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Effects of Restorative Auditory Stimuli on College Students' Psycho Physiological State: An Experimental Study

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Abstract

Natural environmental sounds and music, as forms of restorative auditory stimuli, have potential psychological restorative value. However, changes in short-term state anxiety and electroencephalographic (EEG) activity under different auditory conditions warrant further investigation. This exploratory experimental study recruited 80 healthy university students and randomly assigned them to eight groups (10 participants per group): a natural environmental sound group, three music groups, three groups receiving combined natural sound and music stimuli, and a group with no additional sound. All participants successively underwent a resting baseline stage (Stage 1), an anxiety induction stage (Stage 2), and a restorative auditory intervention stage (Stage 3). State Anxiety Inventory (S-AI) scores and mean spectral amplitudes in the EEG Alpha, Beta, and Theta bands were recorded. EEG measures were averaged with equal weighting across the frontal, parietal, occipital, and temporal regions and then natural-log-transformed. Nonparametric statistical methods were used to analyze psychophysiological changes across experimental stages and auditory conditions. The results showed a tendency for state anxiety to increase following anxiety induction and an overall tendency to decrease following the auditory intervention stage. Different EEG frequency bands exhibited distinct stage-related trajectories, and psychophysiological responses under the various auditory conditions also showed some descriptive differences. These findings indicate that short-term anxiety induction and subsequent recovery are accompanied by dynamic changes in subjective state anxiety and whole-brain EEG activity. Different types of restorative auditory stimuli and their combinations may be associated with changes in individuals' psychophysiological states. This exploratory study provides preliminary evidence regarding psychophysiological responses to short-term restorative auditory environments among university students and offers a basis for future research with larger samples.

Keywords: EEG; music intervention; restorative soundscape; natural soundscape

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1. Introduction

Amid intensifying competition, university students face multiple unprecedented pressures. In contexts such as academic assessment, interpersonal relationships, and future career decisions, external evaluation and uncertainty about outcomes make students susceptible to immediate anxiety responses, including tension, worry, and unease. This emotional experience, whose intensity fluctuates with the situation, is termed state anxiety (Spielberger, 2010). Research indicates that state anxiety may affect attentional control

and the efficiency of cognitive processing and is closely related to students' attention and concentration during examinations (Eysenck et al., 2007; Fernández-Castillo & Caurcel, 2015). State anxiety can also elicit maladaptive cognitive responses, such as self-doubt and self-deprecation, and frequent episodes may accumulate as risk factors for chronic emotional disorders (Macher et al., 2013; Thomas & Cassady, 2021). Therefore, identifying effective ways to alleviate state anxiety is important for improving students' academic performance and emotional experiences and promoting mental health. At present, campus interventions for students' emotional and psychological problems mainly rely on psychoeducation and counseling. However, practical barriers, including limited access to resources, reluctance to seek help, and stigma, leave many students who need immediate emotional support without effective assistance (J. Yang et al., 2023). Developing accessible, low-threshold approaches to emotion regulation is therefore of considerable practical importance.

In recent years, researchers have explored ways to alleviate state anxiety through psychological self-regulation, sensory experiences, and contact with the environment. Studies have found that nonpharmacological interventions such as brief meditation (Edwards et al., 2018), music listening (Harney et al., 2023), and walking in parks (Song et al., 2014) show some anxiety-reducing effects in different research settings. Among these, auditory stimulation has increasingly attracted attention as an accessible, low-threshold form of emotion regulation and has been applied to stress reduction, emotion regulation, and the creation of restorative environments (Payne & Guastavino, 2018; Saskovets et al., 2025). Previous research suggests that both natural environmental sounds and music have some potential for psychological restoration (Ratcliffe, 2021; Suko et al., 2025), while combined auditory stimuli integrating natural sounds and soothing music have also increasingly been used in studies of relaxation and psychophysiological recovery (Yu et al., 2018; Kumpulainen et al., 2025).

The psychophysiological effects of auditory stimulation have been demonstrated using EEG. Researchers have found that emotional and cognitive processing during music listening is accompanied by changes in neural oscillations in frequency bands such as Theta, Alpha, and Beta (Sammler et al., 2007; Arjmand et al., 2017; Malekmohammadi et al., 2023). In the Theta band, studies have found that pleasant music induces greater frontal midline theta (Fm theta) power than unpleasant music, a change that may be associated with interactions between emotional processing and attentional function (Sammler et al., 2007). Further research has identified associations between the emotional valence elicited by music and changes in Theta power in frontocentral regions (Lin et al., 2010). In the Alpha band, frontal Alpha asymmetry has been widely used to investigate emotional processing and the lateralization of brain activity associated with approach–avoidance motivation (Smith et al., 2017). Related music experiments have found that pleasant music is more likely than unpleasant music to elicit EEG patterns reflecting relatively greater left frontal activity (Schmidt & Trainor, 2001; Arjmand et al., 2017). In the Beta band, studies have found that familiar music, compared with unfamiliar music, produces a sustained reduction in low-Beta power in frontocentral and left frontal regions, indicating that music familiarity may influence EEG spectral responses (Malekmohammadi et al., 2023). Beyond music-related emotional processing, EEG activity has also been used to explore subjective experiences in auditory environments. Relevant research has found a significant association between the Theta/Beta power ratio and subjective auditory presence in urban soundscape conditions presented through multiple loudspeakers (S. Zhang et al., 2021). Subsequent analysis of the same experimental data found that greater auditory presence was associated with a lower peak alpha frequency (PAF) (S. Zhang et al., 2022). Although research on the restorative benefits of natural environmental sounds and music has made progress, several issues remain. On the one hand, existing

research has focused largely on the effects of individual music or natural environmental sound conditions, with relatively few comparative studies of different restorative auditory stimuli and their combined effects. On the other hand, existing studies have relied primarily on subjective questionnaires to assess psychological outcomes, while the integration of objective physiological indicators such as EEG remains insufficient.

Based on the relevant literature, this article collectively refers to sound materials with the potential to reduce stress, support attentional restoration, and improve mood as restorative auditory stimuli, with a particular focus on natural sounds and music. Natural sounds mainly include birdsong, flowing water, and wind; previous research suggests that they can promote emotional and cognitive restoration (Ratcliffe, 2021). Music interventions have likewise shown positive psychophysiological effects, and a relevant meta-analysis found improvements in certain psychological and physiological stress indicators (de Witte et al., 2020). In addition, audiovisual integration studies have found that combining natural sounds with visual landscapes can enhance perceived environmental restorativeness and aesthetic preference (Deng et al., 2020).

Given the relatively small sample size within each condition, these findings are intended to provide preliminary insights into psychophysiological responses to different auditory stimuli rather than confirmatory evidence of intervention effectiveness. This exploratory study investigates stage-related changes in state anxiety and EEG activity within a standardized virtual island environment and distinguishes within-participant changes across experimental stages from between-condition differences in recovery. Comparisons before and after anxiety induction were used to evaluate the emotional induction response, while comparisons before and after the intervention were used to describe psychophysiological changes during recovery. Comparisons of different auditory conditions with the no-sound control at the intervention endpoint were used to explore EEG spectral differences between sound configurations, and changes from before to after the intervention within each group were used to describe the corresponding recovery-stage responses. Comparing natural environmental sounds, music, and their combined conditions helps to further explore the potential psychophysiological characteristics of different combinations of auditory elements.

2. Literature Review

The psychophysiological effects of restorative auditory stimuli can be explained through research on restorative environments and on music-related emotional processing. Stress Recovery Theory (SRT) proposes that nonthreatening natural environments help alleviate negative emotions and facilitate physiological recovery after stress (Ulrich et al., 1991). Attention Restoration Theory (ART) emphasizes that characteristics of natural environments such as ‘being away,’ ‘extent,’ ‘compatibility,’ and ‘fascination’ help restore directed attentional resources (Kaplan & Kaplan, 1989). These two theories explain the restorative effects of natural environments from the perspectives of stress recovery and attentional restoration, respectively, and provide a theoretical basis for understanding the potential psychological restorative effects of natural soundscapes (Ratcliffe, 2021). In addition, the biophilia hypothesis suggests that humans may have a tendency to attend to and approach living things and natural environments (Wilson, 1984), offering a complementary perspective on positive evaluations of natural sounds.

In recent years, researchers have increasingly combined psychological scales with physiological indicators such as EEG and heart rate variability (HRV) to evaluate the effects of restorative auditory stimuli at the levels of subjective experience and physiological response. In studies of natural sounds, comparisons of the psychophysiological effects of different natural soundscapes have shown that exposure to natural sounds is associated

with changes in mood states and EEG activity and that sound combinations are also related to restorative outcomes (Bai & Zhang, 2024). A study involving 38 university students found differences between flowing-water sounds and traffic noise at different sound pressure levels in subjective comfort, autonomic nervous system activity, and EEG responses in the Alpha, Beta, and Theta bands (N. Zhang et al., 2025). Further research found that acoustic features of insect sounds, including frequency and amplitude, were associated with EEG-based stress and attentional engagement indicators (J. Zhang et al., 2025). An experiment involving forest biotic sounds and 32 university students found that certain bird and insect sounds could promote relaxation and reduce fatigue, and that subjective restoration ratings correlated with EEG responses (Hui et al., 2026). In addition, a survey of 250 university students found a negative association between satisfaction with the sound environment and anxiety levels, further indicating a relationship between soundscape perception and students' emotional states (Huang et al., 2025).

Regarding music, emotional processing and reward mechanisms provide a neuroscientific basis for understanding its psychological regulatory effects (Koelsch, 2010). Music familiarity is closely related to neural activity in brain regions associated with emotion and reward (Pereira et al., 2011), and music listening has also been found to have potential for alleviating state anxiety (Harney et al., 2023). Previous studies have examined the emotion-regulatory effects of music in terms of state anxiety, musical acoustic features, and neurophysiological activity. A randomized experiment involving 308 nonclinical participants found that brief listening to music combined with monaural beats reduced state anxiety levels from before to after the intervention (Venkatesan et al., 2025). Research combining state anxiety assessment with EEG monitoring found that music with different emotional characteristics can elicit different anxiety experiences and physiological arousal responses; some soothing music was associated with lower state anxiety scores and changes in frontal Alpha-band functional connectivity (Shepherd et al., 2025). Further research found an association between music tempo and EEG spectral activity: slow-tempo music corresponded to higher frontal Theta and Alpha power, whereas fast-tempo music was associated with Beta- and Gamma-band activity and changes in functional connectivity between brain regions (Z. Yang et al., 2025). Together, these studies provide a basis for evaluating the psychophysiological effects of different musical stimuli from the complementary perspectives of subjective emotion and EEG activity.

With the development of soundscape research and virtual reality technology, combinations of natural sounds, music, and visual environments have increasingly been applied in studies of psychophysiological recovery. A randomized crossover experiment involving 53 healthy adults found that nature-themed soundscapes combining natural sounds and musical elements could increase HRV, reduce heart and respiratory rates, and improve certain aspects of subjective emotional experience (Kumpulainen et al., 2025). Related studies have found associations between soundscape satisfaction, connectedness to nature, and immersion in virtual natural environments and psychophysiological recovery indicators (Yoon & Jeon, 2025). An experiment using a virtual winter forest trail found that different audiovisual configurations were related to emotional evaluations and changes in Alpha- and Beta-band EEG activity (Cai et al., 2025). Other research found that virtual environments combining natural landscapes and natural soundscapes were perceived as more restorative (Kawai et al., 2025). Further research using virtual scenarios that varied in vegetation, spatial scale, and sound background found associations between audiovisual environmental configurations and state anxiety, perceived restorativeness, and EEG activity (Liu & Li, 2026). These studies provide a reference for psychophysiological evaluations of restorative auditory stimuli in virtual natural environments.

Overall, the theoretical and empirical literature on restorative auditory stimuli has examined natural sound-source characteristics, music-related emotional processing,

sound combinations, and virtual audiovisual environments and has gradually developed approaches that integrate subjective psychological assessment with objective physiological measurements. Against this background, this study investigated university students in a standardized virtual island visual environment using eight independent experimental groups: natural environmental sound, classical music, traditional Chinese music, popular music, three combined natural sound and music conditions, and a control condition without additional auditory stimulation. The aim was to explore potential differences in psychophysiological responses to different types and combinations of auditory stimuli. The study also combined brief experimental anxiety induction with restorative auditory stimulation and established three stages—baseline, anxiety induction, and restorative auditory intervention—to examine changes in students' state anxiety and EEG activity at different stages. For evaluation, the study combined a state anxiety scale with Alpha-, Beta-, and Theta-band EEG indicators from the frontal, parietal, temporal, and occipital regions to assess different restorative auditory stimuli in terms of subjective emotional experience and neural activity. The study aimed to provide preliminary evidence regarding psychophysiological responses to different types and combinations of auditory stimuli on university students' state anxiety and EEG activity, providing empirical reference for the optimization of short-term restorative soundscapes and everyday emotion regulation among university students.

3. Methods

3.1. Participants

An a priori power analysis was performed using G*Power 3.1.9.7 to estimate the required sample size. The parameters were as follows: Cohen's f = 0.25, significance level α = 0.05, statistical power $1 - \beta = 0.80$, eight independent experimental groups, a correlation of 0.50 among repeated measurements, and a nonsphericity correction $\varepsilon = 1.00$. The power analysis indicated a required total sample of 56 participants. To allow for participant dropout and invalid data, the planned recruitment target was increased to 80 participants. Recruiting 80 participants allowed balanced allocation across eight independent experimental conditions, with 10 participants per group. This design provided a basis for exploratory comparisons of psychophysiological responses across different auditory conditions, generating preliminary insights to inform future studies with larger samples (Faul et al., 2009).

Eighty healthy undergraduate students were recruited online. They were 18–25 years old (mean age: 21 ± 2.0 years), including 35 men and 45 women. All participants were right-handed, had no history of neurological or psychiatric disorders, had normal or corrected-to-normal vision and normal hearing, and had not received professional music training within the preceding five years, to reduce the influence of specialized musical experience. Participants were informed of the procedures and confidentiality principles before the experiment, and all provided written informed consent. The study protocol was approved by the relevant institutional ethics committee (Approval No. SWFU-20251110-01). Participant recruitment and data collection commenced after ethical approval had been obtained.

3.2. Experimental Design

Eight levels of restorative auditory stimulation were adopted as the between-subjects factor: island natural environmental sounds; classical, traditional Chinese, or popular music; natural environmental sounds combined with classical, traditional Chinese, or popular music; and a no-additional-sound control condition. Eighty participants were randomly allocated to eight groups (10 per group). The within-subjects factor comprised

baseline (Stage 1), anxiety induction (Stage 2), and intervention (Stage 3). During Stage 3, all participants watched the same island video, and no sound was played for the no-sound control group.

The actual units of experimental allocation were the eight independent auditory stimulus conditions, each with 10 participants. Based on the composition of the auditory materials, three types of musical stimuli were used: popular music ('Rice Fragrance' [Daoxiang]), traditional Chinese music ('Moonlit Night on the Spring River' [Chunjiang Huayueye]), and classical music ('Güher Pekinel; Süher Pekinel − Sonata for Two Pianos in D Major, K. 448_II. Andante'). These materials were used to analyze differences in psychophysiological responses among music types. Dependent variables included State Anxiety Inventory (S-AI) scores and mean spectral amplitudes in the EEG Alpha, Beta, and Theta bands. After recruitment and eligibility screening, researchers generated a computer-based random allocation sequence to assign the 80 eligible participants to the eight experimental conditions, with 10 participants per group. Each participant received the intervention under only one sound condition to avoid carryover between different auditory stimuli. All groups followed the same experimental procedure, and visual stimuli, experimental duration, equipment settings, and laboratory environment were kept consistent to reduce potential interference from nonsound factors.

For data acquisition, the study used a synchronized measurement mechanism closely integrating 'subjective psychological reporting' and 'objective physiological monitoring.' At the subjective psychological level, participants were asked to complete the state anxiety scale (SAI-S) immediately after each of the three stages (Stage 1, Stage 2, and Stage 3) to obtain their emotional ratings at different experimental time points. At the objective physiological level, a desktop EEG system was used to continuously record time-synchronized EEG signals throughout the experiment. Following data acquisition and preprocessing, mean spectral amplitudes in the Alpha (α), Beta (β), and Theta (θ) frequency bands were extracted and summarized across the frontal, parietal, temporal, and occipital regions. By temporally and spatially relating objective EEG indicators to subjective scale scores, the study was able to systematically and scientifically evaluate the combined benefits of different intervention conditions for stress recovery and anxiety alleviation among university students.

3.3. Experimental Materials and Equipment

3.3.1. Auditory Stimulus Materials

Island natural environmental sounds included waves, birdsong, and other sounds. Three pieces from different musical genres were selected as intervention materials. The classical music selection, 'Güher Pekinel; Süher Pekinel—Sonata for Two Pianos in D Major, K.448_II. Andante,' is the second movement of Mozart's Sonata for Two Pianos in D major, K. 448, characterized by a relatively gentle tempo and lyrical melodies. Prior research using this movement as auditory stimulation found lower scores on certain tension and depressive mood indicators in a music-listening group than in a no-music control group, as well as between-group differences in verbal working memory performance and some prefrontal Alpha (α)- and Beta (β)-band EEG activities, suggesting that this movement may modulate emotional states and neurophysiological activity (Cohen et al., 2025). For the popular music selection, 'Rice Fragrance' (Daoxiang), musical familiarity and positive emotional valence are key determinants of emotion-regulation effects. Research indicates that therapeutic music is often selected according to participants' personal preferences and liking and that familiar popular or other light music with positive valence has clear empirical support for reducing negative emotions such as depression and anxiety (Esfandiari & Mansouri, 2014; Sammler et al., 2007; Zhou et al., 2025). The song has maintained popularity in the mainland Chinese music market. According to the 2025 list of the

most popular songs in mainland China, 'Rice Fragrance' ranked 11th (Apple Music, 2025). It is highly familiar to university students and can effectively activate brain reward circuits, helping participants rapidly downregulate stress responses. As a traditional Chinese instrumental piece, 'Moonlit Night on the Spring River' (Chunjiang Huayueye), selected as traditional Chinese music, features relatively gradual melodic development and distinctive cultural characteristics. Previous research used a cross-cultural randomized controlled pilot trial to preliminarily examine the effects of five-element music therapy and Western art music therapy on indicators related to stress and anxiety (Liao et al., 2023). Another systematic review reported some evidence that five-element music therapy can improve depressive symptoms in patients with post-stroke depression (Zhong et al., 2024). Accordingly, 'Moonlit Night on the Spring River' was selected as the traditional Chinese music stimulus to investigate its effects on university students' state anxiety and EEG activity. Under the no-stimulus condition, neither island natural environmental sounds nor music stimulus materials were present. All auditory stimuli were played through desktop loudspeakers at 60 dB to minimize interference from wearing headphones during EEG recording.

To enhance immersion, the virtual island scene was created in Unreal Engine 5.6.0, as shown in Figure 1. Five-minute, first-person roaming videos were recorded separately according to the different group assignments at a resolution of 1920 × 1080 pixels. Participants in all experimental groups received exactly the same visual content. To minimize additional cognitive load and potential motion sickness caused by active interaction, a passive roaming mode was used for all groups, so that the observed EEG fluctuations would arise primarily from participants' perception of audiovisual stimuli.



Figure 1. Island scene.

3.3.2. Anxiety-Inducing Video

The film-clip emotion induction method is well established in psychological experimentation. Studies using the systematic selection and evaluation of film clips have demonstrated their capacity to induce a range of specific emotions (Gross & Levenson, 1995). A meta-analysis encompassing 45 studies and 6675 participants further indicated that film clips can effectively induce negative emotional states and alter subjective emotional arousal (Fernández-Aguilar et al., 2019). Regarding the mechanisms of anxiety, anticipation of a potential threat and uncertainty about its outcome are considered important psychological processes involved in the development and maintenance of anxiety (Grupe & Nitschke, 2013). Based on this theoretical perspective, this study selected a scene from the

film 'F1: The Movie' (2025), in which a racing driver attempts a risky overtake, loses control of the vehicle, collides, and catches fire, as the experimental induction material. The sudden danger, accident risk, and uncertainty of the event's outcome depicted in the scene theoretically have the potential to elicit tension, fear, and anxiety-related emotional responses. Because film soundtracks can influence viewers' emotions and evaluations of scenes (Boltz, 2001), the clip's original racing-engine sounds, live commentary, impact effects, and background music were retained as part of the complete audiovisual induction stimulus.

3.3.3. State Anxiety Scale

This study used the state anxiety subscale (S-AI) of the State–Trait Anxiety Inventory (STAI) to assess participants' immediate levels of state anxiety. The scale was developed by relevant researchers and has been introduced and applied in Chinese contexts (Spielberger et al., 1970; Zheng & Li, 1997). The subscale comprises 20 items rated on a four-point scale. A psychometric analysis involving 1109 Chinese university students reported Cronbach's α of 0.895 and split-half reliability of 0.87 for the S-AI and examined the measurement structure through factor analysis and other methods (Pang et al., 2019).

3.3.4. EEG Signals

EEG data were collected using a NeuroScan SynAmps2 64-channel EEG system and an electrode cap based on the extended 10–20 system. During online recording, FCz was used as the ground electrode, the left and right mastoids served as reference electrodes, and an electrode was placed below the left eye to record electrooculographic signals, as shown in Figure 2. The sampling rate was set at 1000 Hz, and the impedance of each electrode was maintained below 5 kΩ.

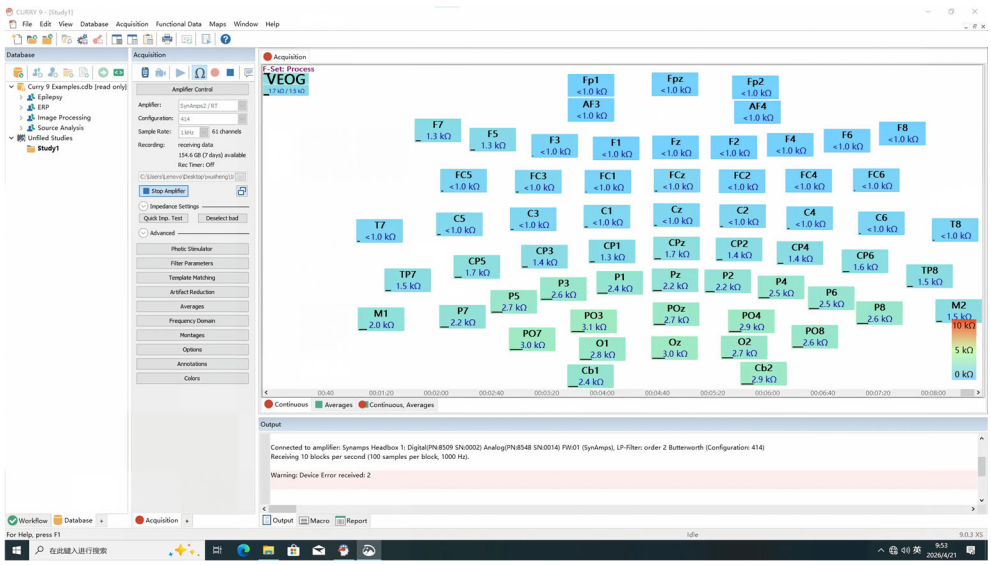


Figure 2. Electrode impedance is compliant.

EEG data were preprocessed offline using CURRY 9 software (Compumedics Neuroscan). The documented preprocessing configuration included common average referencing (CAR), constant baseline correction, notch filtering, and ocular-artifact reduction. Constant baseline correction was configured using a reference interval of 0–10 s. A 50 Hz notch filter with harmonic filtering enabled was used to reduce power-line interference. No additional band-pass filter was enabled in the documented configuration.

Ocular artifacts were identified using threshold-based detection with the vertical electrooculogram (VEOG) as the detection channel. The threshold was set at 200 μV, with

a detection window of −200 to 500 ms and a refractory interval of 700 ms. A covariance-based artifact reduction method was selected to attenuate ocular contamination. The preprocessed EEG data were subsequently used for frequency-domain analysis in MATLAB 2025b.

Following preprocessing, EEG frequency-domain analysis was performed using MATLAB and EEGLAB (Delorme & Makeig, 2004), with spectral analysis based on the fast Fourier transform (FFT) (Cooley & Tukey, 1965). EEG data were imported into MATLAB using the EEGLAB toolbox and the loadcurry function. EEG recordings corresponding to the three experimental stages were extracted according to event markers. For each participant, a 300-s EEG recording from each stage was divided into 150 consecutive, non-overlapping 2-s segments, each containing 2000 samples at a sampling rate of 1000 Hz. For each electrode and segment, a 2048-point fast Fourier transform (FFT) was performed. FFT coefficients were normalized by the original segment length of 2000 samples, and single-sided amplitude spectra were calculated. The amplitude spectra were averaged across the 150 segments separately for each participant and electrode. Frequency-band analyses were conducted separately for Theta (4–8 Hz), Alpha (8–13 Hz), and Beta (13–30 Hz) by specifying the corresponding frequency ranges in the MATLAB script. The spectral amplitudes at the selected frequency points were averaged to obtain the mean spectral amplitude for each frequency band and electrode. These measures retained the same units as the original EEG signals. To characterize regional EEG activity, the electrodes were grouped into four regions: frontal (F), parietal (P), occipital (O), and temporal (T). Mean spectral amplitude was calculated for each frequency band within each region. The four regional values were then combined using equal weighting to obtain a whole-brain summary measure for each frequency band and experimental stage, as follows:

$$A_whole\text{-}brain = (A_F + A_P + A_O + A_T)/4$$

where A_F, A_P, A_O, and A_T represent the mean spectral amplitudes of the frontal, parietal, occipital, and temporal regions, respectively. This measure represents an equally weighted average across the four brain regions rather than a direct average across all individual electrodes. Accordingly, each participant contributed three whole-brain frequency-band measures at each of the three experimental stages, yielding nine participant-level measures. The participant-level regional spectral amplitude data were organized in Microsoft Excel, where the equally weighted whole-brain mean spectral amplitudes and their subsequent natural logarithmic transformations were calculated.

To improve the statistical representation of EEG spectral data, a natural logarithmic transformation was applied to the whole-brain mean spectral amplitude measures. Previous studies have employed logarithmic scaling in analyses of EEG spectral measures, including frequency-band activity and Alpha spectral amplitude (Neuhaus et al., 2021; Smulders et al., 2018). Following this approach, the whole-brain mean spectral amplitude was first calculated from the four regional values and subsequently transformed as ln(A_whole-brain). Because the original exported EEG measure was mean spectral amplitude rather than power spectral density, the term “log-transformed mean spectral amplitude” was used consistently throughout the study. All original values were positive, and no constant was added before logarithmic transformation. The transformed measures were used for subsequent statistical analyses, while the original data remained unchanged.

Overall between-group differences in whole-brain log-transformed mean spectral amplitudes at Stage 3 were examined using Kruskal–Wallis tests. The overall comparisons across the eight auditory conditions were not statistically significant after Holm correction across the three frequency bands. Therefore, subsequent Dunn comparisons between the seven auditory conditions and the no-sound control were treated as exploratory analyses.

Holm correction was applied separately within each frequency band, and an additional joint correction across all 21 comparisons was used to assess the sensitivity of the results to multiple testing.

3.4. Experimental Procedure

Upon arrival at the laboratory, participants signed informed consent forms and provided demographic information. After scalp cleaning, an EEG cap was fitted and conductive gel was applied, as shown in Figure 3, to ensure that electrode impedance met the requirements. The experiment was conducted in a standardized, soundproofed psychological laboratory with controlled lighting. The room temperature was maintained at 15–20 °C, with relative humidity held at 55%. As illustrated in Figure 4, during the baseline stage (Stage 1), participants sat quietly for five minutes while wearing the EEG cap to establish their normal physiological baseline and then completed the State Anxiety Inventory (S-AI). During the anxiety induction stage (Stage 2), participants watched a five-minute anxiety-inducing video intended to simulate psychological stress and elicit state anxiety and completed the S-AI immediately afterward. During the restorative auditory intervention stage (Stage 3), participants received a five-minute auditory intervention according to their group assignment while viewing the virtual island scene and completed the S-AI immediately afterward. The EEG cap was then removed, participants' hair was cleaned, and compensation was provided. The experiment lasted approximately 20 min.



Figure 3. Experimental environment.

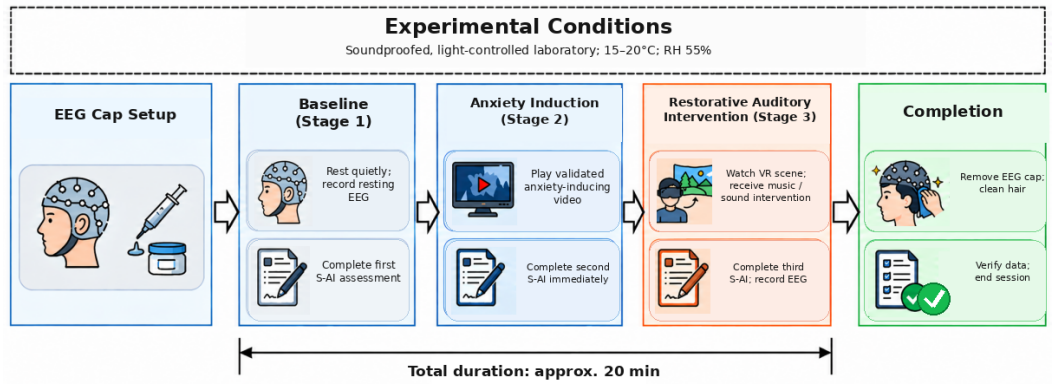


Figure 4. Experimental procedure.

4. Statistical Analysis of Experimental Data

4.1. Psychological State Scale Data and Results

To investigate changes in participants' state anxiety under different auditory stimulus conditions, the State Anxiety Inventory (S-AI) was used to assess state anxiety at three

points: the baseline stage (Stage 1), after the anxiety induction stage (Stage 2), and after the restorative auditory intervention stage (Stage 3). The study included 80 participants divided into eight experimental groups, with 10 participants per group and three measurements per participant. A higher S-AI total score indicates a higher current level of state anxiety, whereas a lower score indicates relatively less state anxiety.

To evaluate the reliability and validity of the scale used in this study, the data from the baseline (Stage 1), anxiety induction (Stage 2), and restorative auditory intervention (Stage 3) stages were analyzed separately. At each of the three measurement points, 80 valid responses were obtained. The scale comprised 20 items, and all reverse-scored items had been appropriately recoded. For reliability assessment, Cronbach's α was used to evaluate internal consistency. Cronbach's α coefficients were 0.883, 0.950, and 0.936 for Stages 1, 2, and 3, respectively, all exceeding 0.80. These results indicate good internal consistency at all three measurement points and a high degree of measurement reliability. In addition, the mean inter-item correlations were 0.276, 0.484, and 0.407 for Stages 1, 2, and 3, respectively, providing further evidence of the internal consistency of the S-AI across the three experimental stages.

4.1.1. Descriptive Statistics and Normality Tests for the Psychological State Scale

The mean score for the 80 participants was 41.09 ± 9.15 at baseline (Stage 1), increased to 50.85 ± 13.19 after anxiety induction (Stage 2), and declined to 36.20 ± 10.84 after the restorative auditory intervention (Stage 3). According to the scoring direction of the S-AI, these results indicate an overall increase in state anxiety following Stage 2 and an overall downward trend after Stage 3.

At the end of the restorative auditory intervention stage (Stage 3), the popular music plus environmental sound group had the lowest mean score (30.70 ± 12.41), followed by the no-sound group (33.80 ± 12.00) and the environmental sound group (34.20 ± 11.84), whereas the traditional Chinese music group had a relatively higher mean score (39.90 ± 12.44). These results show certain numerical differences in post-intervention state anxiety scores among auditory stimulus conditions. In particular, the popular music plus environmental sound group had a relatively low mean anxiety score, while the traditional Chinese music group had a relatively high score, reflecting descriptive characteristics of subjective emotional responses under different auditory configurations. The relative restorative effects of different sound conditions require further between-group statistical comparisons.

To further examine distributional characteristics, Shapiro–Wilk tests were performed on S-AI scores for the eight experimental groups at each of the three stages. Scores for the no-sound group at baseline (Stage 1; $W = 0.836$, $p = 0.039$) and for the popular music plus environmental sound group after the intervention (Stage 3; $W = 0.798$, $p = 0.014$) deviated significantly from normality, while the remaining 22 tests did not reject the assumption of normality ($p > 0.05$). Given that some data did not meet the normality assumption and the group sample sizes were relatively limited, nonparametric statistical methods were subsequently used to analyze score differences across experimental stages and auditory conditions.

4.1.2. Analysis of State Anxiety Changes During Anxiety Induction and Auditory Intervention

To further quantify the uncertainty of the estimated changes in state anxiety, 95% confidence intervals (CIs) for mean paired changes were calculated using a percentile bootstrap procedure with 50,000 resamples at the participant level. For each participant, change scores were calculated as Stage 2 minus Stage 1 and Stage 3 minus Stage 2, respectively. Between-group differences in recovery-stage change scores were examined using

the Kruskal–Wallis test, followed by exploratory Mann–Whitney U comparisons between each auditory condition and the no-sound control, with Holm correction for multiple comparisons. Unadjusted 95% bootstrap confidence intervals were also calculated for the mean differences in change scores between each auditory condition and the no-sound control.

To examine changes in state anxiety across the experimental stages, a Friedman test was used to compare the total S-AI scores of 80 participants at baseline (Stage 1), after anxiety induction (Stage 2), and after restorative auditory intervention (Stage 3). The S-AI scores differed significantly among the three stages ($\chi^2(2) = 36.115$, $p < 0.001$), with Kendall's coefficient of concordance W = 0.226, indicating a statistically significant overall change in state anxiety during the experiment. Wilcoxon signed-rank tests were then used to compare S-AI scores before and after anxiety induction and before and after the intervention; the results are presented in Table 1.

The comparison of Stages 1 and 2 showed that S-AI scores following anxiety induction were significantly higher than at baseline ($Z = -4.370$, $p < 0.001$), with the overall mean rising from 41.09 to 50.85 points, corresponding to a mean paired increase of 9.76 points (95% bootstrap CI: 6.01 to 13.54). Because higher S-AI scores indicate higher levels of current state anxiety, this result suggests that participants experienced a relatively marked short-term anxiety response after viewing the anxiety-inducing video. Descriptive statistics for each experimental group showed that mean S-AI scores at Stage 2 were higher than those at Stage 1 in all eight groups, indicating that subjective emotional changes following anxiety induction were not confined to a few groups but were present across participants assigned to different experimental conditions. In addition, to verify the effectiveness of the anxiety induction procedure, this study compared participants' state anxiety at baseline (Stage 1) with that after anxiety induction (Stage 2). The mean S-AI score of the 80 participants rose from 41.09 to 50.85 points, an average increase of 9.76 points, and the Wilcoxon signed-rank test indicated that the change was statistically significant ($Z = -4.370$, $p < 0.001$). This finding indicates that participants' subjective state anxiety increased substantially after viewing the anxiety-inducing video, demonstrating that the video effectively induced short-term anxiety responses in this sample and providing an experimental basis for evaluating the subsequent restorative auditory intervention.

The comparison of Stages 2 and 3 showed that S-AI scores after Stage 3 were significantly lower than those after Stage 2 ($Z = -5.839$, $p < 0.001$), with the overall mean falling from 50.85 to 36.20 points, corresponding to a mean paired decrease of 14.65 points (95% bootstrap CI: −18.58 to −10.78). This indicates a relatively marked overall decrease in state anxiety during the intervention stage after anxiety induction, suggesting that the auditory intervention stage may have been accompanied by some degree of anxiety alleviation.

Table 1. Nonparametric Test Results for S-AI Scores Across Experimental Stages.

Comparison	Statistical Method	Statistic	*p* Value
Overall comparison of Stages 1, 2, and 3	Friedman	$\chi^2(2) = 36.115$	<0.001
Stage 1 vs. Stage 2	Wilcoxon	$Z = -4.370$	<0.001
Stage 2 vs. Stage 3	Wilcoxon	$Z = -5.839$	<0.001

To further examine whether the magnitude of recovery differed across auditory conditions, individual change scores were calculated as Stage 3 minus Stage 2. The Kruskal–Wallis test showed no statistically significant difference in recovery-stage change scores among the eight groups ($H(7) = 9.080$, $p = 0.247$, $\varepsilon^2 = 0.029$). Exploratory comparisons of the seven auditory conditions against the no-sound control were not statistically significant after Holm correction for multiple comparisons (minimum adjusted $p = 0.088$). Although some unadjusted 95% bootstrap confidence intervals for between-group mean

change differences excluded zero, these exploratory findings should not be interpreted as evidence of superiority after accounting for multiple comparisons. In addition, the no-sound group had a relatively high mean S-AI score following anxiety induction (Stage 2: 62.20), suggesting that differences in post-induction starting levels may have influenced the observed recovery magnitudes. Therefore, the present findings do not provide sufficient statistical evidence that any particular auditory condition produced greater anxiety alleviation than the no-sound control.

4.2. Descriptive Statistics of Whole-Brain EEG Measures

Descriptive statistics and Shapiro–Wilk tests were performed on the nine log-transformed mean spectral amplitude measures of all 80 participants (Table 2). The medians for Alpha at the three stages were 0.180, 0.067, and 0.060; those for Beta were −0.290, −0.342, and −0.384; and those for Theta were 0.340, 0.350, and 0.328, respectively. Alpha and Theta measures deviated from normality at all three stages in the Shapiro–Wilk tests (all $p < 0.001$), whereas normality was not rejected for Beta at any stage ($p > 0.05$). Considering the distributional characteristics of the frequency bands and the paired-measurement structure of the experiment, nonparametric tests were used for subsequent comparisons across stages and groups.

Table 2. Descriptive Statistics and Normality Tests of Whole-Brain Log-Transformed Mean Spectral Amplitude.

Frequency Band	Stage	Median (Q1, Q3)	M ± SD	Shapiro–Wilk W	*p* Value
Alpha	Stage 1	0.180 (−0.018, 0.450)	0.259 ± 0.428	0.924	<0.001
Alpha	Stage 2	0.067 (−0.139, 0.240)	0.094 ± 0.299	0.881	<0.001
Alpha	Stage 3	0.060 (−0.139, 0.189)	0.078 ± 0.298	0.813	<0.001
Beta	Stage 1	−0.290 (−0.502, −0.076)	−0.287 ± 0.346	0.977	0.162
Beta	Stage 2	−0.342 (−0.546, −0.152)	−0.344 ± 0.307	0.982	0.301
Beta	Stage 3	−0.384 (−0.592, −0.147)	−0.381 ± 0.301	0.971	0.063
Theta	Stage 1	0.340 (0.161, 0.563)	0.408 ± 0.389	0.846	<0.001
Theta	Stage 2	0.350 (0.208, 0.457)	0.374 ± 0.299	0.734	<0.001
Theta	Stage 3	0.328 (0.178, 0.475)	0.365 ± 0.296	0.804	<0.001

4.3. Nonparametric Comparison of Whole-Brain EEG Measures Across Three Stages

A Friedman test was used to compare whole-brain log-transformed mean spectral amplitudes for the same participants across Stage 1, Stage 2, and Stage 3. The stage effect was significant for Alpha [$\chi^2(2) = 33.975$, $p < 0.001$, Kendall's W = 0.212] and Beta [$\chi^2(2) = 27.225$, $p < 0.001$, W = 0.170], but not for Theta [$\chi^2(2) = 2.925$, $p = 0.232$, W = 0.018]. The results are presented in Table 3.

Table 3. Friedman Test Results for the Three Whole-Brain Frequency Bands.

Frequency Band	N	χ^2	df	*p* Value	Kendall's W
Alpha	80	33.975	2	<0.001	0.212
Beta	80	27.225	2	<0.001	0.170
Theta	80	2.925	2	0.232	0.018

To further examine changes across the two adjacent stage transitions—anxiety induction and auditory intervention—Wilcoxon signed-rank tests were conducted for Stage 1 versus Stage 2 and Stage 2 versus Stage 3. Six prespecified paired comparisons were performed, and the resulting six *p* values were jointly adjusted using the Holm procedure. From Stage 1 to Stage 2, the median paired differences in log-transformed mean spectral amplitude for Alpha and Beta were both negative and statistically significant (adjusted *p*

< 0.001 and $p = 0.021$, respectively), whereas Theta showed no significant change (adjusted $p = 0.450$). From Stage 2 to Stage 3, Beta continued to decrease significantly (adjusted $p = 0.021$), whereas the changes in Alpha and Theta were not statistically significant (adjusted $p = 0.250$ and 0.450, respectively). Details are given in Table 4.

Table 4. Wilcoxon Paired Comparisons of Whole-Brain Log-Transformed Mean Spectral Amplitude.

Frequency Band	Comparison	Median Paired Difference	Rank-Sum Statistic W	Unadjusted *p* Value	Holm-Adjusted *p* Value
Alpha	Stage 1–Stage 2	−0.121	469	<0.001	<0.001
Alpha	Stage 2–Stage 3	−0.007	1259	0.083	0.250
Beta	Stage 1–Stage 2	−0.030	1024	0.004 *	0.021 *
Beta	Stage 2–Stage 3	−0.038	1025	0.004 *	0.021 *
Theta	Stage 1–Stage 2	−0.027	1367	0.225	0.450
Theta	Stage 2–Stage 3	−0.011	1431	0.365	0.450

Note: * < 0.05.

Based on the three-stage medians and paired changes, Alpha showed a decreasing trend during the anxiety induction stage but no significant further change by the end of the intervention. Beta declined across both stage transitions, from Stage 1 to Stage 2 and from Stage 2 to Stage 3, whereas changes in Theta across the three stages were relatively small. Thus, the stage-related patterns were not entirely consistent across frequency bands.

4.4. Analysis of Whole-Brain EEG Characteristics and Changes During Restorative Auditory Intervention Under Different Auditory Conditions

As shown in Table 5, Dunn's rank-based test was used to compare whole-brain log-transformed mean spectral amplitudes at Stage 3 between each of the seven sound groups and the no-sound control group. Seven control comparisons were performed for each frequency band, and *p* values were adjusted within each band using the Holm method.

Table 5. Dunn Comparisons of the Seven Sound Groups With the No-Sound Group at Stage 3.

Auditory Stimulus Group (vs. No-Sound Group)	Alpha Unadjusted *p*/Holm *p*	Beta Unadjusted *p*/Holm *p*	Theta Unadjusted *p*/Holm *p*
Environmental + Classical	0.0037/0.0143	0.0058/0.0288	0.0114/0.0455
Traditional Chinese + Environmental	0.0022/0.0133	0.0079/0.0316	0.0014/0.0101
Popular + Environmental	0.0008/0.0057	0.0038/0.0227	0.0065/0.0323
Environmental	0.0262/0.0262	0.0311/0.0934	0.0496/0.1104
Classical	0.0086/0.0172	0.0508/0.0934	0.0368/0.1104
Traditional Chinese	0.0029/0.0143	0.0029/0.0200	0.0034/0.0207
Popular	0.0032/0.0143	0.0464/0.0934	0.0799/0.1104

After Holm correction within each frequency band, all seven sound groups differed significantly from the no-sound group in Alpha (all $p < 0.05$). In both Beta and Theta, four sound groups—environmental sound plus classical music, environmental sound plus traditional Chinese music, environmental sound plus popular music, and traditional Chinese music alone—differed significantly from the no-sound group. When the 21 comparisons across the three frequency bands were jointly corrected using Holm's method, significant differences remained for the traditional Chinese music plus environmental sound group and the popular music plus environmental sound group versus the no-sound group in Alpha, and for the traditional Chinese music plus environmental sound group versus the no-sound group in Theta.

Figure 5 shows the distributions of whole-brain log-transformed mean spectral amplitudes in the Alpha, Beta, and Theta bands at Stage 3 under the eight sound conditions. Bar heights indicate group medians, and error bars represent the 25th-to-75th percentile intervals. The medians for the no-sound group were −0.203, −0.792, and 0.158 in Alpha, Beta, and Theta, respectively. The seven sound groups showed different distributional locations and degrees of dispersion across the frequency bands.

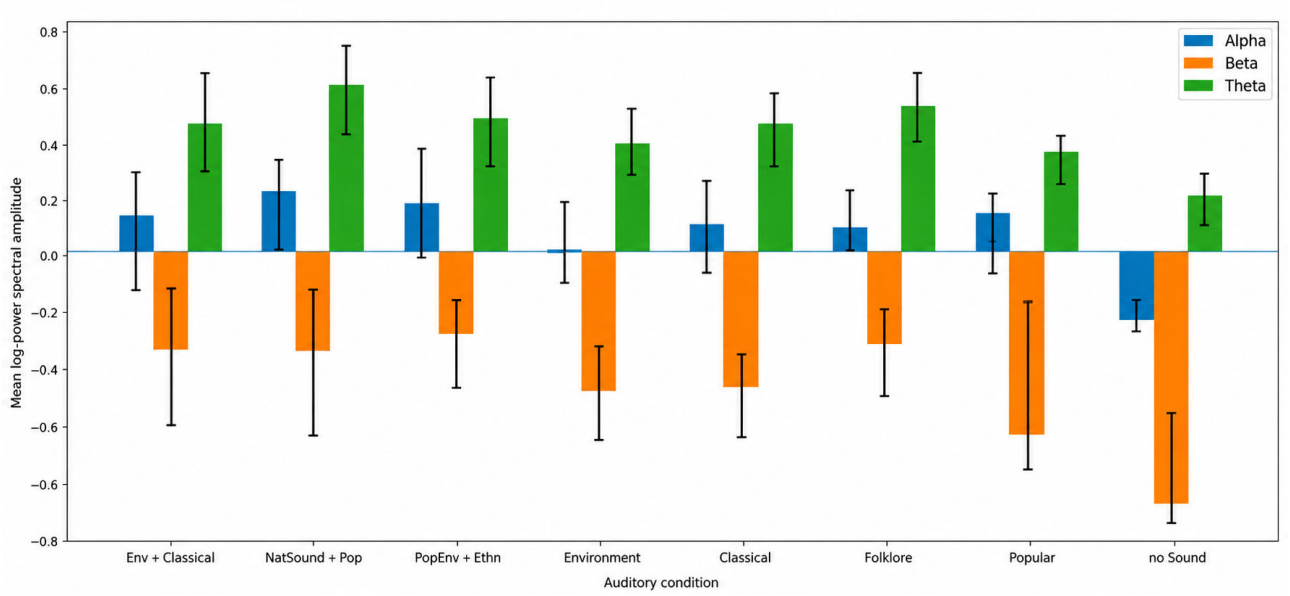


Figure 5. Stage 3 Whole-Brain Log Mean Spectral Amplitude by Condition.

To analyze changes in whole-brain spectral measures before and after the intervention, differences in log-transformed mean spectral amplitude were calculated for each participant as Stage 3 minus Stage 2, and the median paired difference for each group was used to describe the changes. As shown in Table 6, the median changes in Alpha were 0.012 and 0.022 for the environmental sound plus classical music and classical music groups, respectively, while the other six groups showed negative values. In Beta, the corresponding medians were 0.026 and 0.027 for the traditional Chinese music plus environmental sound and popular music groups, respectively, with negative values in the other six groups. In Theta, the corresponding medians were 0.051 and 0.001 for the environmental sound and traditional Chinese music groups, respectively, with negative values in the other six groups. The direction and magnitude of changes differed somewhat among groups and frequency bands.

Table 6. Within-Participant Changes in Whole-Brain Log-Transformed Mean Spectral Amplitude From Stage 2 to Stage 3 Across Auditory Groups.

Experimental Group	Median Alpha Change	Median Beta Change	Median Theta Change
Environmental + Classical	+0.012	−0.064	−0.049
Traditional Chinese + Environmental	−0.034	+0.026	−0.030
Popular + Environmental	−0.020	−0.074	−0.013
Environmental	−0.011	−0.024	+0.051
Classical	+0.022	−0.063	−0.019
Traditional Chinese	−0.016	−0.063	+0.001
Popular	−0.025	+0.027	−0.003
No Sound	−0.016	−0.006	−0.024

Considering the state anxiety scale results, the mean S-AI score of all 80 participants rose from 41.09 at Stage 1 to 50.85 at Stage 2 and then fell to 36.20 at Stage 3. The Friedman test and both adjacent-stage Wilcoxon tests indicated significant stage-related changes in state anxiety (all $p < 0.001$). Meanwhile, whole-brain log-transformed mean spectral amplitudes differed significantly across stages for Alpha and Beta, whereas the overall stage comparison for Theta was not significant. Subjective anxiety scores and EEG spectral measures exhibited their own stage-related patterns.

The mean S-AI score declined from Stage 2 to Stage 3 in every experimental group, with decreases ranging from 7.90 to 28.40 points; the popular music plus environmental sound group had a mean score of 30.70 at Stage 3. EEG analysis showed that the overall Kruskal–Wallis tests across the eight groups were not significant for any of the three bands after Holm adjustment, whereas Dunn comparisons of the seven sound groups against the no-sound group identified statistically significant differences in some bands. Dunn's test compared between-group spectral amplitude levels at Stage 3, while Table 6 presents each group's within-participant paired changes from Stage 2 to Stage 3; together, these show different aspects of the recovery-stage EEG spectral distribution and stage-related changes.

In summary, whole-brain log-transformed mean spectral amplitude in the Alpha band decreased significantly from baseline to anxiety induction; Beta decreased significantly across both adjacent stage comparisons; and Theta showed no significant difference in the overall three-stage comparison. Taken together, the spectral distributions in Figure 5, the comparisons of sound groups with the no-sound group in Table 5, and the paired changes in Table 6 present the distributions and stage-related changes in whole-brain spectral measures under different auditory conditions, providing data for subsequent analysis of psychophysiological mechanisms.

5. Discussion

5.1. State Anxiety Responses to Induction and Changes During the Auditory Intervention Stage

This study recorded state anxiety in 80 university students at three stages under the same experimental procedure. The mean S-AI score rose from 41.09 ± 9.15 at baseline to 50.85 ± 13.19 after anxiety induction and subsequently fell to 36.20 ± 10.84 at the end of the auditory intervention stage. The Friedman test showed a significant difference across the three stages [$\chi^2(2) = 36.115$, $p < 0.001$]; adjacent-stage Wilcoxon tests also showed an increase following induction and a decrease after the auditory intervention stage (both $p < 0.001$). This pattern is consistent with the situation-dependent fluctuation of state anxiety and suggests that the threatening film used in the study induced observable subjective tension over a short period. The effectiveness of film-based emotion induction and the heterogeneity of the emotional responses it produces have been discussed in empirical studies and meta-analyses (Fernández-Aguilar et al., 2019; Gross & Levenson, 1995).

Mean S-AI scores decreased from Stage 2 to Stage 3 in all eight experimental groups. The no-auditory-stimulation group also showed a decline from 62.20 to 33.80 points, a decrease of 28.40 points. Because the no-sound group had a relatively high starting score at Stage 2 and all groups watched the same island visual scene at Stage 3, the decrease during the auditory intervention stage may have involved the cessation of threatening stimuli, a change in context, quiet viewing, and spontaneous individual recovery. The effects of different auditory conditions should be understood against this shared recovery background.

In the descriptive results for Stage 3, the popular music plus environmental sound group had the lowest mean S-AI score among the eight groups (30.70 ± 12.41), while the environmental sound plus classical music group showed a relatively large mean reduc-

tion from Stage 2 to Stage 3 (17.50 points) among the seven sound conditions. These findings show certain descriptive differences in anxiety scores and the magnitude of change under different auditory stimulus conditions, suggesting that different sound configurations may be associated with subjective emotional responses during short-term recovery. Given the differences in starting levels after anxiety induction, future research could compare changes between groups to evaluate the relative restorative effects of different auditory conditions. Consistent with this interpretation, the direct comparison of Stage 2-to-Stage 3 S-AI change scores across the eight auditory conditions was not statistically significant ($H(7) = 9.080$, $p = 0.247$). Therefore, although significant overall recovery-stage changes were observed, the present data do not establish that any particular auditory configuration produced a greater reduction in state anxiety than the no-sound control.

5.2. Restorative Characteristics of Island Natural Environmental Sounds

The mean S-AI score in the natural environmental sound group decreased from 42.10 at Stage 2 to 34.20 at Stage 3, a reduction of 7.90 points. In the Dunn control comparison, the difference in whole-brain Alpha log-transformed mean spectral amplitude between the environmental sound group and the no-sound group at Stage 3 reached $p = 0.0262$ after Holm adjustment of the seven comparisons within that band. Wave sounds, birdsong, and other natural sounds combined with the island visual setting to provide natural environmental cues. Stress Recovery Theory and Attention Restoration Theory offer theoretical perspectives for understanding post-stress emotional changes and the restoration of attentional resources, respectively (Kaplan & Kaplan, 1989; Ulrich et al., 1991).

With respect to experimental evidence on natural sounds, a study comparing natural sounds with environmental noise after a psychological stress task found a tendency toward faster skin conductance recovery under natural sound conditions, while reporting no clear effects on some autonomic nervous system indicators (Alvarsson et al., 2010). A related review also noted that associations among natural sounds, perceived restorativeness, emotional states, and cognitive experiences depend on sound sources, environments, and study designs (Ratcliffe, 2021). The decrease in anxiety scores observed in the natural sound group in the present study is consistent with the direction of restorative changes discussed in the literature and reflects short-term emotional changes when natural sounds and the island visual environment are presented together. Because anxiety scores also decreased in the no-sound group, the independent restorative contribution of natural environmental sounds should be further investigated through between-group comparisons that control for the common visual context and post-induction starting levels.

In addition, the natural sounds used in this study originated from an island context, resulting in a high degree of contextual consistency between the auditory content and island visual information. This consistency may affect participants' overall evaluation of the environment. Future studies could include visual-only, natural-sound-only, and combined audiovisual conditions to further distinguish the relative contributions of environmental sounds and multisensory contexts.

5.3. Psychological Recovery and EEG Responses to Different Types of Music

In the three independent classical, traditional Chinese, and popular music groups, mean S-AI scores decreased by 13.20, 13.20, and 14.30 points, respectively, from Stage 2 to Stage 3, showing a descriptive decline in anxiety scores during the intervention stage in all three groups. The mean decreases were similar, reflecting comparable patterns of subjective emotional change during short-term recovery under the different musical materials. Given differences among the three pieces in melodic structure, musical tempo, and cultural background, the materials may produce listening experiences with distinct charac-

teristics. Future studies could incorporate participants' music familiarity, individual preferences, and corresponding between-group comparisons to explore psychophysiological differences among music types in greater depth.

Previous evidence supports the potential psychological regulatory benefits of music listening. Systematic reviews and meta-analyses have found that music listening is generally associated with reductions in state anxiety (Harney et al., 2023); another systematic review and meta-analysis also reported positive effects of music interventions on certain stress-related outcomes (de Witte et al., 2020). However, these studies differed in intervention type, exposure duration, study population, and control conditions, so their average effects cannot directly substitute for comparisons among the three specific musical materials used in the present study.

From a neurophysiological perspective, musical responses do not correspond exclusively to unidirectional changes in a single frequency band. Exploratory Dunn comparisons with the no-sound group showed that the classical, traditional Chinese, and popular music groups all reached $p < 0.05$ in Alpha after within-band Holm correction at Stage 3; in Beta and Theta, only comparisons between the traditional Chinese music group and the no-sound group reached $p < 0.05$ under the same adjustment. These comparisons primarily reflect whole-brain EEG spectral differences at Stage 3 between the music groups and the no-sound group, suggesting that musical materials may be associated with different neurophysiological activity patterns. Temporal changes in Alpha and low-Beta bands observed in experiments on music familiarity further indicate that familiarity and auditory processing states may influence spectral responses (Malekmohammadi et al., 2023). Future studies could combine assessments of piece preference, spectral analysis of local brain regions, and direct comparisons between music types to explore the neurophysiological characteristics of different musical materials more comprehensively.

5.4. Combined Configurations of Natural Environmental Sounds and Music

This study included three combined auditory stimulus conditions: environmental sound plus classical music, environmental sound plus traditional Chinese music, and environmental sound plus popular music. The respective mean S-AI scores decreased by 17.50, 8.80, and 13.90 points from Stage 2 to Stage 3; the popular music plus environmental sound group had the lowest mean score at Stage 3 (30.70 ± 12.41). The combined auditory stimulus conditions retained the natural sound information of the island environment while incorporating musical melody and rhythm, allowing soundscape structures different from those of individual sound sources to be formed within the same visual setting.

In research on restorative soundscapes, a relevant review emphasized the importance of sounds and their environmental contexts to restorative experiences (Ratcliffe, 2021). A randomized crossover experiment investigated relationships between nature-themed soundscapes and psychophysiological indicators and reported positive changes in some HRV measures and subjective experiences (Kumpulainen et al., 2025). These studies provide a reference for understanding the potential psychophysiological effects of combining natural sounds and music and indicate that sound combinations and listening contexts warrant further attention. By establishing different combined auditory conditions in the same virtual island environment, the present study helps to further observe psychophysiological response characteristics when natural environmental sounds are combined with different musical materials.

Under the combined auditory stimulus conditions, Dunn comparisons with the no-sound group showed that whole-brain log-transformed mean spectral amplitudes in Alpha, Beta, and Theta at Stage 3 differed significantly (all $p < 0.05$) for the environmental sound plus classical music, environmental sound plus traditional Chinese music, and environmental sound plus popular music groups after Holm correction separately across

the seven control comparisons in each band. These findings reflect certain EEG spectral differences between combined sound configurations and the no-sound condition. Meanwhile, the overall Kruskal–Wallis tests across the eight groups were not significant for any of the three bands after Holm adjustment, and the significance of the corresponding Dunn comparisons was affected by the scope of the multiple-comparison correction. These findings suggest that different sound configurations may correspond to different neurophysiological activity characteristics and offer experimental clues for further research on auditory processing under combined natural environmental sound and music conditions. Psychophysiological responses to combined auditory stimuli may be related to musical material selection, the proportions of sound sources, auditory masking, the degree of scene matching, and personal preferences. Future research could incorporate within-participant changes from Stage 2 to Stage 3 and corresponding between-group comparisons to further test the relative restorative benefits and potential mechanisms of combined auditory stimuli.

5.5. Stage-Related Changes in Whole-Brain Alpha, Beta, and Theta and Their Psychophysiological Associations

After equally weighting mean spectral amplitudes from the frontal, parietal, occipital, and temporal regions and applying a natural logarithmic transformation, the three frequency bands displayed different stage-related characteristics. The Friedman tests showed significant three-stage differences for Alpha [$\chi^2(2) = 33.975$, $p < 0.001$, Kendall's W = 0.212] and Beta [$\chi^2(2) = 27.225$, $p < 0.001$, W = 0.170], but not for Theta [$\chi^2(2) = 2.925$, $p = 0.232$]. The six prespecified Wilcoxon paired comparisons after Holm correction showed that Alpha decreased from Stage 1 to Stage 2 ($p < 0.001$) but did not change significantly from Stage 2 to Stage 3 ($p = 0.250$); Beta decreased across both adjacent stage transitions (both adjusted $p = 0.021$); and neither comparison for Theta was significant (both adjusted $p = 0.450$).

These findings suggest that different frequency bands within the same experimental process followed inconsistent response trajectories. The relatively pronounced decrease in Alpha during anxiety induction may be jointly associated with visual processing, attentional engagement, and situational arousal during film viewing. The continued decrease in Beta during both induction and subsequent recovery may reflect multiple influences, including changes in task state, attention, and motor-related activity. Research on auditory music processing has also shown that Alpha and low-Beta activity can vary with listening content and familiarity (Malekmohammadi et al., 2023). In between-group comparisons across auditory conditions, the overall Kruskal–Wallis tests across eight groups at Stage 3 were not significant after Holm adjustment, whereas exploratory Dunn comparisons against the no-sound group identified significant differences in certain bands, with some sensitivity to the scope of multiple-comparison correction. This indicates that different levels of statistical analysis yielded distinct patterns: the omnibus tests reflect overall differences among the eight groups' spectral distributions, while exploratory control comparisons provide indications of EEG activity differences between specific auditory conditions. Together with the paired changes from Stage 2 to Stage 3 within each group, the results allow neurophysiological responses under different auditory conditions to be understood from the perspectives of endpoint distribution and stage-related change. Future studies could combine region-specific EEG measures with more clearly specified between-group comparisons of changes to explore the potential characteristics of different sound configurations.

The subjective scale and EEG findings showed both correspondences and distinctions. S-AI scores increased significantly after anxiety induction and then decreased significantly; Alpha changed most noticeably around induction, Beta continued to vary across

both stage transitions, and Theta remained relatively stable. The two types of measurement represent subjective anxiety experience and cortical activity in different frequency bands, respectively, and their trajectories need not be fully synchronized.

5.6. Research Contributions, Limitations, and Future Directions

This study established eight independent sound conditions within a standardized virtual island visual environment and simultaneously recorded subjective state anxiety and EEG spectral measures across three experimental stages, making it possible to describe stage-related responses among university students under short-term stress from both psychological and physiological perspectives. The inclusion of a no-sound control and groups defined by specific materials facilitated observation of both the general recovery process and descriptive differences among soundscape configurations.

The present study included 80 participants distributed across eight auditory conditions, with 10 participants in each group. This sample structure supported the exploratory examination of psychophysiological response patterns across a range of auditory configurations. Given the modest sample size per condition and the corresponding statistical power considerations for between-group effects, the observed patterns are best interpreted as preliminary findings. Future studies with larger samples will provide opportunities to estimate between-condition effects with greater precision and further examine the consistency of these findings. Furthermore, although the sample size was determined through an a priori power analysis, the relatively small number of participants in each auditory condition may have influenced the sensitivity of the nonparametric between-group comparisons. Nevertheless, the present findings provide preliminary insights into psychophysiological responses under different auditory conditions and offer a useful basis for future studies with larger samples. Second, the study used a five-minute auditory stimulus and thus mainly reflects immediate psychophysiological responses during the intervention. Since all groups experienced the termination of the anxiety-inducing stimulus and the same island visual setting, and baseline anxiety levels after induction differed at Stage 2, the restorative effects of different sound conditions need to be compared against this common experimental background. Furthermore, the current Dunn comparisons mainly describe EEG spectral differences at the intervention endpoint. Future studies could recruit larger samples, prespecify primary conditions and frequency bands for comparison, and conduct between-group tests incorporating post-induction starting levels and within-participant changes. Delayed post-recovery measurements and more detailed audiovisual control conditions could also be added to further evaluate the psychophysiological restorative characteristics of different sound materials.

Regarding measurement and analysis, this study used an equally weighted mean spectral amplitude across four brain regions as a whole-brain summary measure, facilitating overall comparisons of EEG activity across experimental stages and auditory conditions. Future studies could further combine local regional and electrode-level spectral measures, individual differences across frequency bands, HRV, and electrodermal activity to characterize psychophysiological responses to different auditory configurations more comprehensively. Records of sound-source rhythm, spectral features, loudness, and participants' musical familiarity and individual preferences could also be added to improve the evaluation system for restorative auditory stimuli. Statistically, clearly defined between-group questions could be developed around individual changes from Stage 2 to Stage 3, and future research may further examine differences in psychophysiological changes across auditory conditions by incorporating participant-level change measures and appropriate statistical approaches that account for the associations among measurements collected at different experimental stages. Because the study participants were all healthy young university students, the applicability of the results to other age groups or

people with clinical anxiety requires further validation. Regarding EEG data quality, complete 300-s EEG recordings were retained for all 80 participants across the three experimental stages. A standardized preprocessing procedure was applied using CURRY 9, including common average referencing, baseline correction, filtering, and covariance-based ocular-artifact reduction, to improve signal quality and minimize potential interference from non-neural activity. The consistent preprocessing workflow and retention of participant-level EEG data provided a basis for comparing spectral characteristics across experimental stages and auditory conditions. Future studies may further enhance methodological transparency by incorporating detailed preprocessing records and quantitative EEG quality-control indicators.

6. Conclusions

This study investigated 80 university students under eight auditory conditions in a standardized virtual island environment, combining S-AI scores with whole-brain log-transformed mean spectral amplitudes in the Alpha, Beta, and Theta bands to analyze psychophysiological changes across three experimental stages. The overall mean S-AI score rose from 41.09 at Stage 1 to 50.85 at Stage 2 and then declined to 36.20 at Stage 3; mean scores decreased during the auditory intervention stage in all eight groups, including the no-sound control. Three-stage Friedman tests were significant for whole-brain Alpha and Beta, but not for Theta. Adjacent-stage comparisons showed that Alpha decreased primarily from Stage 1 to Stage 2, whereas Beta decreased across both stage transitions. At Stage 3, the overall Kruskal–Wallis tests across the eight groups were not significant in any of the three frequency bands after Holm adjustment, whereas exploratory Dunn comparisons with the no-sound group identified significant differences in some frequency bands, depending on the scope of the multiple-comparison correction. These findings reveal certain differences in EEG spectral distributions under different auditory stimulus conditions and provide experimental clues for further investigation of the relationships between sound configuration and psychophysiological activity. Although the overall reduction in state anxiety from Stage 2 to Stage 3 was statistically significant, the between-group comparison of recovery-stage change scores was not significant. Thus, the observed recovery should not be attributed exclusively to auditory stimulation, and the present findings do not demonstrate the superiority of any specific auditory condition.

This study found that short-term anxiety induction and subsequent recovery were accompanied by significant changes in subjective state anxiety and stage-related changes in EEG frequency bands such as Alpha and Beta. Different auditory stimulus conditions showed certain differences in EEG spectral distributions at the intervention endpoint, reflecting the diversity of neurophysiological responses in restorative auditory contexts. By combining subjective state anxiety assessment with EEG spectral measurements in a standardized virtual natural environment, this study described short-term psychophysiological responses to natural environmental sounds, different musical materials, and their combinations from both psychological and physiological perspectives, providing a reference for the experimental evaluation of restorative soundscapes and subsequent comparative research. Overall, this exploratory study provides preliminary empirical insights into the dynamic psychophysiological responses associated with short-term restorative auditory environments and offers a foundation for future investigations with larger and more diverse samples.

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Institutional Review Board Statement: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research ethics committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The study was approved by the Ethics Committee of Southwest Forest University (Approval No./Reference No.: [SWFU-20251110-01; 10 November 2025]). Informed consent was obtained from all individual participants included in the study.

Informed Consent Statement: Additional informed consent was obtained from all individual participants for whom identifying information is included in this article.

Data Availability Statement: The de-identified data supporting the findings of this study and the MATLAB scripts used for EEG spectral analysis have been deposited in Science Data Bank (ScienceDB). The dataset is currently undergoing repository registration and will be accessible through its registered DOI upon publication.

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Abbreviation

The following abbreviation is used in this manuscript:

EEG	Electroencephalogram

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