scientific reports

OPEN

Entrainment of rhythmic tonal sequences on neural oscillations and the impact on subjective emotion

Jiaxin Ding[1,6], Xiaochen Zhang[1,6], Jingjing Liu[2], Zhishan Hu[1], Zhi Yang[3]✉, Yingying Tang[1,4,5]✉ & Yue Ding[1,4,5]✉

Music possesses a remarkable capacity to evoke a broad spectrum of subjective responses and promote healing in humans, with rhythm playing a crucial role among its various elements. Rhythmic entrainment is considered as one of the fundamental mechanisms, yet its subsequent behavioral responses and quantitative relationship remain unclear. In the study presented here, we combined behavioral and electroencephalography experiments to explore the relationship between neural entrainment and emotional responses to rhythmic auditory stimuli, focusing on the emotional dimensions of valence, arousal, and dominance. Our findings reveal that while all sequences across 12 different presenting rates significantly entrain neural oscillations, sequences at different rates elicit distinct impacts on subjective emotional experience. The intensity of neural entrainment is associated with changes in emotional valence and dominance under specific frequency conditions. This insight addresses a gap in the existing literature regarding the dominance dimension and provides potential for developing more targeted and precise clinical interventions to enhance emotional well-being in the future.

Keywords Rhythmic tonal sequence, Entrainment, Neural osillation, Subjective emotion

Abbreviations

EEG	Electroencephalography
EPS	Evoked power spectrum
ITPC	Inter-trial phase coherence

The therapeutic potential of music in modulating emotional states has been extensively acknowledged across both non-clinical and clinical settings, from alleviating anxiety in cancer patients[1] to improving mood regulation in individuals with neurodegenerative disorders[2]. Notably, rhythmic auditory stimulation, when devoid of the melodic complexity inherent in music, demonstrates comparable efficacy in enhancing emotional well-being[3,4]. Various forms of rhythmic auditory stimulation have been reported to alleviate emotional symptoms. For instance, a study demonstrated that the Schumann resonance frequency (7.83 Hz), a special frequency between the theta and alpha bands, when presented as an isochronous tonal sequence, effectively reduced anxiety and promoted emotional calmness[5]. Furthermore, patients with mild anxiety exhibited significant improvements in anxiety symptoms following exposure to a mixture of theta and delta binaural beats[6]. While the neural mechanisms of rhythmic stimulation are well-established in motor rehabilitation, language therapy, and attention regulation[7], how the structured rhythmic patterns confer emotional benefits remains obscured.

Emotional processing fundamentally relies on distributed neural networks[8] where oscillatory activity coordinates cross-regional communication[9,10]. Crucially, previous studies have shown that specific neural oscillation features are correlated with the key dimensions of emotion: valence (a bipolar continuum from

[1]Shanghai Mental Health Center, Shanghai Jiao Tong University, School of Medicine, Shanghai, China. [2]Department of Psychosomatic Medicine, Shanghai East Hospital Tongji University School of Medicine, Shanghai, China. [3]Beijing Key Laboratory of Mental Disorders, National Clinical Research Center for Mental Disorders & National Center for Mental Disorders, Beijing Anding Hospital, Capital Medical University, Beijing, China. [4]Mental Health Branch, China Hospital Development Institute, Shanghai Jiao Tong University, Shanghai, China. [5]Shanghai Key Laboratory of Psychotic Disorders, Shanghai, China. [6]Jiaxin Ding and Xiaochen Zhang have contributed equally to this work. ✉email: yangz@mail.ccmu.edu.cn; yytang@smhc.org.cn; yueding@smhc.org.cn

displeasure to pleasure), arousal (spanning sleep to frenzied excitement), and dominance (ranging from feelings of helplessness to control), as conceptualized in the three-dimensional emotion model[11]. For instance, high arousal stimuli have been linked to a decrease in alpha and beta band power[12], whereas alpha asymmetry in parieto-occipital networks correlates with emotional valence processing[13]. Dominance, though less studied, may engage beta oscillations in frontoparietal control networks[14]. Overall, low frequency oscillations of delta and theta ranges are associated with motivational and emotional processes[15]. Beyond emotion detection and processing, oscillatory activity also plays a crucial role in emotion regulation. Increased frontal theta power is associated with successful cognitive reappraisal[16], and theta oscillations over frontal-midline regions have been robustly associated with emotional arousal regulation[17], establishing a physiological link between brain oscillations and emotion regulation processes. These frequency-specific dynamics create "oscillatory gateways", where external rhythmic stimuli that match endogenous brain frequencies could selectively modulate emotional dimensions[18,19].

Importantly, these frequency-specific oscillations are also involved in music processing. Rhythmic external stimuli can induce phase locking and enhance the neural oscillatory activity of corresponding frequency bands in the brain. This neural entrainment, defined as the stimulus-driven synchronization of neuronal oscillations to periodic external inputs[19,20], typically manifests through two complementary neurophysiological signatures[21]: phase coherence, which refers to the consistency of phase alignment across stimulus repetitions, reflecting temporal precision of entrainment[22], and stimulus-evoked power enhancement, wherein amplitude amplification at the driving frequency, indicating resonance strength[23]. Previous research has demonstrated various forms of auditory rhythms, such as isochronous sound sequences, monaural or binaural rhythms, and music, can induce entrainment, though the effects vary[24]. Both monaural and binaural beats in the theta frequency band can modulate subcortical response and cortical activity, with monaural beats showing stronger modulation[25]. Research utilizing human intracranial electroencephalography has observed that a 5 Hz binaural beat increases temporal phase synchronization, while a 5 Hz monaural beat leads to decreased mid-temporal synchronization[26]. The synchronization theory between neural oscillations and external rhythms has been validated also in studies using real music beats as stimuli, where beat frequency and its higher-order harmonics modulate neural responses[27,28]. Beat frequencies selectively enhance EEG power through meter-specific synchronization[29], demonstrating the brain's preferential response to rhythmically structured inputs. However, despite these advancements, the precise mechanisms by which rhythmic auditory stimuli—particularly those with frequency-specific characteristics—affect emotional states remain a subject of ongoing debate.

These unresolved questions serve as the impetus for our investigation into how different rhythmic frequencies influence emotion, with a particular focus on neural entrainment and emotional experience. Building on the above framework, we hypothesize that musical rhythm acts as an external "oscillatory pacemaker", entraining emotion-related circuits through frequency-matched phase alignment. Hence, in order to contribute more evidence in this field and investigate the entrainment of neural oscillations to rhythmic auditory stimuli, specifically examining how tonal sequences of varying frequencies affect subjective emotional experiences, we conducted a combined behavioral and EEG experiment in which participants were required to listen to twelve tonal sequences with different frequencies and to assess their affective responses through self-reported valence, arousal and dominance ratings. We hypothesize that rhythmic tonal sequences will induce frequency-specific neural entrainment corresponding to their stimulation rates, modulate emotional dimensions (valence, arousal, dominance) differently through entrainment-mediated oscillatory changes by exhibiting relationships between entrainment strength and emotional response magnitude. Our research aims to elucidate the mechanisms by which rhythmic auditory input influences affective states, focusing on the relationship between neural entrainment and emotional responses. In addition, this study also seeks to provide potential implications and inspiration for the clinical therapeutic use of music in mental disorders, emotional troubles and cognitive training or rehabilitation by offering a deeper understanding of potential mechanisms.

Materials and methods

Participants

A total of 40 graduate students were recruited for this study from colleges and universities. Due to the technical issues, 3 participants' recordings were invalid, who were excluded from the data analysis, ending up with 37 participants (19 males and 18 females, mean age = 22.72 ± 1.91 years) with balanced gender and age. All participants had normal hearing and either normal or corrected-to-normal vision, with no reported history of mental disorders or severe physical illnesses.

The study was conducted in accordance with the Declaration of Helsinki and approved by the local ethics committee (SMHC-IRB: 2021-45). Participants gave their written informed consent and received monetary compensation for their participation.

Stimulus and procedure

The experiments were conducted in a regular room. Acoustic stimuli were delivered to the participant via a wired loudspeaker (BMS09, Lenovo) through a PC (171501-AQ, Xiaomi). Stimuli were delivered at a comfortable sound level (65 ~ 75 dB) adjusted according to each participant's report. Testing protocols were executed with a custom MATLAB (MathWorks, Natick, MA) program developed in our laboratory.

Tonal sequences were composed of eight musical notes from the F major scale (F, G, A, Bb, B, C, D and E). To ensure the tonal sequences were musically structured as defined by the Western tonal system, a transition matrix providing the transition probabilities between pitch classes was adopted[30]. Pitch classes – that is, pitch regardless of octave – form the state space of the Markov chain, while the relative frequencies with which one pitch class leads to the following pitch class form the matrix of transition probabilities. To ensure the naturalness of the sound of the musical note, the sound file of each note was generated by Noteflight[31]. The sound files were imported into MATLAB and 12 tonal sequences were generated based on the transition matrix. The sequences obeyed to 1 to 12 Hz as the presenting rate of the tonal notes (Fig. 1B). That is for 1 Hz stimulus, one note was presented per second; for 2 Hz stimulus, two notes were presented per second, etc. Each sequence lasted for one minute. The selection of the particular frequency range (1–12 Hz) was guided by three key considerations from neuroscientific and music cognition perspectives: (1) As stated in the introduction, the 1–12 Hz spectrum encompasses major oscillatory bands implicated in distinct emotional processes. This coverage allows systematic investigation of frequency-specific emotion-circuit engagement; (2) Ecological validity in musical rhythm perception: While beta/gamma oscillations (> 12 Hz) are relevant for higher-order cognitive processing, musical beat perception exhibits strict temporal constraints. As demonstrated by London[32], the human pulse perception window spans 0.5–10 Hz (30–600 bpm), with upper bounds constrained by auditory temporal resolution. Our 12 Hz upper limit slightly exceeds this range to ensure full coverage of musically-relevant tempi while avoiding non-perceptual pulse rates (> 12 Hz ≈ 720 bpm); (3) Addressing methodological limitations in prior work: Existing studies typically employ sparse frequency sampling (e.g., comparing only fast vs. slow tempo), potentially obscuring nuanced frequency-emotion relationships. Our 1–12 Hz continuum with 1 Hz resolution provides capacity to disentangle overlapping functions within broad bands. All the participants listened to the same 12 sequences but with different orders (Fig. 1A). The 12 sequences were randomly presented to participants. The spectrum of the envelope of the 12 stimuli was showed in Fig. 1C.

The variance in emotional assessments, before and after listening to each piece, were accounted for by three major dimensions: affective valence, arousal, and dominance[33], by a series of Self-Assessment Manikins (SAM)[34] Scales using 9-point scales (1–9).

EEG data collection and preprocessing

The EEG was continuously recorded from 64 Ag/AgCl electrodes using a NeuSenW amplifier (Neuracle, China). Electrode positions conformed to the extended 10–20 system. All channels were digitized at a sampling rate of 1000 Hz. AFz served as the ground and CPz as the online reference. Electrode impedances were below 10 kΩ at the beginning of the experiment.

EEG data were preprocessed offline using a combination of the EEGLAB (version 14.1.2b), and FieldTrip (version 20200130) toolboxes in MATLAB (version 2019b; MathWorks), as well as custom-written MATLAB scripts. Continuous data from each run were imported into EEGLAB and the non-EEG channels were excluded. The data were then high-pass filtered (pass-band edge = 0.5 Hz, transition width = 0.5 Hz) using a zero-phase, hamming-windowed, finite impulse response (FIR) sinc filter (implemented in the pop_eegfltnew function from the frflt plugin; v2.4), followed by a low-pass filter with the stop frequency being 120 Hz. Data were then filtered for line noise using a band-stop filter at 50 and 100 Hz (0.5 Hz bandwidth). The flatline and cross-talk channels were identified and spherically interpolated, which were processed with artifact subspace reconstruction (implemented with the pop_clean_artifacts function from the clean_rawdata plugin; v2.3 with flatline criterion = 5 s; channel correlation criterion = 0.80). Data were then re-referenced to the common average reference (CAR) prior to independent component analysis (binica implementation of the extended logistic infomax ICA algorithm). Resultant decompositions were automatically classified using the ICLabel plugin (v1.342). Components classed as either ocular or cardiac in origin with > 90% probability were subtracted. The ICA weight matrix was subsequently applied to the original data. Note that the maximum number of ICA components to be extracted was determined by the residual degrees of freedom after SSS rank reduction during MaxFiltering. Continuous data were then segmented in epochs of 2 s with no overlap, as the lowest stimulus

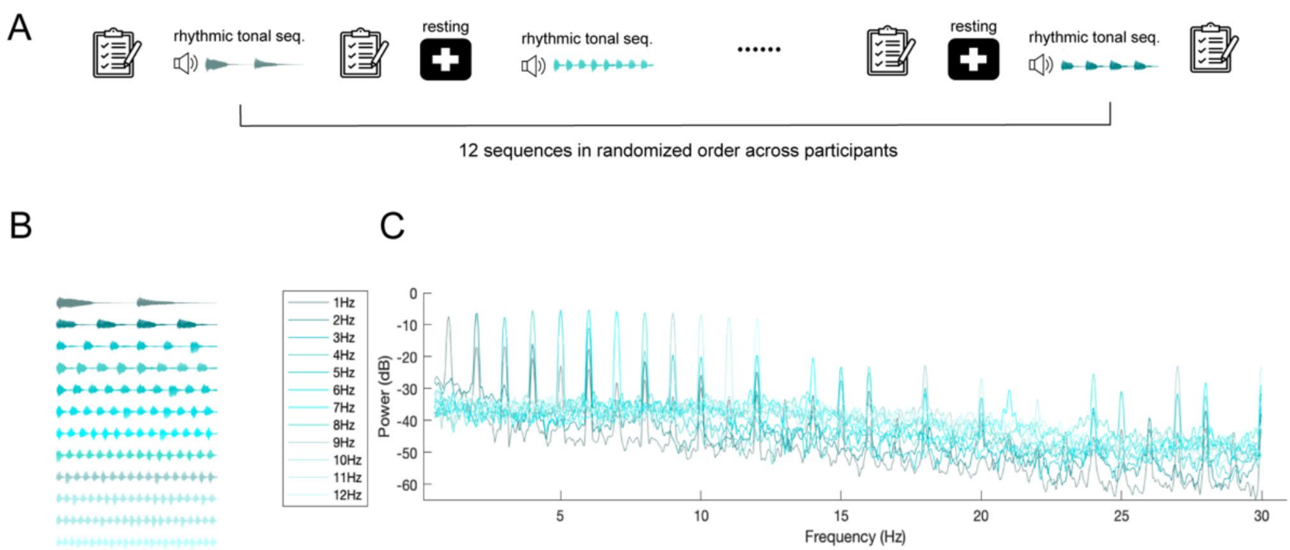

Fig. 1. Schema of the experiment procedure (**A**), stimuli (**B**) and the spectrum of the envelope of the stimuli (**C**). Each row in subfigure B indicates stimuli with different rates ranging from 1 Hz to 12 Hz, from top to bottom.

frequency was 1 Hz and 2 s contained two complete circles for further analyses. The epochs with a maximum amplitude of any channel larger than 100 uV were discarded from further analyses. 31 participants with more than 90% valid trials were included for the further analysis, which resulted in a total rejection of 1.33% of all trials. After these steps, data were exported from EEGLAB into the FieldTrip data format for further analyses.

Extracting entrainment features

We employed two distinct methods to measure the entrainment of rhythmic tonal sequences on neural oscillations: spectral measurement and phase measurement. Specifically, we focused on evoked responses for spectral analysis and inter-trial phase coherence (ITPC) for phase analysis. To extract these entrainment features, each 2 s epoch was taken as a trial. The EEG response in each trial was converted into the frequency domain of 1–15 Hz using the DFT with a 0.5 Hz step.

The complex-valued Fourier coefficient of a certain frequency bin was summed across trials, and evoked power spectrum (EPS) of this frequency is the normalized squared magnitude of the sum by dividing the trial number. It is the same as the power spectrum of the EEG response waveform averaged over trials. The EPS reflects the power of EEG responses that are synchronized to the tonal sequence.

The ITPC reflects the consistency of phase angles across multiple trials at a specific frequency, which measures how aligned or synchronized the phases of a particular frequency component are across different trials. The stimulus-driven phase alignment of endogenous oscillations, quantified through ITPC at the stimulation frequency, could then reflect neural entrainment. First, the complex Fourier coefficients are normalized by their magnitude to isolate the phase information, resulting in complex numbers with unit magnitude. These normalized complex values are then summed across trials for each time-frequency point. The absolute value of this sum is taken and normalized by the number of trials, yielding a value between 0 and 1, where 1 indicates perfect phase coherence across trials and 0 indicates no coherence.

Statistical analysis

The statistical significance of the neural response at a target frequency was tested for EPS and ITPC, respectively. For both features, we conducted repeated measures analyses of variance (ANOVAs) to examine the effects of tonal presenting rate and the response type (target vs. non-target). The target frequency was defined as matching the tonal presenting rate, while non-target frequencies were neither the tonal presenting rate nor its harmonics. If Mauchly's test indicated that the assumption of sphericity is violated, Greenhouse-Geisser correction was adopted for the factors with more than 2 levels. In cases where significant interactions were observed, post hoc tests were conducted using false discovery rate (FDR) corrected pairwise comparisons to identify specific differences between target and non-target for each tonal presenting rate.

Behavioral data were also analyzed using repeated measures ANOVAs. The influence of sampling time (before or after listening) and the tonal presenting rate on the three emotional ratings was examined. Similarly, if Mauchly's test indicated that the assumption of sphericity is violated, Greenhouse-Geisser correction was adopted for the factors with more than 2 levels. In cases where significant interactions were observed, post hoc tests were conducted using FDR corrected pairwise comparisons to identify specific differences between before and after listening for each tonal presenting rate.

Finally, for the frequency which demonstrated a significant emotional influence, a correlation analysis was conducted to explore the relationship between the modulation intensity of neural entrainment at the target frequency and the corresponding emotional changes. Pearson correlation coefficients were computed between entrainment magnitude (averaged across electrodes) and standardized emotion change scores (post- vs. pre-task).

The significance level for all statistical tests was set at $\alpha = 0.05$. Effect sizes were calculated using partial eta-squared (η^2) for ANOVA results and Cohen's d for post hoc comparisons.

Results

Entrainment of rhythmic tonal sequence on neural oscillation

We first analyzed the global field power of EEG responses (Fig. 2A and D). In this analysis, the ITPC and EPS were calculated for each electrode and then averaged over electrodes. In the grand average over subjects, the response to each frequency showed clear peaks at the target rates and their harmonics for both phase (Fig. 2A) and spectral (Fig. 2D) features, respectively. The results of the repeated measures ANOVAs demonstrated significant interaction between tonal presenting rate and the response type for both ITPC [$F(11, 330) = 4.81$, $p < 0.001$, $\eta^2 = 0.14$] and EPS [$F(11, 330) = 14.10$, $p < 0.001$, $\eta^2 = 0.32$]. While further comparison between response to target frequency and non-target frequency of global response showed that, for all the 12 presenting rates, the neural responses at target frequencies were significantly larger than those at non-target frequencies (Table 1) for both ITPC (Fig. 2B) and EPS (Fig. 2E).

To further elucidate the spatial distribution of entrainment effects, we examined the topographical patterns of EEG activity across the scalp. From the topography, we observed that the rhythmic sequences of 12 different rates significantly modulate neural oscillatory activity at corresponding frequencies, with a particularly pronounced effect in the frontocentral area, which is consistent between ITPC (Fig. 2C) and ESP (Fig. 2F).

The impact of rhythmic tonal sequence on subjective emotion

As shown in Fig. 3A, the averaged changes in subjective emotions of three dimensions after listening to the tonal sequences were influenced differently compared with before listening. In particular, all tonal sequences below 6 Hz decreased participants' valence feelings while increasing their dominance feelings (Table 2). Conversely, sequences above 6 Hz increased participants' valence feelings (except for 10 Hz, FDR corrected $p = 0.827$) while decreasing their dominance feelings. While for arousal, the changes were turbulent (Table 2).

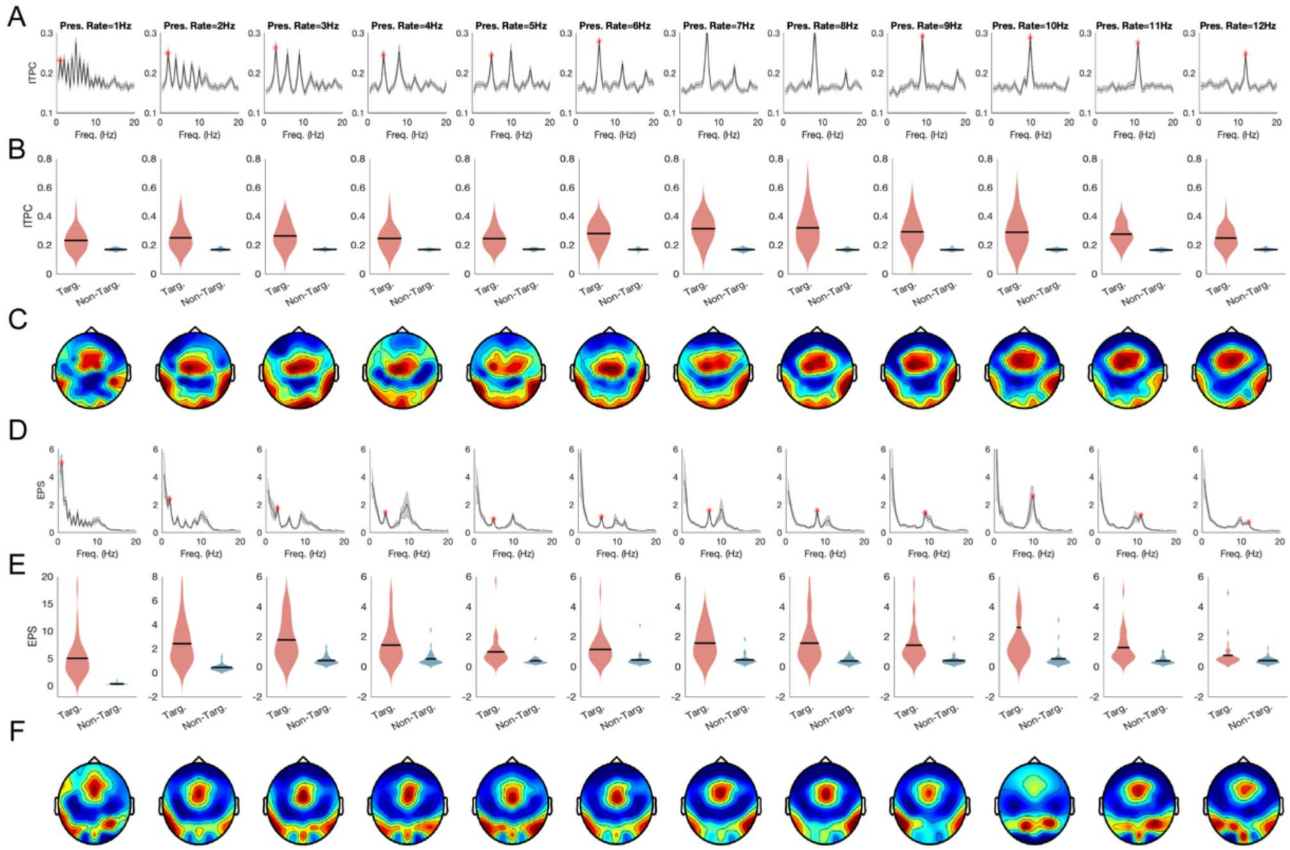

Fig. 2. Neural entrainment of rhythmic tonal sequence for phase and spectral features. (*A*, *D*) The response of both ITPC and EPS to each frequency showed clear peaks at the target rates and their harmonics. (*B*, *E*) For all the 12 presenting rates, the neural responses at target frequencies were significantly larger than those at non-target frequencies for both ITPC and EPS. (*C*, *F*) EEG topography revealed that rhythmic sequences at 12 different rates significantly modulate neural oscillations, particularly in the frontocentral region, with consistent effects observed in both ITPC and ESP.

Entrainment conditions															
Repeated measures analyses of variance (*p*-value)				**Post hoc test (FDR adjusted *p*-value)**											
	Tonal presenting rate	Response type (targ.vs non-trag.)	Interaction	1 Hz	2 Hz	3 Hz	4 Hz	5 Hz	6 Hz	7 Hz	8 Hz	9 Hz	10 Hz	11 Hz	12 Hz
ITPC	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
EPS	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.004	0.002	< 0.001	< 0.001	< 0.001	0.004	< 0.001	0.045

Table 1. Statistical information for EEG results (*p*-value).

The statistical analyses along the 12 presenting rates revealed that the dominance dimension was significantly affected by the interaction between time and frequency [$F(11,396) = 3.20$, $p < 0.001$, $\eta^2 = 0.08$] and marginally significantly affected by the time factor [$F(1,36) = 3.88$, $p = 0.057$, $\eta^2 = 0.10$]. However, the valence and arousal dimensions did not show significant effects for any of the factors (Table 2). Post hoc analysis with FDR correction further investigated the significant interaction effect observed in the dominance dimension. The results showed a significant impact of the tonal sequence at 3 Hz (FDR corrected $p = 0.032$) and 10 Hz (FDR corrected $p = 0.031$), which indicated that 3 Hz and 10 Hz could notably change the level of emotional dominance of participants. No significant differences were found for the valence and arousal dimensions at any specific rates (Table 2).

The relationship between neural entrainment and the changes of emotion

At last, the relationship between the modulation intensity of neural entrainment, in terms of ITPC and ESP, and emotional changes was tested.

Among all the conditions showing at least marginal significance in the behavioral data analysis, the neural entrainment of the tonal sequences with presenting rates above 6 Hz demonstrated a significantly positive correlation between modulation intensity of ITPC and the absolute changes of emotional valence ($r = 0.22$,

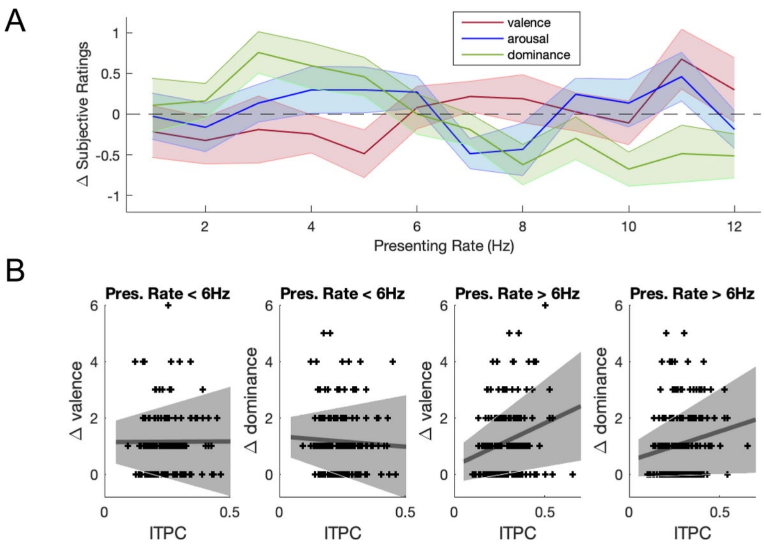

Fig. 3. The impact of rhythmic stimuli on subjective emotion and the relationship between modulation intensity and emotional changes. (*A*) The average changes in subjective emotions across the three dimensions—valence, arousal, and dominance—were assessed by comparing the states before and after listening to the 12 presenting rates. (*B*) The correlation between ITPC modulation intensity and changes in emotional valence and dominance was weak or negligible for tonal sequences below 6 Hz. However, for sequences above 6 Hz, the correlation was significantly positive.

Emotional changes		valence	arousal	dominance
Repeated measures analyses of variance	Tonal presenting rate	0.636	0.461	0.250
	Sampling time (before and after listening)	0.812	0.179	0.057
	Interaction	0.415	0.255	< 0.001
Post hoc test (FDR adjusted *p*-value)	1 Hz	0.787	0.925	0.813
	2 Hz	0.732	0.706	0.544
	3 Hz	0.827	0.706	0.032
	4 Hz	0.732	0.527	0.123
	5 Hz	0.641	0.527	0.131
	6 Hz	0.827	0.527	0.999
	7 Hz	0.732	0.146	0.445
	8 Hz	0.787	0.527	0.069
	9 Hz	0.909	0.527	0.397
	10 Hz	0.827	0.706	0.031
	11 Hz	0.641	0.527	0.297
	12 Hz	0.787	0.630	0.131
Averaged changes (After - Before)	1 Hz	-0.22	-0.03	0.11
	2 Hz	-0.32	-0.16	0.16
	3 Hz	-0.19	0.14	0.76
	4 Hz	-0.24	0.30	0.60
	5 Hz	-0.49	0.30	0.46
	6 Hz	0.08	0.27	0.00
	7 Hz	0.22	-0.49	-0.19
	8 Hz	0.19	-0.43	-0.62
	9 Hz	0.03	0.24	-0.30
	10 Hz	-0.11	0.14	-0.68
	11 Hz	0.68	0.46	-0.49
	12 Hz	0.30	-0.19	-0.51

Table 2. Statistical information for behavior results.

$p = 0.002$) and dominance ($r = 0.16$, $p = 0.030$) (Fig. 3B). That's, as the rhythmic tonal sequences with high presenting rates made participants feel more happy but less dominant of self's emotion, the stronger the modulation intensity is the stronger emotional influence the rhythmic tonal sequences could make. However, the neural entrainment of tonal sequences with presenting rates below 6 Hz showed a weak or negligible correlation between ITPC and absolute changes in valence ($r = 0.00$, $p = 0.969$) and dominance ($r = -0.05$, $p = 0.549$) (Fig. 3B).

Discussion

The present work integrates electrophysiological recordings and subjective emotional assessments to explore the link between neural entrainment and emotional reactions to rhythmic auditory input. Although all the rhythmic tonal sequences of 12 presenting rates can significantly entrain the neural oscillation, sequences at varying rates have distinct effects on the subjective emotional states. Furthermore, under the specific frequency stimuli, the strength of neural entrainment correlates with changes in emotional valence and dominance. This approach addresses three limitations of prior research: First, complex musical stimuli often conflate rhythmic and melodic effects[35]; Second, more comprehensive assessment of emotional changes including the neglected dominance dimension is conducted; Third, links between entrainment magnitude and emotional changes are quantified.

Music is known to induce strong affective reactions in listeners both in the form of pleasure and emotional responses. However, the psychological mechanisms that drive these processes are still poorly understood. Entrainment is the physical principle whereby temporally organized systems, or oscillators, tend to become synchronized as they interact with each other. Given the ubiquity of rhythmical patterns in both music and humans, rhythmic entrainment has been proposed as a potential emotion induction mechanism during music listening. The analysis results from our experiments provide deep insights into how different presenting rates with varying frequencies influence neural responses, as evidenced by both EPS and ITPC measures (Fig. 2). The choice of EPS and ITPC as indicators of neural entrainment aligned with two characteristics of entrainment at the population level, i.e. phase alignment and amplitude-increase[19]. The clear peaks observed in the global field power of EEG response of EPS and ITPC at target frequencies and the harmonics suggest that the brain's neural ensembles can robustly synchronize to those external tonal stimuli (Fig. 2A and D). This synchronization is not merely a general phenomenon but appears to be strongly frequency-specific, as indicated by the significantly larger neural responses at target frequencies compared to non-target frequencies across all 12 presenting rates (Fig. 2B and E). Other study also found similar results. Nozaradan and colleagues found that the magnitude of the SS-EPs elicited at frequencies related to beat and meter perception was significantly higher compared to the SS-EPs elicited at frequencies not associated with beat and meter[36]. Furthermore, our results aligned with the auditory steady-state response, which describes the phenomenon where neural ensembles exhibit an increase in power amplitude at the frequency of the auditory stimulation[37]. Previous researchers using intracranial electroencephalography (iEEG) recordings also demonstrated that auditory steady-state responses can occur at various frequencies (4–16 Hz) across different regions of the primary auditory cortex[38]. The spatial distribution of entrainment effects is shown in Fig. 2C and F. The topography revealed that this neural entrainment effect is not uniformly distributed across the whole scalp but is particularly pronounced in the frontocentral area. These patterns align closely with the scalp topographies observed in previous EEG measurements of entrainment responses to the acoustic envelope, which are characterized by a prominent fronto-central to posterior dipole[21,36,39]. The low-frequency BOLD signals that characterize the frontoparietal network are linked to relatively slow brain oscillations, particularly in the θ or α frequency range detectable through electrophysiological recordings. This connection likely plays a crucial role in facilitating the coordination of activities across the entire brain network[40].

Previous research has often directed attention to dichotomous categories of musical emotions, such as pleasant emotions against unpleasant emotions or emotions arranged along the same two fundamental dimensions of valence and arousal as other basic emotions[41]. However, the emotional dominance has been insufficiently addressed for an extended period. Previous literature has also highlighted the potential and the often overlooked importance of the dominance component in contextualized music listening[42]. Dominance refers to the feelings of control or influence on events or surroundings to what extent, which makes it possible to distinguish angry from anxious, alert from surprised, relaxed from protected, and disdainful from impotent[11]. Based on the data-driven analysis, a boundary emerged. Tonal sequences below 6 Hz heightened participants' feelings of dominance, while sequences above 6 Hz diminished these feelings. Furthermore, among the twelve stimulating rates tested, 3 Hz and 10 Hz could particularly alter participants' levels of emotional dominance, which may have unique implications for quantitative manipulation for precise intervention of emotional regulation in therapeutic interventions. While this division was based on data-driven discovery, its neurobiological plausibility can be supported by two key observations: (1) Theta-alpha transition zone: 6 Hz resides at the theoretical interface between theta (4–8 Hz) and low-alpha (8–10 Hz) bands. Recent work identifies 5–7 Hz as a functional transition point where sensory-driven theta rhythms shift to cognitive alpha oscillations[43]. (2) Cortico-subcortical resonance split: Aligns with hippocampal-cortical theta (3–6 Hz) crucial for emotional memory consolidation[44] and 6 Hz corresponds to thalamocortical alpha generation (8–10 Hz) involved in affective filtering[45].

By contrast, our results indicated that valence alteration has the opposite pattern compared to the change of dominance. All tonal sequences below 6 Hz decreased participants' valence feelings while sequences above 6 Hz increased their valence feelings. The former part may align with the fact that theta (4–8 Hz) has been shown to increase negative affect in some circumstances[46]. However, the previous research related to the application of auditory beat stimulation manipulating cognitive processes or modulating affective states yielded contradictory results[3]. Meanwhile, the effectiveness of beat stimulation can be influenced by various factors, including the length of time the stimulus is applied. For instance, quite a few researches have pointed out that exposure to the delta range (0–4 Hz) binaural beat would reduce the anxiety level[6,47,48], conforming to our findings since when anxiety decreases, individuals typically feel a greater sense of control over the situation, leading to a corresponding increase in the dominance dimension. Nevertheless, among these effective treatments mentioned above, except for one intervention lasting only thirty minutes, the remaining extended from one month to sixty days, and maybe this is the reason why their findings are inconsistent with our results of stimuli below 6 Hz decreasing valence. What's more, patients who received 10 Hz binaural-beat stimulation for 20 minutes showed a notable reduction in anxiety scores after the intervention compared to those who did not receive the stimulation[49], which means a rise in the emotional dominance. Given the divergence between our findings and those of Weiland, further research is needed to explore the underlying factors contributing to these differences.

Interestingly, we found that the average changes in emotional arousal are turbulent and do not show significant effects for time factor and the interaction between time and frequency. It aligned with a previous study in which found no variations in heart rate or skin conductance, utilized as indicator of emotional arousal, were detected across any of the beat frequencies used[50]. The lack of clear patterns could suggest that while rhythmic stimulation impacts other dimensions of emotion, like valence or dominance, its effect on arousal might be less straightforward, potentially requiring more nuanced or longer-term studies to fully capture its dynamics. Further exploration into these factors could provide deeper insights into how and when rhythmic sequences effectively modulate emotional arousal.

In the final part, we try to study in detail the affective consequences of neural modulations, thereby enhancing the understanding of relationship between modulation intensity and emotion alteration. We found that the neural entrainment induced by tonal sequences with presentation rates exceeding 6 Hz showed a significant positive correlation between the modulation intensity of ITPC and the absolute changes in emotional valence and dominance. In other words, as the high-rate rhythmic tonal sequences made participants feel happier but less in control of their emotions, the greater the modulation intensity, the more pronounced the emotional impact of the rhythmic sequences. This suggests that the degree of neural entrainment significantly influences emotional valence and dominance, providing evidence that rhythmic entrainment, specifically in the neural level, may be one of the underlying mechanisms through which music evokes emotions. The observed correlation between entrainment magnitude and emotional intensity may arise from two distinct yet complementary pathways. In the interoceptive channel, theta-band entrainment modulates autonomic resonance via vagal nerve regulation, generating visceral feedback that anchors emotional qualia in the body[51]. Simultaneously, even passive listening to musical rhythms recruits motor regions of brain[52], and neural synchronization in the motor channel could engage cortico-striatal circuits involved in predictive movement planning, generating approach-avoidance motivational states that translate rhythmic patterns into embodied affect[53]. Such sensorimotor predictions may simulate emotional resonance through corticospinal coherence with auditory rhythms, as posited by embodied simulation theories. These findings underscore the complex relationship between neural oscillations and emotional experiences, suggesting that different frequency ranges might differentially impact affective states. The proposed framework represents a testable hypothesis, rather than an established mechanism, warranting further investigation. Understanding these nuanced interactions could have implications for developing therapeutic interventions that utilize rhythmic auditory stimuli to modulate emotional states, particularly in clinical settings where managing affective disorders is crucial. Future research should explore the underlying neural mechanisms more deeply and consider individual differences in susceptibility to these frequency-specific effects.

While these findings provide valuable insights into the relationship between neural oscillations and emotional experiences, it's important to acknowledge the limitations of the current study and consider directions for future research. A key limitation is the relatively small sample size, which may affect the generalizability of the findings. Additionally, the specific frequencies selected and the duration of the stimuli may have influenced the outcomes, potentially limiting the broader applicability of the results. Previous research by Thut et al.[19] has reported that sustained entrainment effects are likely short-term, ceasing shortly after the end of the stimulus. This observation raises questions about the duration for which the evoked emotions are retained and highlights the need for further investigation into the temporal dynamics of these effects. Understanding this could have significant implications for designing clinical interventions that aim to induce or sustain particular emotional states. Except for further considering the duration of stimulation mentioned above, future research should explore a broader range of rates in rhythmic stimulation to better understand how different stimulating rates influence neural entrainment and emotional responses. This could identify specific ranges that are particularly effective for mood and cognitive interventions, leading to more targeted and efficient intervention. Additionally, using advanced brain imaging techniques like fMRI or MEG could offer deeper insights into the neural mechanisms of neural entrainment. These tools would help visualize the brain regions and networks involved, paving the way for developing more precise and personalized therapeutic approaches.

Conclusion

This study employed a combination of electrophysiological measurements and subjective emotional evaluations to investigate the relationship between neural entrainment and subjective emotional responses triggered by the rhythmic tonal stimuli. Across the 12 presentation rates of rhythmic tonal sequences examined, sequences at varying frequencies influenced the subjective emotion in varying ways. Notably, it sheds light on the emotional dimension of dominance, an area often underappreciated in previous studies. As all the sequences significantly entrain the neural oscillation, the nuanced relationship between neural entrainment and subjective emotional responses warrants further exploration. Expanding on these aspects could provide deeper insights into the neural mechanisms underlying emotional processing and contribute to more effective clinical applications for emotional health.

Data availability

Data is provided within the manuscript or supplementary information files.

Received: 19 October 2024; Accepted: 14 April 2025
Published online: 20 May 2025

References

1. Burns, D. S. The effect of the Bonny method of guided imagery and music on the mood and life quality of Cancer patients. *J. Music Ther.* **38** (1), 51–65. https://doi.org/10.1093/jmt/38.1.51 (2001).
2. Raglio, A. Effects of music and music therapy on mood in neurological patients. *World J. Psychiatry*. **5** (1), 68. https://doi.org/10.5498/wjp.v5.i1.68 (2015).
3. Chaieb, L., Wilpert, E. C., Reber, T. P. & Fell, J. Auditory beat stimulation and its effects on cognition and mood States. *Front. Psychiatry*. **6** https://doi.org/10.3389/fpsyt.2015.00070 (2015).
4. Chee, Z. J. et al. The effects of music and auditory stimulation on autonomic arousal, cognition and attention: A systematic review. *Int. J. Psychophysiol.* **199**, 112328. https://doi.org/10.1016/j.ijpsycho.2024.112328 (2024).
5. Ray, R. W. Isochronic Tones in the Schumann Resonance Frequency for the Treatment of Anxiety: A Descriptive Exploratory Study (Order No. 10618726). Available from ProQuest Dissertations & Theses Global. (1980860439). (2017). https://www.proquest.com/dissertations-theses/isochronic-tones-schumann-resonance-frequency/docview/1980860439/se-2
6. Scouranec, R. P. L. et al. &. Use of binaural beat tapes for treatment of anxiety: A pilot study of tape preference and outcomes. *Altern. Ther. Health Med.* **7** (1), 58–63. (2001).
7. Thaut, M. & Hoemberg, V. *Handbook of Neurologic Music Therapy* (Oxford University Press, 2014).
8. Malezieux, M., Klein, A. S. & Gogolla, N. Neural circuits for emotion. *Annu. Rev. Neurosci.* **46** (1), 211–231. https://doi.org/10.1146/annurev-neuro-111020-103314 (2023).
9. Buzsáki, G. & Draguhn, A. Neuronal oscillations in cortical networks. *Science* **304** (5679), 1926–1929. https://doi.org/10.1126/science.1099745 (2004).
10. Knyazev, G. G. EEG delta oscillations as a correlate of basic homeostatic and motivational processes. *Neurosci. Biobehav. Rev*. **36** (1), 677–695. https://doi.org/10.1016/j.neubiorev.2011.10.002 (2012).
11. Russell, J. A. & Mehrabian, A. Evidence for a three-factor theory of emotions. *J. Res. Pers.* **11** (3), 273–294. https://doi.org/10.1016/0092-6566(77)90037-X (1977).
12. Schubring, D. & Schupp, H. T. Emotion and brain oscillations: High arousal is associated with decreases in Alpha- and lower Beta-Band power. *Cereb. Cortex*. **31** (3), 1597–1608. https://doi.org/10.1093/cercor/bhaa312 (2021).
13. Harmon-Jones, E., Gable, P. A. & Peterson, C. K. The role of asymmetric frontal cortical activity in emotion-related phenomena: A review and update. *Biol. Psychol.* **84** (3), 451–462. https://doi.org/10.1016/j.biopsycho.2009.08.010 (2010).
14. Lindquist, K. A., Satpute, A. B., Wager, T. D., Weber, J. & Barrett, L. F. The brain basis of positive and negative affect: Evidence from a Meta-Analysis of the human neuroimaging literature. *Cereb. Cortex*. **26** (5), 1910–1922. https://doi.org/10.1093/cercor/bhv001 (2016).
15. Harmony, T. The functional significance of delta oscillations in cognitive processing. *Front. Integr. Nueurosci.* https://doi.org/10.3389/fnint.2013.00083 (2013). 7.
16. Ertl, M., Hildebrandt, M., Ourina, K., Leicht, G. & Mulert, C. Emotion regulation by cognitive reappraisal—the role of frontal theta oscillations. *NeuroImage* **81**, 412–421. https://doi.org/10.1016/j.neuroimage.2013.05.044 (2013).
17. Aftanas, L. I. & Golocheikine, S. A. Human anterior and frontal midline theta and lower alpha reflect emotionally positive state and internalized attention: High-resolution EEG investigation of meditation. *Neurosci. Lett.* **310** (1), 57–60. https://doi.org/10.1016/S0304-3940(01)02094-8 (2001).
18. Fries, P. Rhythms for cognition: Communication through coherence. *Neuron* **88** (1), 220–235. https://doi.org/10.1016/j.neuron.2015.09.034 (2015).
19. Thut, G., Schyns, P. & Gross, J. Entrainment of perceptually relevant brain oscillations by Non-Invasive rhythmic stimulation of the human brain. *Front. Psychol.* **2**, 170. https://doi.org/10.3389/fpsyg.2011.00170 (2011).
20. Zoefel, B., ten Oever, S. & Sack, A. T. The involvement of endogenous neural oscillations in the processing of rhythmic input: More than a regular repetition of evoked neural responses. *Front. NeuroSci.* **12** https://doi.org/10.3389/fnins.2018.00095 (2018).
21. Ding, N. et al. Characterizing neural entrainment to hierarchical linguistic units using electroencephalography (EEG). *Front. Hum. Neurosci.* **11**. https://doi.org/10.3389/fnhum.2017.00481 (2017).
22. Cohen, M. X. *Analyzing Neural time Series Data: Theory and Practice* (MIT Press, 2014).
23. Norcia, A. M., Appelbaum, L. G., Ales, J. M., Cottereau, B. R. & Rossion, B. The steady-state visual evoked potential in vision research: A review. *J. Vis.* **15** (6), 4. https://doi.org/10.1167/15.6.4 (2015).
24. Lehmann, A., Arias, D. J. & Schönwiesner, M. Tracing the neural basis of auditory entrainment. *Neuroscience* **337**, 306–314. https://doi.org/10.1016/j.neuroscience.2016.09.011 (2016).
25. Orozco Perez, H. D., Dumas, G. & Lehmann, A. Binaural beats through the auditory pathway: From brainstem to connectivity patterns. *Eneuro* **7** (2), ENEURO0232–192020. https://doi.org/10.1523/ENEURO.0232-19.2020 (2020).
26. Becher, A. K. et al. Intracranial electroencephalography power and phase synchronization changes during monaural and binaural beat stimulation. *Eur. J. Neurosci.* **41** (2), 254–263. https://doi.org/10.1111/ejn.12760 (2015).
27. Tierney, A. & Kraus, N. Neural entrainment to the rhythmic structure of music. *J. Cogn. Neurosci.* **27** (2), 400–408. https://doi.org/10.1162/jocn_a_00704 (2015).
28. Doelling, K. B. & Poeppel, D. Cortical entrainment to music and its modulation by expertise. *Proc. Natl. Acad. Sci. U.S.A.* **112** (45), E6233–6242. https://doi.org/10.1073/pnas.1508431112 (2015).
29. Nozaradan, S. Exploring how musical rhythm entrains brain activity with electroencephalogram frequency-tagging. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **369** (1658), 20130393. https://doi.org/10.1098/rstb.2013.0393 (2014).
30. Collins, T., Laney, R., Willis, A. & Garthwaite, P. H. Chopin, mazurkas and Markov: Making music in style with statistics. *Significance* **8** (4), 154–159. https://doi.org/10.1111/j.1740-9713.2011.00519.x (2011).
31. McConville, B. Noteflight as a web 2.0 tool for music theory pedagogy. *J. Music Theory Pedagogy*. **26** (1), 8 (2012).
32. London, J. *Hearing in Time: Psychological Aspects of Musical Meter* (Oxford University Press, 2012).
33. Bakker, I., van der Voordt, T., Vink, P. & de Boon, J. Pleasure, arousal, dominance: Mehrabian and Russell revisited. *Curr. Psychol.* **33** (3), 405–421. https://doi.org/10.1007/s12144-014-9219-4 (2014).
34. Bradley, M. M. & Lang, P. J. Measuring emotion: The self-assessment manikin and the semantic differential. *J. Behav. Ther. Exp. Psychiatry*. **25** (1), 49–59. https://doi.org/10.1016/0005-7916(94)90063-9 (1994).
35. Wollman, I., Arias, P., Aucouturier, J. J. & Morillon, B. Neural entrainment to music is sensitive to melodic spectral complexity. *J. Neurophysiol.* **123** (3), 1063–1071. https://doi.org/10.1152/jn.00758.2018 (2020).
36. Nozaradan, S., Peretz, I. & Mouraux, A. Selective neuronal entrainment to the beat and meter embedded in a musical rhythm. (2012).
37. Trost, W., Labbé, C. & Grandjean, D. Rhythmic entrainment as a musical affect induction mechanism. *Neuropsychologia* **96**, 96–110. https://doi.org/10.1016/j.neuropsychologia.2017.01.004 (2017).
38. Fujioka, T., Trainor, L. J., Large, E. W. & Ross, B. Beta and gamma rhythms in human auditory cortex during musical beat processing. *Ann. N. Y. Acad. Sci.* **1169** (1), 89–92. https://doi.org/10.1111/j.1749-6632.2009.04779.x (2009).
39. Baltzell, L. S., Srinivasan, R. & Richards, V. Hierarchical organization of melodic sequences is encoded by cortical entrainment. *NeuroImage* **200**, 490–500. https://doi.org/10.1016/j.neuroimage.2019.06.054 (2019).

40. Marek, S. & Dosenbach, N. U. The frontoparietal network: Function, electrophysiology, and importance of individual precision mapping. *Dialog. Clin. Neurosci.* **20** (2), 133–140 (2018).
41. Vuilleumier, P. & Trost, W. Music and emotions: From enchantment to entrainment. *Ann. N. Y. Acad. Sci.* **1337** (1), 212–222. https://doi.org/10.1111/nyas.12676 (2015).
42. Krause, A. E. & North, A. C. Pleasure, arousal, dominance, and judgments about music in everyday life. *Psychol. Music.* **45** (3), 355–374. https://doi.org/10.1177/0305735616664214 (2017).
43. Helfrich, R. F., Breska, A. & Knight, R. T. Neural entrainment and network resonance in support of top-down guided attention. *Curr. Opin. Psychol.* **29**, 82–89. https://doi.org/10.1016/j.copsyc.2018.12.016 (2019).
44. Hutchison, I. C. & Rathore, S. The role of REM sleep theta activity in emotional memory. *Front. Psychol.* **6**, 1439 (2015).
45. Hughes, S. W. & Crunelli, V. Thalamic mechanisms of EEG alpha rhythms and their pathological implications. *Neurosci. Rev. J. Bringing Neurobiol. Neurol. Psychiatry*. **11** (4), 357–372. https://doi.org/10.1177/1073858405277450 (2005).
46. Mallik, A. & Russo, F. A. The effects of music & auditory beat stimulation on anxiety: A randomized clinical trial. *PLoS ONE.* **17** (3), e0259312. https://doi.org/10.1371/journal.pone.0259312 (2022).
47. Padmanabhan, R., Hildreth, A. J. & Laws, D. A prospective, randomised, controlled study examining binaural beat audio and pre-operative anxiety in patients undergoing general anaesthesia for day case surgery. *Anaesthesia* **60** (9), 874–877. https://doi.org/10.1111/j.1365-2044.2005.04287.x (2005).
48. Wahbeh, H., Calabrese, C., Zwickey, H. & Zajdel, D. Binaural beat technology in humans: A pilot study to assess neuropsychologic, physiologic, and electroencephalographic effects. *J. Altern. Complement. Med. (New York N Y)*. **13**, 199–206. https://doi.org/10.1089/acm.2006.6201 (2007).
49. Weiland, T. J. et al. Original sound compositions reduce anxiety in emergency department patients: A randomised controlled trial. *Med. J. Aust.* **195** (11–12), 694–698. https://doi.org/10.5694/mja10.10662 (2011).
50. López-Caballero, F. & Escera, C. Binaural beat: A failure to enhance EEG power and emotional arousal. *Front. Hum. Neurosci.* https://doi.org/10.3389/fnhum.2017.00557 (2017). 11.
51. Critchley, H. D. & Garfinkel, S. N. Interoception and emotion. *Curr. Opin. Psychol.* **17**, 7–14 (2017).
52. Chen, J. L., Penhune, V. B. & Zatorre, R. J. Listening to musical rhythms recruits motor regions of the brain. *Cereb. Cortex*. **18** (12), 2844–2854 (2008).
53. Witek, M. A. Rhythmic entrainment and embodied cognition. *Science-Music Borderlands*, 161–182. (2023).

Acknowledgements

We thank Hongjian Huang, Yufeng Xia who helped with data collection, and Dr. Yifan Xu for his expertise in music-related professional knowledge.

Author contributions

Y.D., Z.Y. and YY. T. conceptualized the study. Y.D. also handled data curation, formal analysis, methodology, visualization, and was responsible for writing the original draft. JX.D. contributed to formal analysis and writing the original draft. XC.Z. secured funding and contributed to reviewing and editing the manuscript. JJ.L. was responsible for data collection, and ZS.H. provided resources. YY.T. supervised the study. Y.D. is the guarantor. All authors reviewed and approved the final manuscript.

Funding

The work described in this study was supported by the National Natural Science Foundation of China (62101324 and 32100885), the Fundamental Research Funds for the Central Universities (YG2025QNB13), Shanghai Municipal Health Commission (2024ZZ2066), Shanghai Municipal Education Commission (2024AIYB012), Shanghai Mental Health Center (2020-QH-01, 2020-YJ01) and the Shanghai Sailing Program (20YF1442000).

Declarations

Consent for publication

All the participants gave informed consent to participate in the study before taking part.

Competing interests

The authors declare no competing interests.

Ethical approval

This study involves human participants and was approved by the Shanghai Mental Health Center Institutional Review Board (SMHC-IRB ethics approval ID: 2021-45). Participants gave informed consent to participate in the study before taking part.

Additional information

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-025-98548-1.

Correspondence and requests for materials should be addressed to Z.Y., Y.T. or Y.D.