied to 51 electrodes, 5 frequency bands (i.e., theta, alpha, low-beta, high beta, and gamma), and 18 time-points (1 to 10 s with the temporal resolution is 0.5 s: (10 s – 1 s) / 0.5 s = 18 time-points). A cluster is significant if the p-value is<0.05 ($P < 0.05$).

6.11. Descriptive analysis

This study concentrates on specific regions of interest (TFR-ROIs) for applying TFR analysis to determine the spectral characteristic of familiarization. Therefore, based on the findings of the previous studies in this context (Birbaumer et al., 1996; Peterson & Thaut, 2007; Sammler et al., 2011), three TFR-ROIs are considered in this work named the frontal midline area, left prefrontal area, and right prefrontal area. All the analyses in this section are descriptive and have not been tested for generalization. As is mentioned in the protocol section, since all three repetitions of each music excerpt lasted between 20 s and 80 s, neural activity related to short-term memory rather than long-term memory is expected to be elicited during the perception of music. Therefore, the frontal and bilateral prefrontal areas (corresponding to short-term memory) are our main concern in this study rather than the temporal and posterior areas (corresponding to long-term memory) (Koelsch, 2011; Schaefer et al., 2011). However, it is important to note that the power changes during music familiarization were analyzed across all electrodes, using a pre-specified statistical threshold (P-value = 0.05). Electrodes Fz, F1, and F2 indicate the activity of the first area (frontal midline area) (Gärtner et al., 2014). The second area is defined based on the previous studies, indicating that electrodes F3, FC3, F5, and FC5 represent the activity of the dorsolateral prefrontal cortex (DLPFC) (Casula et al., 2016); and electrode Af3 represents the overlap of BA9 and BA46 of the DLPFC (Daskalakis et al., 2008). Therefore, it is assumed that pooled electrodes Af3, F3, FC3, F5, and FC5 represent the activity of the left prefrontal area. Likewise, the activity of the third area (the right prefrontal area) is represented by pooling electrodes Af4, F4, FC4, F6, and FC6.

6.12. General linear model: A statistical relationship between participants' behavioral and neural data

Although performing a discrete statistical analysis for each behavioral and neural data provides a vivid perspective of how both data statistically change between every-two repetitions (3rd rep vs 1st rep, 3rd rep vs 2nd rep, and 2nd rep vs 1st rep), performing a general linear model (GLM) tests any potential links between increased familiarization and power changes of each frequency band (theta: 5–9 Hz, alpha: 9–13 Hz, low-beta: 13–21 Hz, high beta: 21–32 Hz, and gamma: 32–50 Hz). Therefore, a GLM was applied for each ROI (i.e., frontal midline, left prefrontal, and right prefrontal electrodes) to explore any direct relationship between neural and behavioral changes obtained from comparing every-two repetitions. In this regard, we employed implemented GLM in Matlab with default parameters: considering normal distribution, existing linear link function (i.e., identity function: $f(\mu) = \mu$), and removing the constant term to return one p-value ($P < 0.1$). Since 45 statistical GLM was performed in total (three ROIs * three conditions * five frequency bands), the false discovery rate (FDR) was performed to correct the p-values of multiple testing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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