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Research report

Lost in music: Neural signature of pleasure and its role in modulating attentional resources

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HIGHLIGHTS

- We studied the neural signature of positive and neutral valence with music.
- We examined performance in a visual memory task in different music conditions.
- Longer exposure to pleasant music led to higher spectral power and pleasantness score.
- Theta power was positively correlated with pleasantness scores in the course of music.
- Memory task performance during pleasant music was lower compared to neutral music.

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ABSTRACT

We investigated the neural correlates of pleasure induced by listening to highly pleasant and neutral musical excerpts using electroencephalography (EEG). Power spectrum analysis of EEG data showed a distinct gradual change in the power of low-frequency oscillations in response to highly pleasant, but not neutral, musical excerpts. Specifically, listening to highly pleasant music was associated with (i) relatively higher oscillatory activity in the theta band over the frontocentral (FC) area and in the alpha band over the parieto-occipital area, and (ii) a gradual increase in the oscillatory power over time. Correlation analysis between behavioral and electrophysiological data revealed that theta power over the FC electrodes was correlated with subjective assessment of pleasantness while listening to music. To study the link between attention and positive valence in our experiments, volunteers performed a delayed match-to-sample memory task while listening to the musical excerpts. The subjects' performances were significantly lower under highly pleasant conditions compared to neutral conditions. Listening to pleasant music requires higher degrees of attention, leading to the observed decline in memory performance. Gradual development of low-frequency oscillations in the frontal and posterior areas may be at least partly due to gradual recruitment of higher levels of attention over time in response to pleasurable music.

1. Introduction

Throughout history, music has played an important role in human culture. Its ubiquity in most human lives is indicative of its role in producing pleasure and a sense of reward. The modulatory role of music and musical emotions in other cognitive processes (Soto et al., 2009; Masataka and Perlovsky, 2012) suggests common mechanisms underlying these processes and make music a valuable tool for investigating the neural correlates of emotions (Koelsch, 2014).

Composers use dynamic variations in multiple attributes of music, such as loudness, rhythm, tempo, timbre, and pitch, which can influence musical emotions (Gomez and Danuser, 2007). The sequential unfolding of music takes us on a journey. The uniqueness of the emotional responses to music is related to the dynamic nature of this specific stimulus. Most studies on the neural correlates of listening to music and the psychological responses to musical stimuli have only

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considered the mean responses to music samples lasting tens of seconds to several minutes (Blood and Zatorre, 2001; Baumgartner et al., 2006; Flores-Gutiérrez et al., 2007; Koelsch et al., 2013). To date, only a few studies have investigated the dynamics of music processing in the brain (Chapin et al., 2010; Jäncke et al., 2015) and the temporal changes in the neural correlates of musical emotions (Koelsch et al., 2006, 2013; Sammler et al., 2007; Salimpoor et al., 2011). Due to the dynamic nature of musical stimuli with changing acoustic features, it is more plausible to investigate the temporal dynamics of musical emotions and also, importantly, the time-varying neural responses that induce the associated emotional experiences.

Emotionally significant stimuli are particularly effective in capturing attention (Markus et al., 2003; Schupp et al., 2004; Phelps et al., 2006). Attentive listening to natural music recruits attentional resources (Janata et al., 2002). The modulatory role of top-down attentional processes while listening to pleasant music (selected by the investigator) has been suggested, due to the positive emotional valence of music (Koelsch et al., 2006). Moreover, increased fMRI BOLD signal responses in the anterior cingulate cortex have been associated with targeted attention toward pleasant music (Mitterschiffthaler et al., 2016). It has also been suggested that modulation of fMRI BOLD activity in the auditory cortex while listening to pleasant music is due to more detailed acoustic analysis, because of a shift of attention in response to music (Koelsch et al., 2013), as well as its influential role in the networks underlying the affective processing of auditory information (Koelsch et al., 2018). Being absorbed by music has also been associated with “narrowed awareness” (Becker, 2014; Palazzi et al., 2018). People even report unsolicited personal thoughts and memories, as well as ‘mind wandering’ episodes, while listening to their favorite music‘ (Becker, 2014; Koelsch et al., 2018; Palazzi et al., 2018). It has been suggested that neural activity in the medial frontal cortex and posterior regions while listening to one’s own favorite music (Wilkins et al., 2015) and observation of highly moving artworks (Vessel et al., 2012, 2013; Cela-Conde et al., 2013) may be indicative of a ‘self-referential’ state.

The aim of this study was to investigate the temporal dynamics of the neural response to pleasant music in comparison to neutral (N) music. On the basis of the aforementioned studies, we hypothesized that variations in the level of pleasure experienced and the temporally developing emotional response while listening to highly pleasant (HP) music could potentiate and build up sustained attention in response to a HP musical stimulus. In the light of the findings reported above, we addressed (i) whether HP music enhances activity in the cortical regions that mediate attention over time as positive valence develops; and (ii) whether this phenomenon manifests behaviorally as a deterioration of performance in a simultaneous attention-demanding task. For this purpose, 1) power spectrum analysis of EEG data was performed at different time intervals while listening to music, in order to evaluate the time-course of the cortical response to HP and N music conditions, 2) correlation analyses were conducted under different HP and N music conditions between behavioral assessment and spectral power at different time intervals of exposure to the different conditions, in order to investigate the relationship between cortical oscillations and behavioral manifestations of musical emotions, and finally 3) volunteers were asked to perform a visual memory task while listening to HP and N music with recording of their electrodermal activity (EDA) to study the effects of music-induced emotions on attentional recruitment in a visual task unrelated to music or auditory processes.

2. Results

2.1. Behavioral results

Values for subjective assessments of pleasantness for the six 60-second musical excerpts tested are presented in Table 1. Pleasantness scores for two excerpts, namely MS1 and MS6, were equal to 8.75 (0.58) and 8.81 (0.54), respectively. Considering ~4–5 as the middle of the scale (1–9), the participants rated excerpts MS3 and MS5 as neutral (with mean scores of 4.13(0.8) and 3.98(0.67), respectively). In the light of this observation, together with initial inspections of neural responses, data corresponding to MS1 and MS6 and data corresponding to MS3 and MS5 were pooled to create two conditions of HP and N excerpts for further investigation on the neural substrate and the corresponding behavioral manifestation of listening to HP/N music. Repeated measures ANOVAs followed by *post hoc* analysis conducted with the music condition factor revealed that ratings of pleasantness did not differ significantly ($p > 0.05$) for 60 s musical excerpts corresponding to the same condition, but were significantly different ($p < 0.001$) for 60s musical excerpts corresponding to different conditions. The results corresponding to MS2 and MS4 were excluded (the results are presented as Supplementary data) from the report to provide greater contrast and to facilitate comparison between the two HP and N conditions.

Table 1
Average ratings of pleasantness for the six musical excerpts reported as mean (standard deviation).

Musical Selection (MS)	Name	Mean (SD)
MS1	Mozart, Eine kleine Nachtmusik (Allegro)	8.75(0.58)
MS2	Mozart, Eine kleine Nachtmusik (Rondo Allegro)	7.43(1.32)
MS3	Bach, Badinerie (Overture No. 2, BWV 1067)	4.13(0.8)
MS4	Pournazeri, Heart’s Moan	7.89(1.02)
MS5	Payvar, Four Mezrab	3.98(0.67)
MS6	Pournazeri, Hidden as heart	8.81(0.54)

2.2. Cortical response to music stimuli: power spectra analysis (Group 1)

Global cortical response: Maps of the grand-averaged theta/alpha power changes for the 60-second HP music condition with respect to the N music condition are depicted in Fig. 1. A frontocentral (FC) region of interest (ROI) consisting of Fz and FCz, corresponding to the highest theta power, was chosen for statistical analysis of theta band power changes (ROI I). Theta power over FC electrodes was significantly higher during HP compared to N excerpts, as reflected by a significant effect of condition ($F(1–10) = 75.261$, $p < 0.001$), while comparing the MS from the two HP and N music conditions, in an ANOVA with factor condition followed by *post hoc* analysis conducted over ROI I. The effect size (Cohen, 1988) when comparing HP and N music over the ROI was situated in the very large range of Cohen’s standard ($d = 3.83$). A ROI consisting of parieto-occipital (PO) electrodes P3, Pz, and P4, corresponding to the most pronounced alpha power, was chosen for statistical analysis of alpha band power (ROI II). Alpha power over parietal electrodes was significantly greater during HP compared to N excerpts, as revealed by a significant effect of condition ($F(1–10) = 31.128$, $p < 0.001$) in an ANOVA with condition factor followed by *post hoc* analysis over ROI II. The effect size when comparing HP and N music over the aforementioned ROI was situated in the large range of Cohen’s standard ($d = 1.67$). No significant effect ($p > 0.05$) of MS was observed in this analysis when comparing 60-second musical excerpts from the same HP or N conditions in either of the frequency bands (see Fig. 1 for comparisons between MS corresponding to the two conditions). These results support our decision to pool data corresponding to MS1 and MS6 and data corresponding MS3 and MS5 under HP and N conditions, respectively.

Time course of the cortical response: Global theta (although more pronounced in the FC electrodes) and posterior alpha oscillatory power both increased over the time course of the 60-second exposure to the HP music condition (Fig. 2). A Spearman correlation analysis between

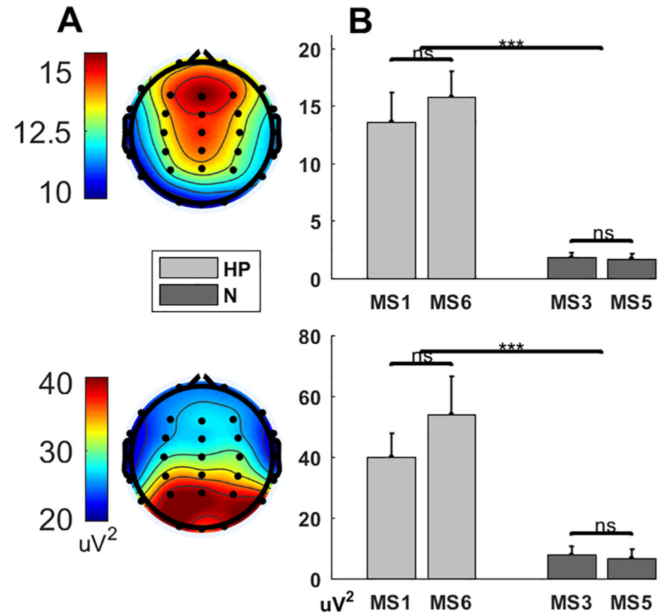

Fig. 1. (A) Maps of the grand-averaged theta (top) and alpha (bottom) power changes for the HP music condition with respect to the N music condition. (B) Top: mean theta power averaged over the frontocentral electrodes Fz and FCz for the four musical excerpts. Bottom: mean alpha power averaged over the parieto-occipital electrodes P3, Pz, and P4 for the four musical excerpts. Asterisks indicate significant differences in mean power over conditions (HP vs N). However, the effect was not significant (ns) when comparing MSs from the same condition. $^{***}p < 0.001$. Error bars indicate standard deviations.

theta power over ROI I and alpha power over ROI II revealed a significant positive correlation ($R = 0.84$, $p < 0.01$) between these two variables, indicating a similar trend for the oscillatory power over the two frequency bands for the HP music condition. However, this increasing pattern was not observed for the N music condition, and correlation analysis between oscillatory powers over ROI I and ROI II did not demonstrate a significant correlation ($p > 0.05$). The time course

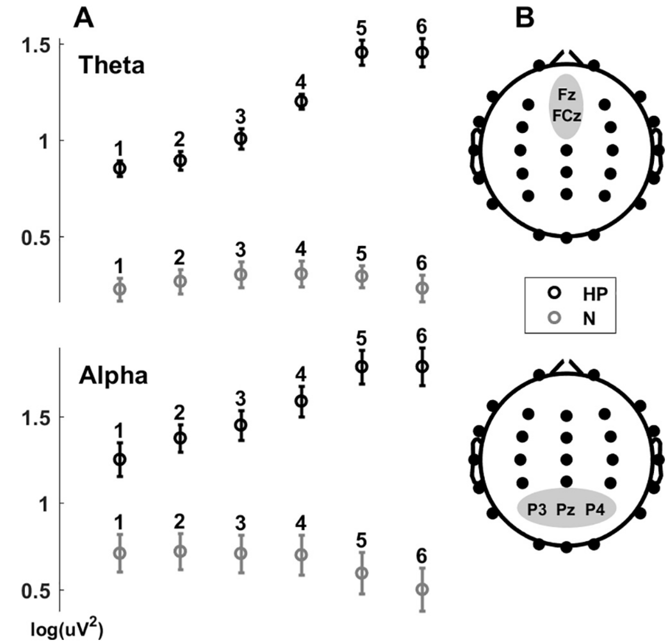

Fig. 3. (A) Time course of variations in the mean theta power (top) averaged over ROI I and mean alpha power (bottom) averaged over ROI II for both HP and N music conditions. The shaded regions indicate the ROIs of statistical analysis. (B) ROI I for statistical analysis of theta (top) and ROI II for statistical analysis of alpha (bottom) band power. Numbers 1 to 6 indicate the first to sixth time windows, respectively.

of changes in the average theta and alpha power is depicted in Fig. 3 over ROI I and ROI II, respectively. Repeated measures ANOVAs for the two ROIs were conducted with condition and time factors for theta and alpha frequency ranges, respectively. Theta power over ROI I was greater during the HP condition compared to the N music condition, as reflected by a significant main effect of condition ($F(1–10) = 68.738$, $p < 0.001$). In addition, the effect of time ($F(1–10) = 27.292$, $p < 0.001$), and the interaction between factors ($F(1–10) = 27.759$,

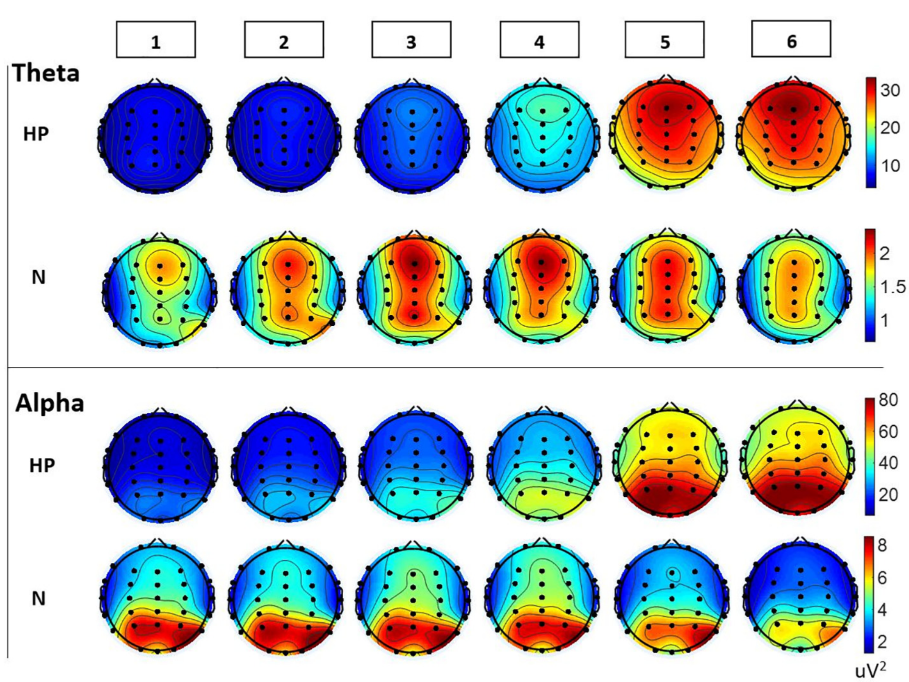

Fig. 2. Maps of the average values of theta (top) and alpha (bottom) power over six time windows while listening to highly pleasant (HP) and neutral (N) music. Numbers 1–6 indicate the first to sixth time windows, respectively.

$p < 0.001$) was significant. Two follow-up repeated measures ANOVAs were performed for HP and N music conditions separately, with time factor. A significant effect of time was observed for the HP music condition ($F(1–10) = 28.256$, $p < 0.001$), showing a significant increase in the theta power over the FC electrodes toward the end of HP musical excerpts. This effect was not significant for the N music condition ($p > 0.05$). Repeated measures ANOVA over ROI II for the alpha frequency range with condition and time factors revealed a significant main effect of condition ($F(1–10) = 30.082$, $p < 0.001$), suggesting relatively higher alpha power for the HP music condition. The effect of the time factor ($F(1–10) = 12.007$, $p < 0.01$) and the interaction between factors ($F(1–10) = 14.649$, $p < 0.01$) were also significant. On separate follow-up ANOVAs for the two conditions, the effect of time was only significant for the HP music condition ($F(1–10) = 13.308$, $p < 0.01$), with a significant increase while listening to HP (but not N) musical pieces.

2.3. Correlation analysis of time-dependent spectral power and behavioral assessments (Group 1 and Group 2)

Behavioral assessments of pleasantness were higher in response to longer durations of pleasant music (Fig. 4). Spearman correlation analysis for the HP music condition revealed a significant correlation between exposure time and pleasantness ratings ($R = 0.7$, $p < 0.001$). However, no significant correlation was observed between pleasantness ratings and exposure time in the N music condition ($p > 0.05$). Inspection of the time course of ratings for the N music condition suggested an increase toward the middle of the excerpts, followed by a decline toward the end of the excerpts. A similar temporal pattern was also observed for theta spectral power over the frontal area for the N music condition together with a gradual increase in theta spectral power over the same area for the HP music condition (Fig. 2), leading us to investigate the relationship between the variation of mean z-scored spectral power (as average over subjects) over time at different electrodes and the behavioral data (as average over subjects) shown in Fig. 4. HP and N excerpts were not pooled for this analysis, therefore providing 24 data points (4 excerpts × 6 time intervals). The scatter plot of the mean z-scored theta power over another ROI consisting of FC electrodes Fz, FCz, and Cz versus average ratings of pleasantness is depicted in Fig. 5A.

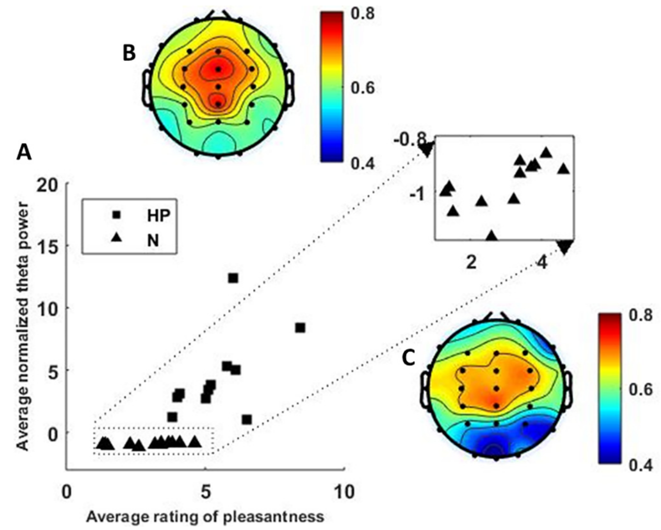

Fig. 5. (A) Scatter plot of the averaged normalized theta power versus the average pleasantness ratings. Each data point was created by computing the group average of the normalized theta power (and pleasantness ratings) in response to listening to cumulative fragments of the four musical stimuli (corresponding to HP or N conditions). For greater clarity, the figure is also zoomed over the N excerpts. Spearman's correlation coefficient of the pattern of variations between the two variables, shown in (A), is given over different electrodes for HP (B) and N (C) music conditions. Color bars indicate the value of the correlation coefficient.

When considering all four excerpts, Spearman correlation analysis revealed a significant positive correlation ($R = 0.76$, $p < 0.001$) between the average normalized theta power over the ROI and the average pleasantness ratings. A significant positive correlation ($R = 0.69$, $p < 0.05$) was still observed when only two excerpts corresponding to the N condition were taken into account. The maximum correlation was observed over the frontal and central electrodes for both the HP and N music conditions (although it was more pronounced for the HP music condition). The pattern of correlation variation over the electrode locations is depicted in Fig. 5B and C for the two conditions. No significant correlation ($p > 0.05$) was observed between the

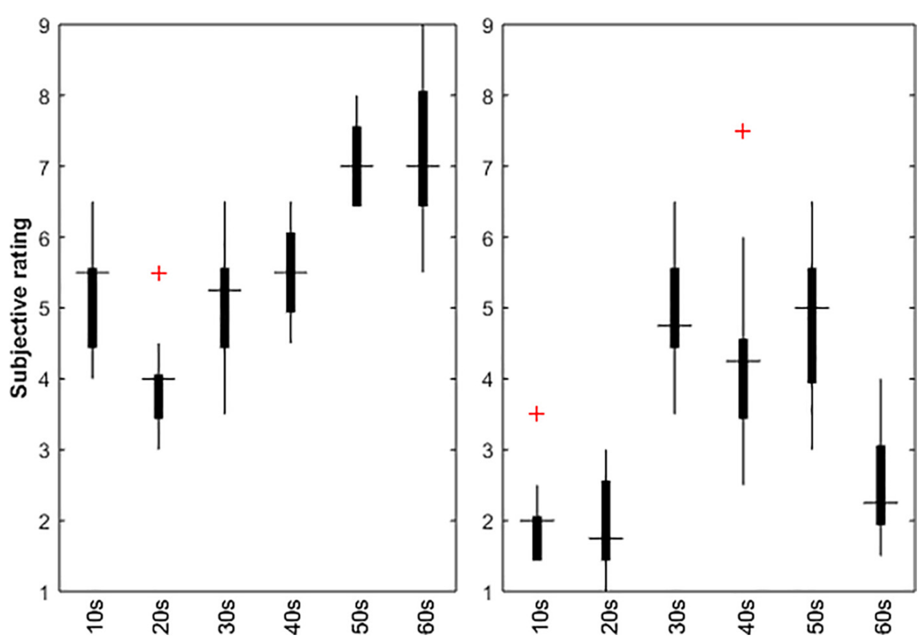

Fig. 4. Subjective ratings of pleasantness while subjects were exposed to fragments of HP (left) and N (right) music stimuli of different lengths. Red plus signs represent outliers.

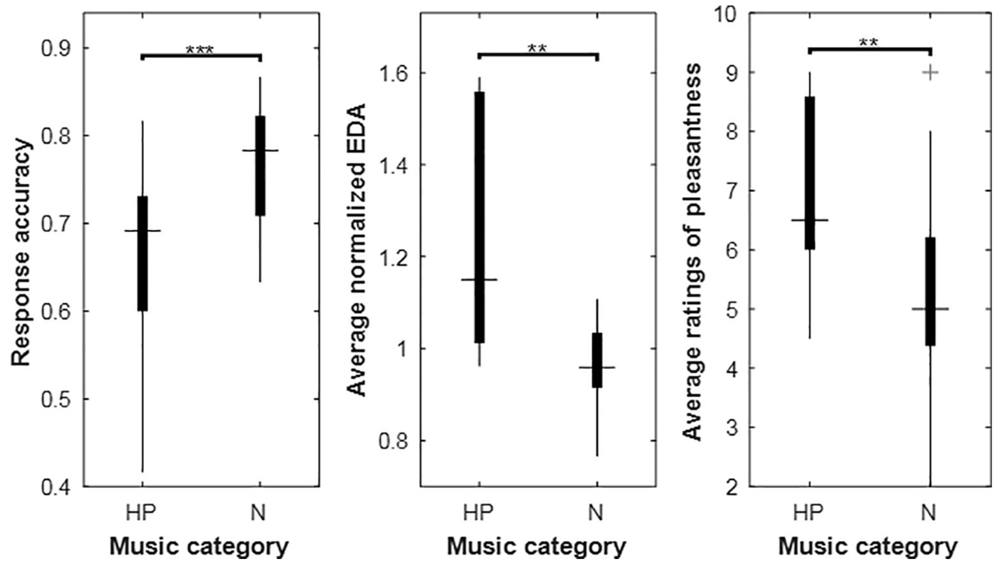

Fig. 6. DMS response accuracy averaged over blocks corresponding to HP and N music conditions (left). Mean normalized EDA for HP and N music conditions (middle). Mean subjective pleasantness scores for the two conditions (right). ** for $p < 0.01$ and *** for $p < 0.001$. The red plus sign represents an outlier.

group average of normalized alpha power at any electrode location and the group average of pleasantness ratings. In addition, in order to check the role of the acoustic features of the stimuli, namely tempo and spectral centroid, in the elicited neural and behavioral response, we performed Spearman correlation analysis between the average normalized theta power over the ROI (as well as the average ratings of pleasantness) and the two aforementioned features. This analysis did not lead any significant correlation either between the acoustic features and the theta power or between the acoustic features and average ratings of pleasantness (Supplementary Fig. S2).

2.4. Attentional-emotional task (Group 3)

As depicted in Fig. 6, performance (in terms of response accuracy) during the delayed match-to-sample (DMS) task concurrent with the HP music condition was lower, and the standard deviation was higher, compared to the N music condition; the difference was significant, as revealed by a paired-sample t-test ($t(15) = -5.83$, $p < 0.001$). Electrodermal activity (EDA) was significantly higher and the distribution was wider during the HP music condition compared to the N music condition. Fig. 6 shows the normalized EDA values, averaged over the duration of the musical excerpts, for the two conditions. Paired-sample t-test revealed that the average normalized EDA values corresponding to the HP excerpts were significantly larger than those corresponding to the N music condition ($t(15) = 3.4$, $p < 0.01$). The average subjective pleasantness scores for the HP music condition concurrent with the DMS task, although lower than those in the EEG experiment (Table 1), were still significantly higher than the pleasantness scores for the N music condition ($t(15) = 3.42$, $p < 0.01$) (see also Fig. 6). No significant gradual pattern was observed in the task performance for either of the two conditions. The response time during the DMS tasks was also not significantly different between the two conditions.

3. Discussion

This study investigated the neural signature of positive and neutral valence in human volunteers as they listened to pleasant and neutral music and also examined the subjects' behavioral performances in an attention-demanding visual memory task during these positive and neutral valence perceptual musical conditions. A significant effect of music-induced emotional states was observed in the theta and alpha power bands over the frontocentral (FC) and parieto-occipital (PO) regions between highly pleasant (HP) and neutral (N) music conditions. In addition, spectral analysis over the regions of interest (ROIs) and behavioral analysis also revealed that longer exposure to HP music resulted in significantly increased spectral power and higher pleasantness scores. Theta power over the FC ROI and alpha power over the PO ROI were significantly correlated while listening to music during the HP music condition, but not the N music condition. FC theta power in both the HP and N music conditions was positively correlated with pleasantness scores while listening to music. EDA values were significantly higher for the HP music condition than for the N music condition. Performances in terms of response accuracy during the DMS task concurrent with the HP music condition were lower compared to those during the N music condition.

Fronto-midline (FM) theta power has been reported to indicate heightened mental effort (Sauseng et al., 2010) and has also been reported during encoding, rehearsal, and retrieval of working memory (WM) tasks, possibly as a consequence of functions such as sustained attention (Mitchell et al., 2008). Increased FM theta has also been reported to be a signature of successful regulation of emotion (Ertl et al., 2013) and has been associated with emotional processing of music (Sammler et al., 2007). The source of FM theta is believed to be in the anterior cingulate cortex (ACC) and several studies have reported the role of the ACC in the processing of musical emotions (Koelsch and Siebel, 2005; Koelsch, 2014). Widespread heightened theta activity and a gradual increase of this activity while listening to pleasant music has recently been reported (Jäncke et al., 2015) and widespread theta activity has also been observed during meditation (Aftanas and Golocheikine, 2001; Aftanas and Golocheikine, 2003) and 'mind wandering' (Braboszcz and Delorme, 2011). Subjective scores of internalized attention and pleasantness of the emotional experience during meditation have been shown to be positively correlated with frontal theta power (Aftanas and Golocheikine, 2001), and mean FM theta power (averaged over 44s) while listening to pleasant music is positively correlated with valence (Sammler et al., 2007). Providing further evidence, the present study demonstrated that a positive correlation between FC theta power and pleasantness scores existed during the course of listening to music under both HP and N conditions. The results of the present study support (i) affective modulation of frontal theta power during the experience of pleasantness and (ii) a gradual build-up of emotional response while listening to HP music. Increased alpha band power, mostly in the centro-parietal regions, has been observed while listening to pleasant music (Jäncke et al., 2015), and during meditation (Aftanas and Golocheikine, 2001) and has been suggested to be indicative of suppressed external attention and is associated with inhibition of networks not required for controlling the ongoing task at hand (Sadaghiani et al., 2009; Jäncke et al., 2015). Our observation of gradually increasing alpha power in posterior regions, together with widespread increasing frontal theta power, corresponding to categories of both general and FM theta processing, and their positive correlation over time under the HP music condition may indicate switching off mechanisms of external attention related to the auditory experience of pleasurable music. Three observations support our hypothesis; (i) the gradual increase in pleasantness scores during the behavioral study under the HP music condition, (ii) the significant correlation between theta power and pleasantness score while listening to music, accompanied by (iii) significantly decreased performances in the DMS task under the HP music condition, which requires a shift of attention from the pleasurable music.

During the DMS task, subjective assessment of pleasantness and average EDA values were both significantly higher for the HP music condition than for the N music condition. EDA is usually considered to be an indicator of emotional arousal (Bradley and Lang, 2000; Khalfa et al., 2002). However, the psychophysiological dimensions of emotion (valence and arousal) were deliberately not separated in the present study, as such an approach might have incited the subjects to try to evaluate the emotional content of music, instead of reporting the emotions that they personally experienced. Our definition of pleasantness may therefore contain both valence- and arousal-related information. Alternatively, elevated EDA has been reported during exposure to stress (Jackson Payne et al., 2005; Shin and Liberzon, 2010). Although the EDA during our experiment may have been modulated by the level of stress induced by the DMS task, this factor was the same under both the HP and N music conditions.

It is suggested that when attentional resources are directed toward a certain temporal location, expectation and preparedness is increased and behavior is more efficient (Correa et al., 2005). Most music is based on temporally structured sequences of events (Large, 2008; Large et al., 2015). The metrical structure of music with its strong and weak beats can shape expectancies about the salient temporal locations, which might in turn modulate temporal attention, and movement coordination (Janata and Grafton, 2003; Correa et al., 2005; Levitin et al., 2018). Recent findings demonstrate that entrainment to an auditory rhythm can influence visual attention (Escoffier et al., 2010; Bolger et al., 2014; Trost et al., 2014) and that music listening can entrain attentional resources in synchrony with the musical meter (McAuley, 2010; Bolger et al., 2013). This effect might have been present in the current study, however, it is less probable that the performance of subjects in the DMS task has benefited from rhythmic entrainment of attentional processes, since the visual stimuli in the DMS task were not time-locked with the musical beat.

The subjects' performance in the DMS task concurrent with the HP music condition was significantly lower than that concurrent with the N music condition. It has been suggested that listening to music enhances cognitive performance. For instance, enhanced visual awareness (Soto et al., 2009) and WM performance (Mammarella et al., 2013), as well as reconciliation of cognitive dissonance (Masataka and Perlovsky, 2012) have been reported while subjects listened to music. However, in the literature, either a specific musical piece was generally used (Introna and Wood, 2004; Masataka and Perlovsky, 2012; Mammarella et al., 2013; Xing et al., 2016) or the effect of preferred music was contrasted with non-preferred music (Rowe et al., 2007; Soto et al., 2009) or a different kind of activity (Särkämö et al., 2008). In our study, none of the musical excerpts were rated as unpleasant. Moreover, during selection of music excerpts, we did not include any musical excerpts with negative valence. Our findings are therefore consistent with previous reports of the enhancing role of music on cognitive performance. We suggest that, while listening to HP music, the subjects were probably 'drawn into' the music and hence paid less attention to the outside world, resulting in relative deterioration of performance in the DMS blocks concurrent with HP music compared to the DMS blocks concurrent with N music. Reduced performance in a concurrent WM task under the HP music condition reflects the negative effect of highly pleasurable music in an attention-demanding cognitive task, and the possible advantages for preferred but not highly pleasurable music. The demonstrated effect therefore suggests the need for detailed investigation of subjects' musical preferences in interventions designed to enhance cognitive functions by means of music (Särkämö et al., 2008; Soto et al., 2009; Bottiroli et al., 2014).

There are a few limitations to this study. First, although we tried to control for participants age range, musical/educational background, and familiarity with the musical pieces used in the study, individuals' personal musical experiences might have varied among participants. Second, acoustic features such as tempo and timbre could systematically differ between the HP/N musical excerpts in our study. Neural oscillation and therefore behavioural responses could have been affected by the physical differences rather than valence per se. To examine a potential relationship between acoustic features and our EEG and behavioural results, we performed correlation analysis between acoustic features and neural/behavioural responses and between behavioral and neural responses. Our findings suggest that low level acoustic features have not contributed to the reported results. However, further studies are needed to address this issue by using a large number of musical excerpts belonging to the two musical categories or selecting the musical excerpts as well as subjects in a way that a stimulus rated as highly pleasant by one subject is considered as neutral by another subject. Such experiments can, more reliably, rule out the role of variations in acoustic features between the stimuli belonging to the two categories.

4. Materials and methods

4.1. Participants

We recruited 117 volunteers for different experiments of this study. Participants were non-musicians (49 females; mean age: 22 ± 6 years) with similar educational backgrounds (undergraduate or MSc students). All subjects were right-handed, had normal hearing, and had no history of any neurological disease. They reported normal nocturnal sleep patterns (7–9 h starting from 10 pm to 12am) during the week before the experiment. They had not consumed caffeine, nicotine, or energy drinks on the day of the experiment and had not performed excessive exercise during the 24 h before the experiment. None of the subjects had received formal musical training. However, they reported that listening to music was a part of their daily activities (at least 2 h per day). Written informed consent was obtained from all subjects and the study was conducted according to the Declaration of Helsinki. The experimental protocols were approved by the Ferdowsi University of Mashhad Ethics Committee. All volunteers were rewarded by either monetary compensation or course credits. Participants were recruited into three groups according to the purpose of the study and in the course of the whole experiments; Group 1: n = 16 for EEG recording and analysis, Group 2: n = 72 for behavioral assessment, Group 3: n = 29 for the attentional-emotional task.

4.2. Stimuli

The musical stimuli used in this study comprised the first 60 s of the following six non-vocal compositions: Mozart, Eine kleine Nachtmusik (Allegro and Rondo Allegro) (MS1 and MS2, respectively), J.S. Bach, Badinerie (Overture No. 2, BWV 1067) (MS3); Pournazeri, Heart's Moan (MS4), Payvar, Four Mezrab (MS5), Pournazeri Hidden as heart (MS6). Each of these 60-second musical excerpts were recorded from commercially available CDs (tempo of the musical excerpts is provided as Supplementary information) and were chosen on the basis of the results of an initial pilot study (Supplementary information) to include excerpts with both positive and neutral emotional content. The sound level was faded in and out at the beginning and at the end of the stimulus in order to reduce the risk of eliciting a startle response. During the experiments, the 60-second musical excerpts were rated according to the degree of pleasantness, ranging from one (highly unpleasant) to nine (highly pleasant). Subjects were instructed to rate their own emotional state and were asked not to assess the emotional content of the music (Krumhansl, 1997; Koelsch et al., 2006). To ensure that all participants were equally familiar with the musical excerpts, they were presented with the complete version of the musical pieces three to five days before the experiment and were instructed to listen to the pieces in a calm environment. During each experiment, stimuli were delivered via high quality stereo loudspeakers placed approximately two meters behind the subjects, who were seated in a comfortable chair in dim light.

4.3. EEG recording and data analysis

4.3.1. Experimental paradigm, EEG recording and preprocessing

Each trial started with a beep sound, followed by 30 s of silence and 30 s of brown noise. Each 60-second musical excerpt was presented once. The 60-second musical excerpts were presented to the subjects in random order in different trials. Subjects were instructed to close their eyes when they heard the beep sound, and to open their eyes once the excerpt had faded out. At the end of each trial and immediately after exposure, the subjects were asked to rate the pleasantness of the excerpts. The next trial began three seconds after the subject had indicated the pleasantness score (Fig. 7).

EEG was recorded using the Neuroscan system (Neuroscan, El Paso, TX) with 30 Ag/AgCl sintered electrodes mounted on an elastic cap at locations Fp1, Fp2, F7, F3, Fz, F4, F8, FT7, FC3, FCz, FC4, FT8, T7, C3, Cz, C4, T8, TP7, CP3, CPz, CP4, TP8, P7, P3, Pz, P4, P8, O1, Oz, O2. Recordings were performed in AC mode (0.05–60 Hz) at a 1 kHz sampling rate. Channel impedance was kept at $< 5\,\mathrm{k}\Omega$. Data were resampled offline at a 500 Hz sampling rate. EEG data were subsequently re-referenced to the algebraic mean of the left and right mastoid electrodes (M1, M2). Artifacts (e.g., eye-blink, eye-movement, and muscle activity) were removed by Independent Component Analysis (ICA) using EEGLAB toolbox (Delorme and Makeig, 2004). For artifact reduction, EEG data were excluded whenever, during an 800 ms sliding window, the standard deviation of EEG amplitude exceeded 40 μV, or any sampling point exceeded ± 75 μV at any electrode location. Finally, the first two seconds and the last second of EEG signals corresponding to each stimulus were removed from the data. Data from five out of 16 subjects were discarded because of the poor SNR (n = 2), and discomfort and lack of attention during the experiment (n = 3).

4.3.2. Power spectra analysis

First for each subject, 60-second musical excerpt, and at each electrode location, the remaining 57 s (after removing the first two seconds and the last second) of data was z-scored. EEG data corresponding to each 60-second musical excerpt were then divided into segments with a 1.5-second Hamming window with 30% overlap. For each segment power spectra were computed via Fast Fourier Transform (FFT) over artifact-free EEG epochs and then averaged to yield the mean power spectrum. The time course of the brain response to musical stimuli was then investigated by computing the mean power spectra over 10-second segments (with 2-second overlap, except for the last segment which had a 3-second overlap. The same segmentation strategy was also applied to the EEG data corresponding to 30 s of silence, after removing the first 2 s and the last 1 s. Mean values corresponding to four power bands, namely, theta (4–8 Hz), alpha (8–13 Hz), beta (13–30 Hz), and gamma (30–40 Hz), were then calculated for each subject, excerpt, segment, and electrode location by averaging power values across frequency bins. The results corresponding to beta and gamma bands, although analyzed, are not presented here, as no robust significant effect was observed in either of the two frequency bands.

4.3.3. Correlation analysis of time-dependent spectral power and behavioral assessments

During EEG experiments, subjects were asked to open their eyes and provide a pleasantness score for each excerpt after the music had faded out. Participants were asked to rate the entire 60 s of each musical excerpt. As the purpose of this study was to examine the time course of EEG signals (in terms of spectral power), it was more plausible to try to detect time-varying psychological responses. Some authors have asked the participants to rate the musical stimuli continuously by cursor movement (Mikutta et al., 2014). However, this rating approach is conscious driven where the subjects decide to manipulate the cursor location to indicate their appraisal. The required introspection, which is associated with particular brain activations (Hutcherson et al., 2005), may affect the subjective assessment. To investigate the time course of pleasantness appraisal while listening to the musical excerpts a behavioral study, with no physiological recording was performed. The four 60-second musical excerpts, with the highest and lowest scores of pleasantness scores were used for this study. Six copies of different durations of each initial 60-second musical excerpt were created. The beginning of each copy was the same as that of the original excerpt, while the endings were separated by 10-second intervals, so that the durations of the first and last copies were 10 s and 60 s, respectively. Sound faded in and out at the beginning and at the end of each copy. During the experiment, subjects listened to each copy of each 60-second musical excerpt only once with their eyes closed. At the end of each copy and immediately after exposure, participants were asked to rate the pleasantness of the copies by using the pleasantness rating scale.

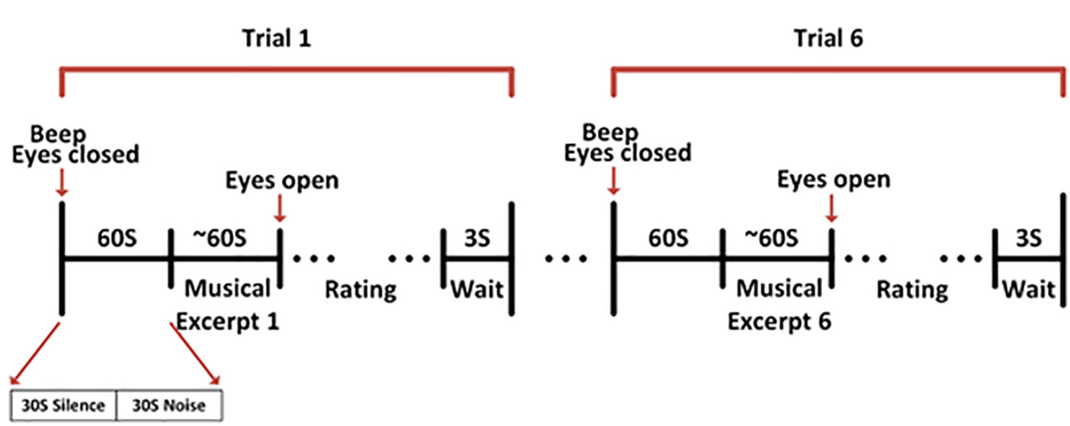

Fig. 7. Diagram of the experimental protocol for EEG recording while listening to musical stimuli.

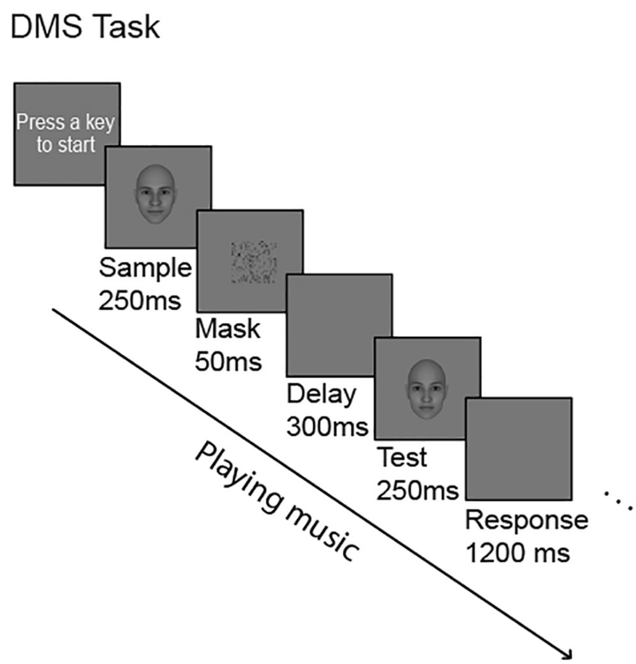

Fig. 8. Paradigm for one trial in the DMS task.

Once the participant had completed the rating, a beep sound indicated the upcoming stimulus and the next copy was presented after 3 s. The 24 stimuli (4 × 6 copies of 60-second musical excerpts) were presented in random order to the subjects. Each subject listened to only one copy of each excerpt (no subject listened to two or more copies of each excerpt), resulting in 12 exposures to each copy of each excerpt (72 subjects/6 copies). The scores corresponding to each copy were subsequently averaged among participants, thereby creating 24 average scores (4 excerpts × 6 copies).

During correlation analysis between behavioral and electrophysiological data for each subject, musical excerpt (*m*), electrode (*e*), and frequency band of interest (*f*), the individual average EEG band power was z-scored using the average and standard deviation of power corresponding to silence (*s*), $\bar{P}_m(e, f) = \frac{P_m(e,f) - \mu_{P_S(e,f)}}{\sigma_{P_S(e,f)}}$. For each frequency band of interest, participant, excerpt, and electrode, the mean z-scored spectral power was then computed over the six segments 2–10 s, 2–20 s, 2–30 s, 2–40 s, 2–50 s, 2–59 s, and averaged among participants. This calculation was performed for the EEG data corresponding to the four excerpts with the highest and lowest pleasantness scores, thereby resulting in 24 values (4 excerpts × 6 segments) for each electrode location. The time intervals chosen for calculation of the mean spectral power were the same as those of the six copies of each excerpt used when studying the time course of subjective assessment, except for the first 2 s and the last 1 s that were removed for EEG spectral analysis. The correlation between the 24 average scores (4 excerpts × 6 copies) and the 24 mean z-scored spectral power values (4 excerpts × 6 time intervals) was determined in order to investigate the relationship between behavioral and electrophysiological data for each frequency band of interest.

4.4. Attentional-emotional task

To further address the interaction between HP music and attention, a psychophysical task was performed. Participants were asked to perform a working memory (WM) task while listening to the musical stimuli. We hypothesized that attention modulation by the musical excerpts would manifest behaviorally as relative deterioration of performance in the WM task.

A delayed match-to-sample (DMS) task was performed with stimuli consisting of nine computer-generated face images developed for a previous study from our group (Salehi et al., 2017). The task consisted of six blocks, with each block comprising 30 trials (15 match and 15 non-match trials). In each trial, a sample face image was presented on a computer monitor for 250 ms. The stimulus was immediately followed by a 50 ms mask. After a 300 ms blank period, the test stimulus was presented for 250 ms and participants had 1200 ms to indicate whether the two stimuli were identical or different (match and non-match trials, respectively). The next trial did not start before 1200 ms whether or not the participant had provided a response before 1200 ms (Fig. 8). The sample and test stimuli were subtended 6.5 visual degrees at their longest dimension. Masks were produced by scrambling the sample stimuli. Each possible non-match stimulus pair was displayed 12 times for each specific category (see (Salehi et al., 2017) for the definition of category) with equal probability for the sample or test stimuli. The 15 match trials in a block included all nine faces as well as another six randomly selected faces. Order and selection of the face pairs were random in each block and in each run of the task. Response time for each trial was also recorded during the experiment. Subjects had to press the Space button to start each block. Four 60-second musical excerpts (two with the highest and two with the lowest pleasantness scores) as well as 60 s of silence and 60 s of brown noise accompanied the six DMS blocks (random order, with an inter-block interval of 3–5 min). At the beginning of the experiment, subjects were informed that they had to perform the DMS task and still pay attention to the musical stimuli. After the experiment, subjects had to evaluate (on a scale from 1 to 9) whether or not they paid attention to each 60-second musical excerpt.

To measure the emotional response of subjects to 60-second musical excerpts during the experiment, electrodermal activity (EDA) was recorded using g.GSR sensor (g.tec Medical Engineering GmbH, Austria) sampled at 20 Hz from index and ring fingers of the left hand. Prior to the DMS task, 60 s of baseline recording was performed which was later used to normalize EDA data for each subject. Response accuracy was computed as $\frac{\text{number of correct responses}}{\text{total number of trials}}$. Data from 13 of the 29 subjects were discarded because of insufficient DMS trials (n = 3), lack of attention to music (n = 5), poor EDA SNR (n = 2) or outlier EDA values and subjective scores (n = 3).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.brainres.2019.01.011.

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