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Effects of different natural soundscapes on human psychophysiology in national forest park

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Most of the current soundscape research content is limited to the discussion of the restoration effect of single-element soundscapes, but it is the combination of sounds that is common in outdoor activities, and there is no evidence that the restoration of natural soundscapes is better with multi-element combinations. In this study, the Zhangjiajie National Forest Park in China was used as the research object, and the physiological indices of the subjects were collected through electroencephalogram signals, and the POMS short-form psychological scale was used to understand the subjective psychological responses of the subjects to the soundscape. The results showed that (1) The psychophysiological restorative ability of the natural soundscape of the National Forest Park was confirmed, and the subjects' psychological and physiological indices changed significantly and positively after listening to each section of the natural soundscape ($p = 0.001$). (2) The restorative effect of the multi-natural sound combination was ranked first in the overall ranking of the five natural soundscapes, and the multi-natural sound combination did indeed provide better restorative effects than the single-element sounds. (3) Gender does not usually have a significant effect on the restoration effect, and only Windy Sound among the four single-element nature sound landscapes and one multi-element combination of nature sound landscapes showed a significant gender difference, so in general, the effect of gender on the restoration effect of nature sound landscapes is not significant. In terms of research methodology, this study used cluster analysis to cluster the five types of natural soundscapes according to psychological and physiological recovery ability, and used ridge regression to construct mathematical models of the psychological and physiological recovery of each of the four natural soundscapes. The study of human physiological and psychological recovery from different types of natural soundscapes in China's national forest parks will provide a basis for soundscape planning, design, and policy formulation in national forest parks.

Keywords Natural soundscapes, Psychophysiology recovery, EEG, POMS, Zhangjiajie national forest park

In recent years, the accelerated pace of life and the multifaceted pressures of modern society have subjected long-term urban residents to the intrusion of challenges such as population congestion, excessive stimulation, intense competition, and noise pollution. These issues significantly elevate the likelihood of mental exhaustion[1–6], particularly evident post-COVID-19, where individuals harbor unease and even aversion toward prolonged urban confinement[7–10]. Notably, the World Health Organization's "World health statistics 2023: monitoring health for the SDGs, sustainable development goals"[11]highlights: (1) The entire global population (99%) breathes unhealthy levels of fine particulate matter (PM) with no immediate sign of reversion. (2) Noncommunicable disease affect people from all walks of life, and in all parts of the world. The epidemic of NCDs poses devastating health consequences for individuals, families and communities. Prevention and control of these diseases are a major development imperative for the twenty-first century. (3) War has brought great mental anxiety and worry to people, especially the global turmoil led by the war, which has intensified people's uncertainty about the future, which has led to frequent anxiety and depression. Additionally, the "Mental Health Atlas" released by the World Health Organization in 2021[12] reveals: (1) Globally, less than 50% of individuals in need of specialized care for mental health issues receive it, with an average of 40% for individuals with depression and a mere 29%

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for those with psychiatric disorders. (2) Government expenditure on mental health remains stagnant, hovering around 2%, underscoring the escalating global severity of mental health issues and their significant economic impact on ordinary households[13].

Consequently, an increasing number of researchers are turning their attention to the relationship between open, natural environments and psychological well-being[14–18]. Substantial empirical evidence indicates that exposure to natural landscapes contributes to attention restoration, mood improvement, stress recovery, and overall health[18–22]. For instance, Jackson and Stevenson conducted a survey on 624 American adolescents, revealing a strong correlation ($R^2 = 0.42$) between changes in subjective well-being and outdoor activities ($B = 0.44$, $p < 0.001$) and nature-based activities ($B = 0.21$, $p = 0.016$). This suggests that increasing outdoor activities in natural settings enhances adolescents' adaptive capacity against stress. Dzhambov and Lercher, in an online survey of 323 students (21.99 ± 3.10 years; 31% male), found that approximately 33 and 20% of students reported clinically significant moderate depressive and anxiety symptoms. Visible rich greenery from homes or nearby locations was associated with a reduction in depressive/anxiety symptoms and lower rates of depression/anxiety, indicating a significant supportive role of greenery in mental health[19]. Mattila and Korhonen utilized immersive virtual reality (VR) technology to explore the restorative effects of forest environments, demonstrating that forest environments possess high restorative properties, improving perceived restoration effects, vitality, and mood[20]. Meuwese and Dijkstra, focusing on individuals with depression, exposed them to different videos (architectural and natural environments) after a disturbance. The experiment noted a greater abundance of positive emotions provided by natural environments[21]. Wang and Xu employed EEG technology and surveys to assess psychological and physiological responses to seasonal landscapes. The experiment revealed significant differences between winter and summer landscapes, with only winter landscapes showing significant gender differences. Furthermore, values for The questionnaire of restoration outcomes scale (ROS) and willingness to visit (WTV) were higher in summer landscapes compared to winter landscapes[23].

In conclusion, these studies compellingly demonstrate from various perspectives that nature contributes significantly to mental health, particularly in reducing stress levels. Summarizing extensive research, we find: (1) Natural environments possess evident restorative effects[24–27]. (2) Natural environments exhibit more pronounced restorative effects than other environments (urban environments, built environments, etc.) [26,28–30]. (3) Natural environments yield discernible restorative effects across most age groups and social demographics[24,31–34].

In the course of numerous studies on the restorative effects of natural environments, two prominent and classical theories have provided fundamental conceptual explanations and pathways for their impact: Stress Recovery Theory (SRT)[35] and Attention Restoration Theory (ART)[36]. This paper is grounded in these two prominent theories.

Stress Recovery Theory (SRT), initially proposed by Ulrich in the United States, focuses primarily on the visual perception of the environment in his psychoevolutionary theory. Humans exhibit an evolutionary aesthetic preference for natural environments. Visiting natural environments visually provides a pleasant setting, facilitating stress reduction by limiting negative thoughts, eliciting positive emotions, and enhancing the activity of the parasympathetic nervous system[35,37]. Attention Recovery Theory (ART), introduced by Kaplan, suggests that individuals experiencing directed attention fatigue recover more quickly through soft fascination. This refers to effortless attention, drawn by inherently engaging stimuli that require no mental resources and are quite complex and coherent[38]. Kaplan later added that walking in nature is considered a form of soft fascination, while watching television is a form of strong fascination. Individuals use soft fascination to replenish non-directed attention, which subsequently supplements directed attention[39].

Building upon these two theories, numerous scholars have conducted research on the psychological restorative effects of natural environments[4,25,27,40–42]. Based on empirical evidence, these studies robustly demonstrate from various perspectives that proximity to nature is beneficial for psychological restoration. These studies generally agree that: (1) Natural environments can provide effects that restore attention and alleviate stress. (2) These effects not only impact psychology but also influence behavior[43–46].

Based on various studies on psychologically restorative environments, R.M. Schafer conducted field recordings to study the psychological restorative effects of the soundscape in natural environments in "The tuning of the world: Toward a theory of soundscape design"[47]. He emphasized that experiencing the soundscape should be approached like listening to a musical composition and is often referred to as the "father of acoustic ecology"[1]. Schafer subsequently conducted research in his home country, exploring the impact of sound on individuals and striving to find positive environmental acoustic means in line with ecological strategies. He initiated the World Soundscape Project, conducting systematic investigations into the ecological soundscapes of several cities and rural landscapes in Europe, subsequently publishing works such as "European Sound Diary" and "Five Village Soundscape," marking the exploration phase of European soundscape research.

From this point onward, scientists have progressively turned their attention to the psychological restorative effects of natural soundscapes. Numerous studies have demonstrated the value of natural soundscapes in providing emotional and psychological restoration[48–56]. Building on these studies, an increasing number of scholars have begun to analyze the psychological restorative effects of soundscapes from various perspectives. Examples include investigations into the restorative effects of natural soundscapes from different locations (rural areas[57], urban parks[58], forest parks, national parks[1]) and the restorative effects of different elements within natural soundscapes (birdsong, flowing water[59], wind sounds[60], insect chirping[61], etc.).

Research indicates that natural soundscapes from different locations have varying effects on individuals' restoration outcomes. Here are specific examples from different studies: Chen and Yu conducted an experiment in Shangri-La, China, and found that visitors preferred natural sounds containing biotic elements, such as the sounds of streams and bird calls. They gathered insights into people's soundscape preferences in rural locations through the distribution of 452 questionnaires[57]. Van Renterghem and Vanhecke studied urban parks, playing eight different types of natural sounds for 165 participants. They discovered that in urban parks, most people preferred a balanced combination of various types of natural sounds, with notable emphasis on bird songs and house sparrows[58]. Uebel and Marselle treated urban green spaces as soundscapes for their research, delving into the perceived restorative qualities of urban green soundscapes. One of their findings highlighted that a rich perception of bird sounds provided the greatest restorative effect for park soundscapes. The study involved 162 participants[62]. Fang and Gao conducted a soundscape study in an urban recreational forest park, revealing that people favored the rustling of leaves and the sound of water in natural soundscapes. These sounds may contribute to a more effective restoration experience for individuals[63]. These research findings underscore the significance of soundscapes in different environments and suggest that preferences for natural sounds may be influenced by geographical location and environmental context.

Restorative effects of natural soundscapes with different elements: Wang and He focused on the Qianjiangyuan National Park experimental area in China. They collected physiological indicators from participants using the biopAC-MP150 multi-channel physiological signal acquisition platform and measured subjective psychological responses to soundscapes using Likert scales. The experiment showed that water sounds had the most significant impact on participants' heart rate and respiratory rate. Agricultural sounds had the greatest impact on skin conductance level. Different soundscapes exhibited significant differences in terms of comfort, excitement, and significance ($p < 0.001$). Insects' sounds were more likely to evoke feelings of comfort and excitement, while bird sounds were more likely to arouse curiosity. There was no significant correlation between physiological and psychological indicators[1]. Soeta and Ariki conducted preference analysis in Japan. They found that the bird songs of *Horornis diphone* and *Cuculus canorus* appeared to be ideal information signals, as they were both significant and preferred. Regarding the songs of insects, the song of *Tanna japonensis* seemed to be an ideal signal as it was prominent and preferred, possibly because they are ubiquitous in Japan and are popular there[64]. Wang and Zhang investigated the characteristics of soundscapes (such as loudness, frequency, preference, and auditory satisfaction) in the Qianjiangyuan National Park pilot area using 394 valid questionnaires from residents. They analyzed the impact of soundscapes on visual aesthetics using PLS-SEM. The results showed that the components of street vendors' sounds and insect sounds were the loudest in soundscapes, while the sounds of flowing water and birdsong were the most frequently heard and liked[65]. Liu combined six types of blue spaces with 14 sounds, using 65 volunteers to measure the restoration quality of audiovisual combinations through the Shortened Revised Restoration Scale (SRRS). Within a range of 1–9, the results were as follows: the water sound with the highest restoration quality was river sound (6.94), followed by fountain sound (6.59) and stream sound (6.41), while the restoration quality of ocean waves sound was the lowest (5.85)[66].

In summary, with the efforts of a large number of scholars, the psychological restorative effects of natural soundscapes on people have been confirmed from multiple perspectives. However, we found that the current restorative research on soundscape still has the following four problems: (1) National forest parks have very rich and original natural soundscapes, but few scholars have focused on the analysis of natural soundscapes in national forest parks. (2) The comparative study of the restorative effect between different natural soundscapes is still weak. (3) When going out to play, people cannot hear only one or two kinds of natural sounds, so it is very important to explore the restorative effect of natural combined sounds, yet there are few examples comparing the restorative effect difference between combined sounds and single-element sounds. (4) It is worth mentioning that a large number of studies have talked about the restorative effects of natural soundscapes, but there are basically no studies that specifically quantify how much restorative capacity each natural soundscape has. In addressing these issues, this study sampled the natural soundscapes, including Hydroacoustics,Windy Sound, Birdsong, Insect Chirping, and Combined Sound, of Zhangjiajie National Forest Park in China during the summer season (hereinafter referred to as Zhangjiajie National Forest Park). The creation of three research hypotheses was made:

H1 National forest parks' natural sounds have a significant restorative effect on human psychophysiology.

H2 Multiple-element natural soundscapes are more restorative than single-element natural soundscapes.

H3 Psychophysical recovery outcomes are significantly influenced by gender.

In this study, we explored the relationship between natural soundscape and human psychological and physiological recovery in Zhangjiajie National Forest Park in summer by analysing the changes in physiological indicators and data on psychological indicators, revealed the comparative restorative effects between different elements of natural soundscape, and carried out a hierarchical clustering analysis of the restorative effects of the five types of natural soundscape according to psychological and physiological influences by means of experimental data. Finally, we constructed a mathematical model of the psychological and physiological restorative effects of natural soundscapes using ridge regression equations. Following implications will be provided by our study: (1) For the government: To find an alternative way to save public health care costs. It will help to increase the government's attention to mental problems, increase financial expenditures to build and protect the natural soundscape of the National Forest Park, and provide free psychological restorative places for ordinary families. (2) For NFP management authorities, the aim is to provide new insights into soundscape assessment and restorative soundscape planning and design of NFPs, and to improve soundscape layout planning and design. (3) For the public: to help the public understand more intuitively and clearly the restorative differences between different elements of the natural soundscape, and to guide the public to carry out recreational activities that are conducive to mental health.

Materials and methods

Area of experiment

Zhangjiajie National Forest Park is situated at the junction of Hunan, Hubei, Guizhou, and Sichuan provinces, lying between approximately 110°24′–110°28′ E longitude and 29°17′–29°21′ N latitude Specifically, the location at which each sound was measured was this: Birdsong: (29°20′52″ N, 110°32′43.6″ E); Hydroacoustics (29°20′42″ N, 110°33′36.6″ E); Windy Sound (29°32′52.8″ N, 110°32′52.8″ E); Insect Chirping (29°20′32.4″ N, 110°20′32.4″ E); Combined Sound (29°20′0″ N, 110°30′0″ E). It spans an area of approximately 4,810 hectares (Fig. 1). Renowned globally for its unique "Zhangjiajie Landform," the park is celebrated as a utopia far removed from the hustle and bustle of urban life. Additionally, it served as the backdrop for the film "Avatar."In February 2004, Zhangjiajie National Forest Park was designated as a World Geopark. Subsequently, in 2007, it was included among the first batch of China's national 5A-level tourist attractions. The park, situated in the subtropical climate zone of Central Asia, boasts an impressive forest coverage of 98%, rendering it a well-known biodiversity conservation area in China. Owing to the diverse array of flora and fauna, the soundscape here is rich and varied, encompassing, but not limited to, bird calls, rustling leaves, flowing water, and insect sounds. Therefore, this study selected Zhangjiajie National Forest Park as the soundscape sampling site.

Methods and processes

Sound recordings and materials

This study employed a combined approach of outdoor (audio collection) and indoor (physiological and psychological measurements) experiments to mitigate the impact of uncontrollable factors such as ambient noise and weather conditions on the experiment. The five audio segments used in this study were collected on days with a mild breeze and light rain (this is from biological activities, in order to collect more abundant natural sounds) from August 13 to August 14, 2023. The audio data collection occurred during the time periods of 7:30–11:30 and 15:00–18:00, with humidity ranging from 92 to 94% and temperatures between 22.7 and 23.4 °C. Sony ICD-PX470 recording devices were positioned approximately 1.5 m above the water surface. During recording, the microphone end of the recording pen was kept perpendicular to the main wind direction to avoid wind-induced noise interference. In light of previous research, which commonly includes the study of natural sounds such as hydroacoustics, windy sound, birdsong, and insect chirping, this study selected one representative areas as sound sampling sites (Fig. 2). Considering potential factors of sound interference, the selected sound materials were edited to approximately 60 s using Foxit Audio Clip software. After editing the sound, we invited three professors from the School of Tourism, Central South University of Forestry and Technology to evaluate the sound, and they believed that such sound quality could meet the basic needs of the experiment.

Participants

Past research has indicated that college students are ideal subjects for environmental psychology[1,67]. In this study, volunteers were recruited through online recruitment links and offline promotional methods, with each volunteer receiving a compensation of 10 Chinese Yuan. Ultimately, a total of 52 students (This is based on the sample size of previous psychophysiological experiments, the evaluation and recommendations of statistical experts, and the constraints of realistic conditions) from Central South University of Forestry and Technology participated in the experiment (males: 26 individuals, 50%; females: 26 individuals, 50%), with ages ranging from 18 to 21 years. Participants were asked to have no history of mental illness, no alcohol abuse within 12 h, and no cardiovascular disease.

Physiological indicators

The physiological parameter selected for this study is electroencephalogram (EEG) signals, primarily due to the extensive utilization of EEG signals as physiological indicators in environmental psychology research[68–70].

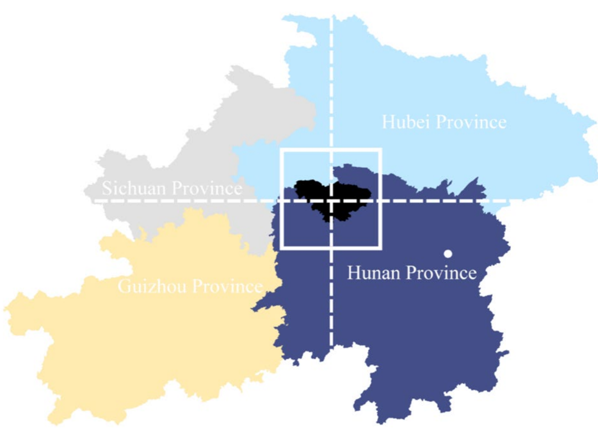

Figure 1. Location of Zhangjiajie National Forest Park. *Note*: Land use data from the National Geographic Information Resources Directory Service System (https://www.webmap.cn/).

Figure 2. Viewfinder for natural soundscapes.

These studies validate that EEG signals indeed encapsulate rich emotional information and provide a relatively accurate understanding of subjects' reactions to their surroundings.

Electroencephalogram (EEG) signals represent the integrated response of millions of neurons in the human brain cortex, with different electrical potential changes intuitively reflecting one's psychological activities and emotional states[71]. EEG signals consistently serve as a pivotal physiological indicator in psychological research, fundamentally because human perceptions and cognitions can be manifested through brainwave patterns. When the brain processes external stimuli such as olfactory, auditory, visual, gustatory, and tactile stimuli, corresponding changes occur in EEG waves. The physiological manifestations include enhanced sympathetic nervous system activity, increased blood pressure, accelerated respiration, while psychological manifestations encompass heightened anxiety and emotional arousal[72].Specifically, Zeng employed the Emotiv EPOC X device to dynamically measure six neural-emotional indicators (engagement, excitement, attention, interest, relaxation, and stress) while investigating the interplay between vegetation density (VD) and comprehensive sound environment (ISE) within green spaces[73]. Olszewska-Guizzo, using electroencephalography (EEG) experiments, explored how window views from different floors of high-rise buildings with varying degrees of green coverage influenced the emotional states of 29 healthy residents[74]. These studies collectively affirm that EEG signals serve as conspicuous observational indicators of changes in subjects' psychological states.

We used Mind Wave, an EEG acquisition device with Think Gear ASIC Module (TGAM) as the core from Neurosky, which is famous for its stable performance and wearability. It has numerous development platforms. It is suitable for personal computers (PCs), Androids, the iPhone operating system (iOS), microprocessors, and so on. In the EEG, more applications have currently been used for mind control games to train attention, brainwave recording, and analysis. Meanwhile, it is a single-channel acquisition device. The EEG signal acquisition device is placed on the forehead. The frequency band collected ranges from 0 to 100 Hz, which means it covers the 4 types of brain wave bands, namely α, β, θ, and δ. The signal sampling frequency in this study was 512 Hz, and the effective distance of wireless transmission was 10 m. The collected EEG data were processed to obtain the eSense index, which was used to describe the degree of attention and relaxation state of the participants. When people's attention is focused on, the y-wave and Y-wave account for a larger proportion of EEG signal energy. In a fatigued state, the proportion of EEG energy accounted for by EEG waves and δ waves is larger. Therefore, the methods to calculate the concentration and relaxation indices can be obtained, and the formula of eSense Concentration Index is as follows: The eSense attention index (Pa) signifies the intensity of participants' mental "focus" and "attention," with the index ranging from 0 to 100. A higher score indicates greater concentration.

The formula for calculating the eSense attention index (Pa) is as follows:

$$\mathrm{Pa} = (\mathrm{mY} + \mathrm{n}\beta + \mathrm{t}\alpha) \times 100 \tag{1}$$

Here, Pa represents concentration, and Y, β, α denote the percentages of Y wave, β wave, and α wave in EEG signal energy, respectively. The coefficients m, n, t represent the weighting coefficients of Y wave, β wave, and α wave, respectively. The eSense concentration index indicates the strength of the user's mental "concentration" or "attention" level, with a range of values from 0 to 100. Disturbance, mental distraction, lack of focus, and anxiety are all factors that reduce the concentration index.

The formula for calculating the eSense relaxation index (Pm) is as follows:

$$\mathrm{Pm} = \left(\mathrm{x}\theta + \mathrm{y}\delta + \mathrm{z}\alpha\right) \times 100 \tag{2}$$

Here, Pm represents relaxation, and θ, δ, α denote the percentages of θ wave, δ wave, and α wave in EEG signal energy, respectively. The coefficients x, y, z represent the weighting coefficients of θ wave, δ wave, and α wave, respectively. The eSense relaxation index indicates the user's mental "calmness" or "relaxation" level. The range of this index is 0 to 100. Simply relaxing the muscles throughout the body cannot rapidly increase the level of relaxation. However, for most individuals, bodily relaxation in a normal environment generally contributes to mental relaxation. The increase in relaxation level is significantly associated with a decrease in brain activity.

In this auditory landscape experiment, the primary focus is on monitoring the eSense attention index and eSense relaxation index. The objective is to observe variations in different frequency bands before and after the auditory landscape experience, as well as throughout the process. This analysis aims to determine the emotional states and physiological responses of the participants.

Psychological indicators
In terms of psychological indicators, this study employed the abbreviated Profile of Mood States (POMS) psychological inventory, as introduced by Grove in 1992[75]. It is widely used in psychological research[76–78]. The instrument comprises 40 concise emotion-related terms designed to assess seven different states: tension, anger, depression, fatigue, confusion, vigor, and self. Each emotional word within each dimension is rated on a scale ranging from "almost none" to "very much," with five levels of intensity. The five options correspond to scores ranging from 0 to 4. Notably, tension, anger, depression, fatigue, and confusion represent negative factors, while vigor and self are positive factors within the assessed states. The 7 questions are summarized as follows:

Tense: Questions 1, 8, 15, 21, 28, 35;
Anger: Questions 2, 9, 16, 22, 29, 36, 37;
Fatigue: Questions 3, 10, 17, 23, 30;
Depression: Questions 4, 11, 18, 24, 31, 38;
Energy: Questions 5, 12, 19, 25, 32, 39;
Panic: Questions 6, 13, 20, 26, 33;
Self-esteem: Questions 7, 14, 27, 34, 40;

POMS were statistically analyzed by two factors: positive affect (PA) and negative affect (NA). The positive emotion score includes energy score and self-esteem score. The higher the value, the more positive the emotion, while the lower the score appears indifferent and low self-esteem. The negative emotion score includes tension score, anger score, fatigue score, depression score and panic score. The larger the score, the more negative emotion. The subjects rated the indicators according to their emotional state, with higher scores indicating a higher emotional state. The POMS-SF scale we used this time is shown in Table 1.

Introduction of soundscape material
The soundscape materials we collected include Hydroacoustics, Windy Sound, Birdsong, Insect Chirping, and Combined Sound. Their specific information is as follows: First, the water speed is 2.1 m/s, and the decibel is 35dBA; Secondly, the wind speed is 3.1 m/s, which belongs to the second-level breeze. Then, the sound level of bird song is 43.1dBA. According to the frequency spectrum, four species of birds are finally identified, they are *Horn lark* (2 k–3.1 k Hz), *House sparrow* (3.3 k–4 k Hz), *Mynah*(4.3 k–5 k Hz), and *European Robin* (6 k–7 k Hz). Fourth, the same method was used to examine the species of insects, which mainly included Cicadas and Bees. Finally, after the analysis of experts, the Combined Sound in addition to the above natural sounds, there are more obvious monkey calls.

Experimental control
To ensure the effectiveness of the experiment and minimize interference with the participants, the current study was conducted within the laboratory of the National Forestry and Grassland Administration Forest Tourism Engineering Technology Research Center. The following measures were implemented: (1) Temperature and Humidity Control: The laboratory environment was maintained at approximately 26 degrees Celsius, with humidity around 80%, to regulate tactile sensations. (2) Participant Familiarization: Prior to the commencement of the experiment, participants were given 5–8 min to acclimate to the environment, aiming to alleviate any tension arising from unfamiliar surroundings. (3) Visual Control: Throughout the experiment, experimenters wore light-blocking eye masks to reduce visual interference and maintain control over the laboratory's visual environment. (4) Individual Experimentation: To ensure experimental quality and prevent mutual interference among participants, each participant underwent the experiment individually. (5) Odor and Air Quality Management: The room was kept odor-free, and normal air circulation was maintained. During the experiment, efforts were made to preserve a quiet environment, with doors and windows tightly closed to minimize noise and its impact on participants' auditory experiences.

Experimental process
The experiment was conducted in three distinct steps, with meticulous preparation of experimental instruments and comprehensive explanations provided to participants regarding the purpose, process, and usage of the equipment. Upon entering the laboratory, participants were guided through the wearing and testing of the instruments to ensure their proper functioning. Participants were then required to complete an informed consent form and a recent health status questionnaire (To ensure that all participants had normal hearing, were calm, and had no alcohol for 12 h). The experiment comprised the following phases (Fig. 3).
T0: Pre-Experiment

Participants filled out the informed consent form.
Subsequently, baseline EEG data were recorded without exposure to auditory stimuli.
Following the data recording, participants completed the abbreviated POMS mood state inventory.

Emotions	Number	Feeling
Tense	1	Anxious
	8	Troubled
	15	Restless
	21	Restless
	28	Easily excited
	35	Worried
Anger	2	Angry
	9	Furious
	16	Irritated
	22	Annoyed
	29	Angerful
	36	Enraged
	37	Complaining
Fatigue	3	Listless
	10	Fatigued
	17	Exhausted
	23	Weary
	30	Worn out
Depression	4	Unhappy
	11	Sad
	18	Depressed
	24	Melancholic
	31	Worthless
	38	Helpless
Energy	5	Relaxed
	12	Energetic
	19	Proactive
	25	Eager
	32	Active
	39	Full of Pep
Panic	6	Panicked
	13	Unable to concentrate
	20	Flustered
	26	Forgetful
	33	Uncertain
Self-esteem	7	Distressed
	14	Confident
	27	Capable
	34	Satisfied
	40	Proud

Table 1. The POMS-SF scale used in the experiment: Emotion, serial number and corresponding topic list of POMS-SF scale.

Upon completion, participants were instructed to relax, adjust to a comfortable sitting position, and stabilize their mood.

T1: Experiment commencement

Participants were instructed to wear the light-blocking eye masks and the experimental equipment, with a thorough examination and testing of the instruments conducted by experimenters to ensure proper functionality.
After the examination, auditory stimuli (1 min of flowing water sounds, followed by 3 min of calm, 1 min of wind rustling leaves, followed by 3 min of calm, 1 min of bird calls, followed by 3 min of calm, 1 min of insect chirping, followed by 3 min of calm, and a combination of various nature sounds) were presented using an iPhone 14 Pro and AirPods Pro (Bluetooth earphones).

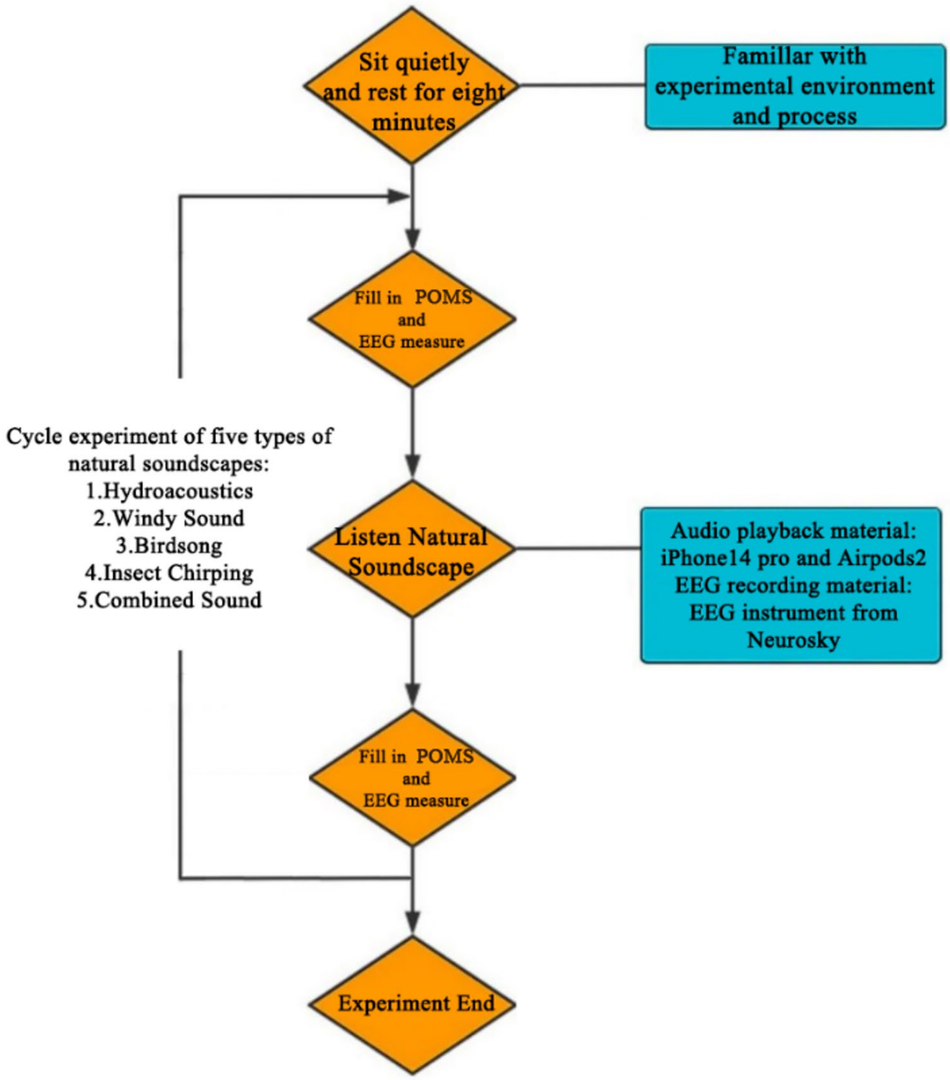

Figure 3. Experiment flow chart.

eSense attention and eSense relaxation indices were measured both before and after each segment of the auditory stimuli.

T2:Experiment conclusion

After the completion of the auditory stimuli sequence, participants removed the eye masks.
Participants then filled out the POMS inventory again.
Following the completion of the inventory, a second measurement of eSense attention and eSense relaxation indices was conducted.

All data collected in this study were analyzed by Microsoft Excel 2021 and IBM SPSS Statistics 21, SPSSAU, SPSSPRO. The main statistical methods were one-way ANOVA and multiple comparisons. Psychological data came from the questionnaire survey. In order to ensure the quality of the data, the authors conducted a reliability and validity analysis.

The results showed that Cronbach's alpha was 0.795, falling between 0.6 and 0.8, which suggested the internal consistency of the data. The results of the Kaiser–Meyer–Olkin (KMO) and Bartlett's test of sphericity were obtained by factor analysis. The KMO was 0.696, close to 0.7.The chi-square value of Bartlett's test of sphericity was 2700.121, and the degrees of freedom were 3, which were significant at the 95% or even 99% confidence level, respectively, and indicated the high effectiveness of the data.

Human and animal participants

The authors promise that: (1) The research protocol has been reviewed and approved by the Academic Ethics Committee of the Central South University of Forestry and Technology and conforms to the ethical standards for medical research involving human subjects as set out in the 1964 Declaration of Helsinki and its later amendments. (2) All participants signed a written informed consent prior to participating in the study.

Results

The influence of natural soundscape on physiology

Difference in relaxation (Pm)

Firstly, a normality test was conducted on the Pm values before and after exposure to the five natural soundscapes. For data not conforming to a normal distribution, paired-sample Wilcoxon tests were employed, while paired-sample t-tests were utilized for data exhibiting normal distribution. The results of the tests revealed that the hydroacoustics, birdsong, and the combined sound of various natural elements did not exhibit normal characteristics, whereas Windy Sound and Insect Chirping demonstrated normal distribution.

Subsequently, paired-sample t-tests were employed to ascertain whether there were significant differences in Pm levels after exposure to Windy Sound and Insect Chirping. Paired-sample Wilcoxon tests were applied to investigate potential significant differences in Pm levels after exposure to the soundscapes of hydroacoustics, Birdsong, and the Combined Sound. The findings indicated: (1) a significant level of 0.001 ($p = 0.000 < 0.001$) for the Pm levels before and after exposure to hydroacoustics; (2) a significant level of 0.001 ($p = 0.000 < 0.001$) for the Pm levels before and after exposure to Windy Sound; (3) a significant level of 0.001 ($p = 0.000 < 0.001$) for the Pm levels before and after exposure to Birdsong; (4) a significant level of 0.001 ($p = 0.000 < 0.001$) for the Pm levels before and after exposure to Insect Chirping; (5) a significant level of 0.001 ($p = 0.000 < 0.001$) for the Pm levels before and after exposure to the Combined Sound. This robustly indicates that all five natural soundscapes significantly influenced Pm levels in the experiment (Fig. 4).

We observed that, after listening to soundscapes predominantly featuring Hydroacoustics, the Pm levels decreased for 3 participants and increased for 49 participants. Following exposure to Windy Sound-themed soundscapes, the Pm decreased for 1 participant while increasing for the remaining 51 participants. In the case of Birdsong-themed soundscapes, the Pm decreased for 3 participants and increased for 49 participants. After exposure to Insect Chirping-themed soundscapes, the Pm decreased for 6 participants and increased for 46 participants. Following the experience of a Combined Sound-themed soundscape, all participants showed an increase in Pm levels.

To further explore the differences in the impact of different soundscapes on Pm, we utilized effect sizes to examine the magnitude of differences. Cohen's d values from paired-sample t-tests represented the effect sizes, with threshold scores of 0.20, 0.50, and 0.80 distinguishing small, medium, and large effect sizes, respectively. The results revealed: (1) The Cohen's d value for Pm levels before and after exposure to Hydroacoustics-themed soundscapes was 0.945, indicating a large effect size; (2) For Windy Sound-themed soundscapes, the Cohen's d

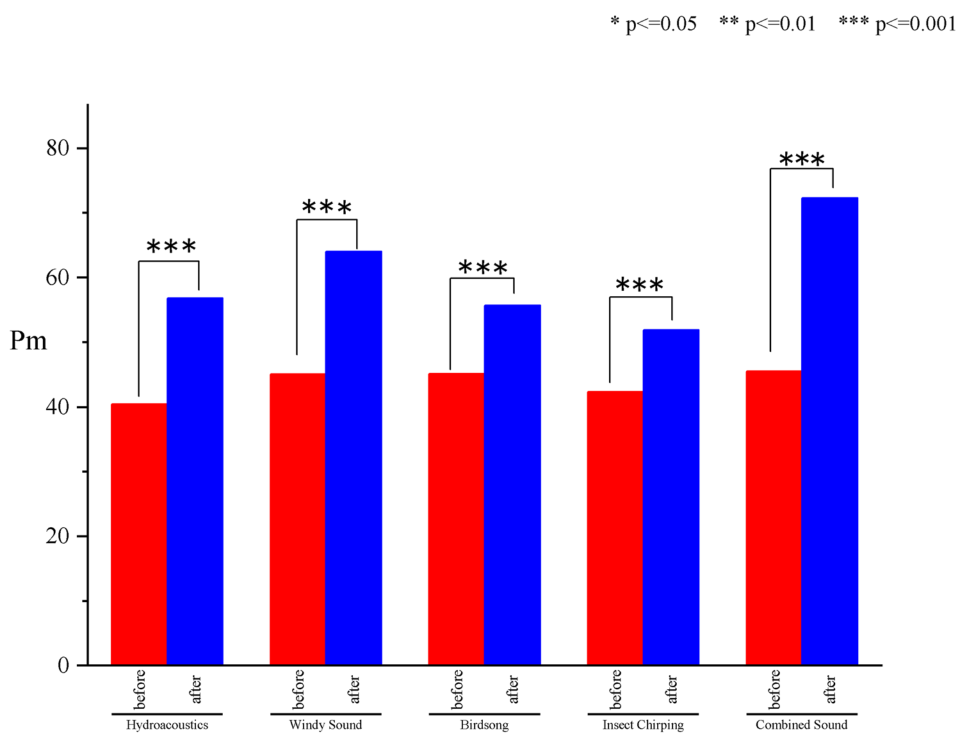

Figure 4. Differences in Pm after listening to the five types of natural soundscape.

value was 4.873, representing an extremely large effect size; (3) For Birdsong-themed soundscapes, the Cohen's d value was 2.985, indicating a large effect size; (4) For Insect Chirping-themed soundscapes, the Cohen's d value was 1.752, indicating a large effect size; (5) For Combined Sound-themed soundscapes, the Cohen's d value was 3.400, representing an extremely large effect size. In summary, listening to all five types of natural sounds significantly affected the improvement of Pm, with Windy Sound having the greatest impact, followed by Combined Sound, Birdsong, and Insect Chirping. Hydroacoustics had the least restorative effect on Pm.

Therefore, the results of one-way ANOVA for gender and Pm were gender had no apparent influence on Pm changes after experiencing the specified soundscapes (Table 2). No significant differences between genders were observed in the difference values 1, 3, 4, and 5 ($p > 0.05$). This implies that individuals of different genders exhibited consistency in the values of differences 1, 3, 4, and 5 after exposure to the four aforementioned soundscapes. The significance level for difference value 2 was 0.01 ($p = 0.00$), indicating a significant impact of gender on Pm changes after exposure to Windy Sound.

Differences in concentration (Pa)

Continuing, a normality test was conducted on the Pa values before and after exposure to the five natural soundscapes. For data not conforming to a normal distribution, paired-sample Wilcoxon tests were employed, while paired-sample t-tests were utilized for data exhibiting normal distribution. The results indicated that, in the case of Pa, the soundscapes of Hydroacoustics, Birdsong, Insect Chirping, and a Combined Sound of various natural elements did not exhibit normal characteristics, whereas Windy Sound demonstrated normal distribution.

Subsequently, paired-sample t-tests were employed to ascertain whether there were significant differences in Pa levels after exposure to Windy Sound. Paired-sample Wilcoxon tests were applied to investigate potential significant differences in Pa levels after exposure to the soundscapes of Hydroacoustics, Birdsong, Insect Chirping, and the Combined Sound. The findings were as follows: (1) A significant level of 0.001 ($p = 0.000 < 0.001$) for the Pa levels before and after exposure to Hydroacoustics; (2) A significant level of 0.001 ($p = 0.000 < 0.001$) for the Pa levels before and after exposure to Windy Sound; (3) A significant level of 0.001 ($p = 0.000 < 0.001$) for the Pa levels before and after exposure to Birdsong; (4) A significant level of 0.001 ($p = 0.000 < 0.001$) for the Pa levels before and after exposure to Insect Chirping; (5) A significant level of 0.001 ($p = 0.000 < 0.001$) for the Pa levels before and after exposure to the Combined Sound. This experiment robustly indicates that all five natural soundscapes significantly influenced Pa levels (Fig. 5).

We observed that, after listening to soundscapes predominantly featuring Hydroacoustics, the Pa levels decreased for 6 participants and increased for 46 participants. Following exposure to Windy Sound-themed soundscapes, the Pa decreased for 2 participant while increasing for the remaining 50 participants. In the case of Birdsong-themed soundscapes, the Pa decreased for 5 participants and increased for 47 participants. After exposure to Insect Chirping-themed soundscapes, the Pa decreased for 6 participants and increased for 46 participants. Following the experience of a Combined Sound-themed soundscape, all participants showed an increase in Pa levels.

To further investigate the differences in the impact of different natural soundscapes on Pa, we employed effect sizes to examine the magnitude of differences. Cohen's d values from paired-sample t-tests represented the effect sizes. The results revealed: (1) For Hydroacoustics-themed soundscapes, the Cohen's d value for Pa levels before and after exposure was 1.352, indicating a large effect size; (2) For Windy Sound-themed soundscapes, the Cohen's d value was 1.043, representing an extremely large effect size; (3) For Birdsong-themed soundscapes, the Cohen's d value was 2.937, indicating a large effect size; (4) For Insect Chirping-themed soundscapes, the Cohen's d value was 1.547, indicating a large effect size; (5) For Combined Sound-themed soundscapes, the Cohen's d value was 3.179, representing an extremely large effect size. In summary, exposure to all five types of natural sounds significantly affected Pa, with the greatest contribution from Combined Sound, followed by Birdsong, Insect Chirping, Hydroacoustics, and Windy Sound having the least restorative effect on Pa.

Therefore, the results of one-way ANOVA for gender and Pa indicate that gender has an effect on the change of Pa after experiencing the specified soundscape (Table 3). The difference values 1, 3 and 4 showed no significant difference between the sexes ($p > 0.05$), indicating that the difference values 1, 3 and 4 showed consistency between the sexes after individuals of different genders were exposed to the above three soundscapes. The significance level of difference values 2 and 5 was 0.01 ($p = 0.000$), indicating that gender had a significant effect on the change of Pa after exposure to Windy Sound and Combined Sound.

Difference value of Pm	Gender (standard deviation)		F	p
	1.0 ($n = 26$)	2.0 ($n = 26$)		
Difference value 1: Hydroacoustics	10.91 ± 15.91	21.83 ± 17.23	5.646	0.021*
Difference value 2: Windy Sound	16.04 ± 2.31	21.80 ± 2.85	64.014	0.000**
Difference value 3: Birdsong	10.18 ± 3.59	11.00 ± 3.52	0.688	0.411
Difference value 4: Insect Chirping	8.95 ± 4.67	10.80 ± 5.02	1.883	0.176
Difference value 5: Combined Sound	25.51 ± 7.85	28.07 ± 7.85	1.380	0.246

Table 2. One-way ANOVA of gender and Pm before and after listening to five types of natural soundscape. *$p < 0.05$ ** $p < 0.01$***$p < 0.001$.

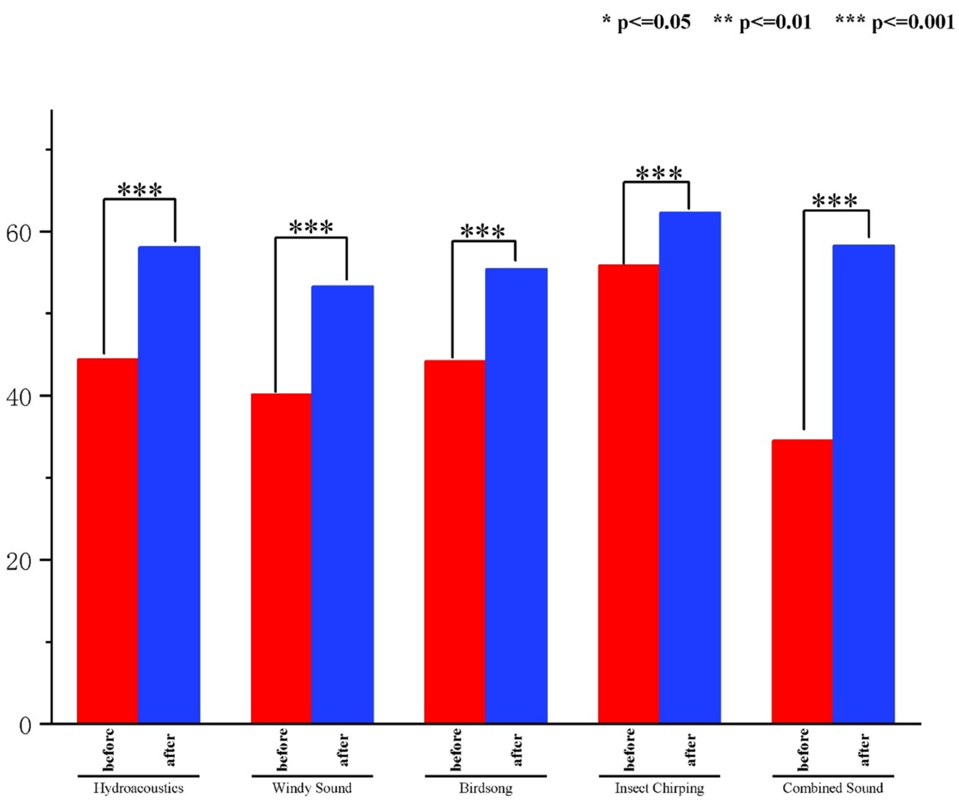

Figure 5. Differences in Pa after listening to the five types of natural soundscape.

Difference value of Pa	Gender (standard deviation)		F	p
	1.0 (n = 26)	2.0 (n = 26)		
Difference value 1: Hydroacoustics	9.04 ± 4.94	− 13.84 ± 14.30	2.622	0.112
Difference value 2: Windy Sound	14.58 ± 3.27	− 7.28 ± 3.03	69.656	0.000**
Difference value 3: Birdsong	11.43 ± 4.47	− 11.01 ± 3.20	0.152	0.698
Difference value 4: Insect Chirping	7.46 ± 4.64	− 5.33 ± 3.42	3.561	0.065
Difference value 5: Combined Sound	19.87 ± 7.43	− 27.54 ± 5.46	17.981	0.000**

Table 3. One-way ANOVA of gender and Pa before and after listening to five types of natural soundscape. * $p < 0.05$ ** $p < 0.01$***$p < 0.001$.

The influence of natural soundscape on psychology

In terms of psychological impact, it can be categorized into positive emotions (PA) and negative emotions (NA). Specifically, positive emotions include Vigor and Self-esteem, while negative emotions encompass Tension, Anger, Anxiety, Depression, and Fatigue. Among positive emotions, the most significant changes occur in Vigor, followed by Self-esteem. Within negative emotions, the most substantial changes are observed in Fatigue, followed by Tension and Depression, with Anger exhibiting the least variation (Fig. 6).

After listening to the natural soundscapes of the national forest park, there was a decrease in PA for 3 participants, while PA increased for 49 participants. Regarding negative emotions, 44 participants experienced a slight decrease in NA, while 8 participants showed an increase in NA.

A one-way analysis of variance (ANOVA) indicates that the significance levels for the differences in PA and NA between different genders are not high ($p > 0.05$), suggesting consistency in these difference values (Table 4). Therefore, the influence of gender on psychological changes is minimal. This implies that the soundscapes of the national forest park have a restorative effect on both genders.

Cluster analysis

The hierarchical clustering analysis conducted on the electroencephalogram (EEG) and emotion index data in the study (see the graph) reveals that participants can be grouped into three clusters based on Pm, Pa, PA, and NA. In Cluster 1, participants with experiment numbers 1–9, 11–41, 46, 49, 50, and 51 are included. Cluster 2

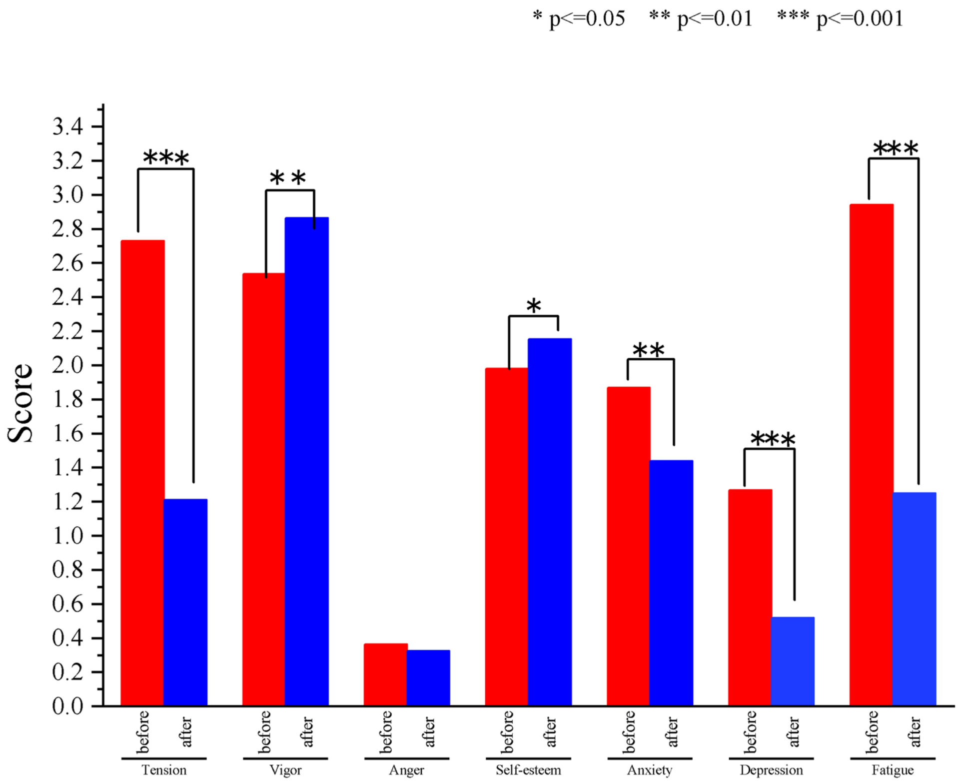

Figure 6. The difference of psychological index before and after listening to five natural soundscapes.

Difference of PA or NA	Gender (standard deviation)		F	p
	1.0 (n = 26)	2.0 (n = 26)		
Difference of NA	− 10.89 ± 4.96	− 10.45 ± 3.78	0.131	0.719
Difference of PA	9.53 ± 2.73	10.77 ± 5.09	1.201	0.278

Table 4. One-way ANOVA of changes in psychology (PA or NA) and based on gender. * $p < 0.05$ ** $p < 0.01$ $p < 0.001$.

comprises 8 samples, including 42, 43, 44, 45, 47, 48, and 52. Cluster 3 consists of 2 samples, namely 10 and 27. Hierarchical clustering was performed based on Pm, Pa, PA, and NA indicators for different types of natural soundscapes (Fig. 7).

The results (Fig. 8) show that hierarchical clustering based on Pm divides the natural soundscapes into 2 groups. Hydroacoustics, Insect Chirping, and Combined Sound are grouped together, while Windy Sound and Birdsong form a separate category. This suggests consistent effects of Hydroacoustics, Insect Chirping, and Combined Sound on Pm.Based on Pa (Fig. 9), the hierarchical clustering of virtual tourist destinations resulted in 2 clusters. Hydroacoustics and Insect Chirping are grouped together, while Windy Sound, Birdsong, and Combined Sound form a separate category.Hierarchical clustering based on PA (Fig. 10) divides virtual tourist destinations into 2 clusters. Hydroacoustics, Insect Chirping, and Birdsong are grouped together, while Combined Sound and Windy Sound form a separate category. This indicates consistent effects of Hydroacoustics, Insect Chirping, and Birdsong on PA. Hierarchical clustering based on NA (Fig. 11) divides virtual tourist destinations into 2 clusters. Hydroacoustics is grouped separately, while the other four types of natural soundscapes are collectively placed in another category. The results suggest consistent effects of the four soundscapes, except Hydroacoustics, on NA.

Construction of ridge regression model of recovery effect

The data below show ridge regression equation models between five natural soundscapes and psychological and physical recovery from national forest parks, and we hope to quantify the recovery effects of soundscapes as much as possible through such mathematical models.

From Table 5, The results of ridge regression indicate that the significance level based on the F-test is 0.000***, demonstrating significance at a high level. This suggests a regression relationship between the five natural soundscapes from the national forest park and Pm. Additionally, the goodness of fit for the model, represented by R^2, is 0.973, indicating excellent model performance. The formula for the Pm model is:

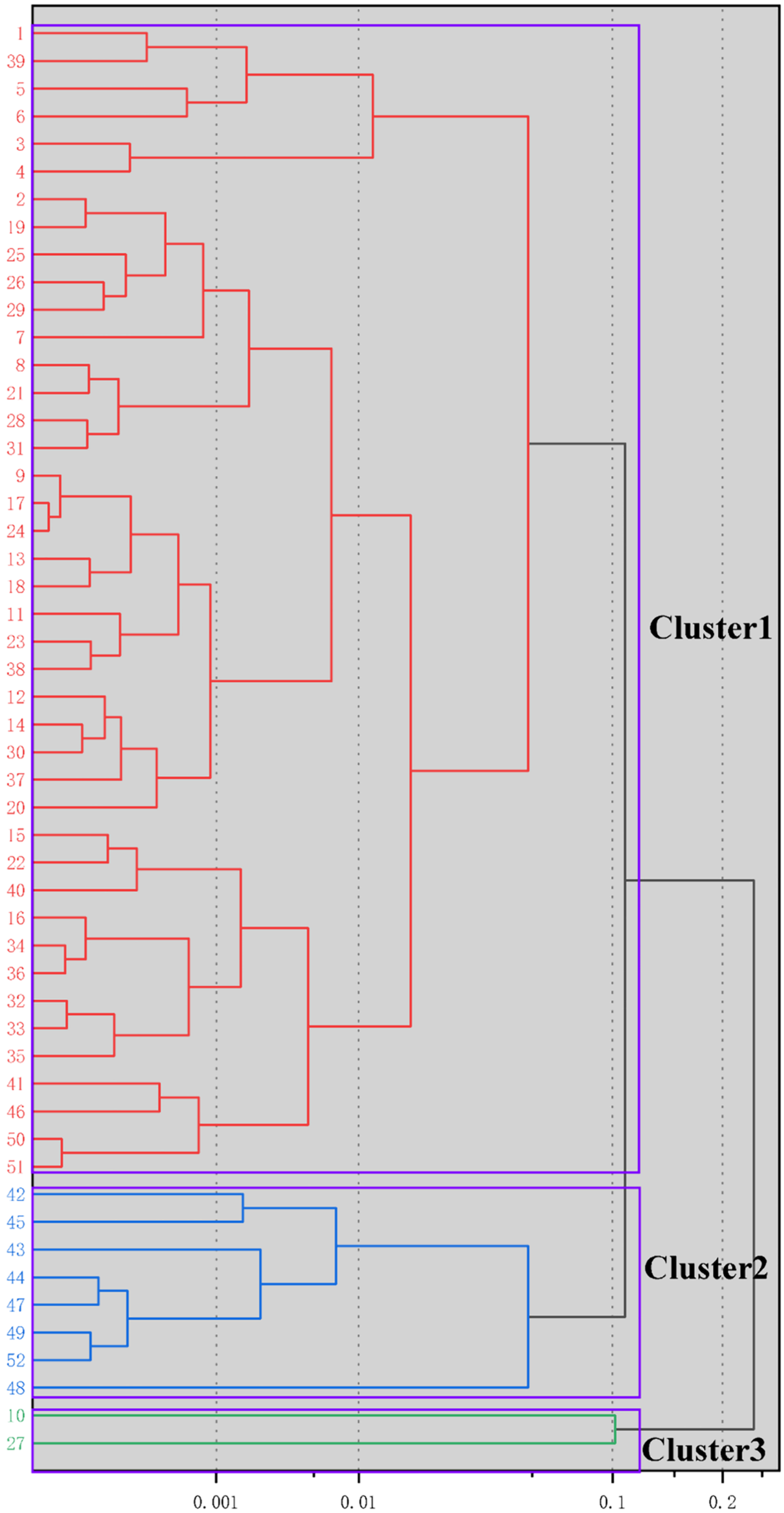

Figure 7. Clustering analysis of total participates.

$$\begin{aligned} Pm = \ & 6.448 + 0.382 \times \text{ Windy Sound} \\ & + 0.065 \times \text{ Birdsong} \\ & + 0.13 \times \text{ Hydroacoustics} \\ & + 0.078 \times \text{ Insect Chirping} \\ & + 0.412 \times \text{ Combined Sound.} \end{aligned}$$

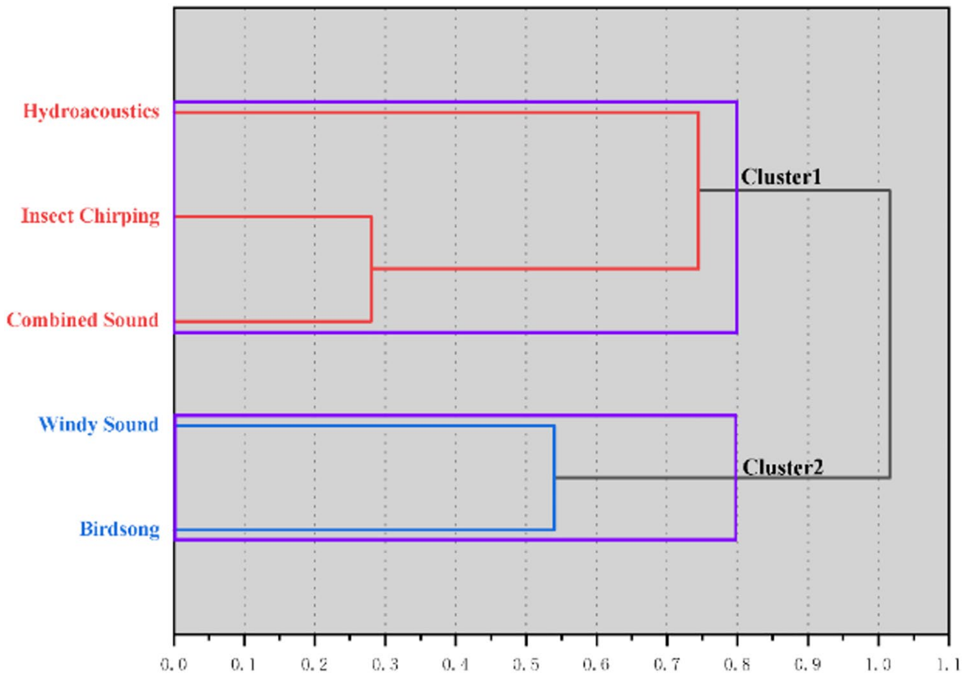

Figure 8. Cluster analysis based on Pm data.

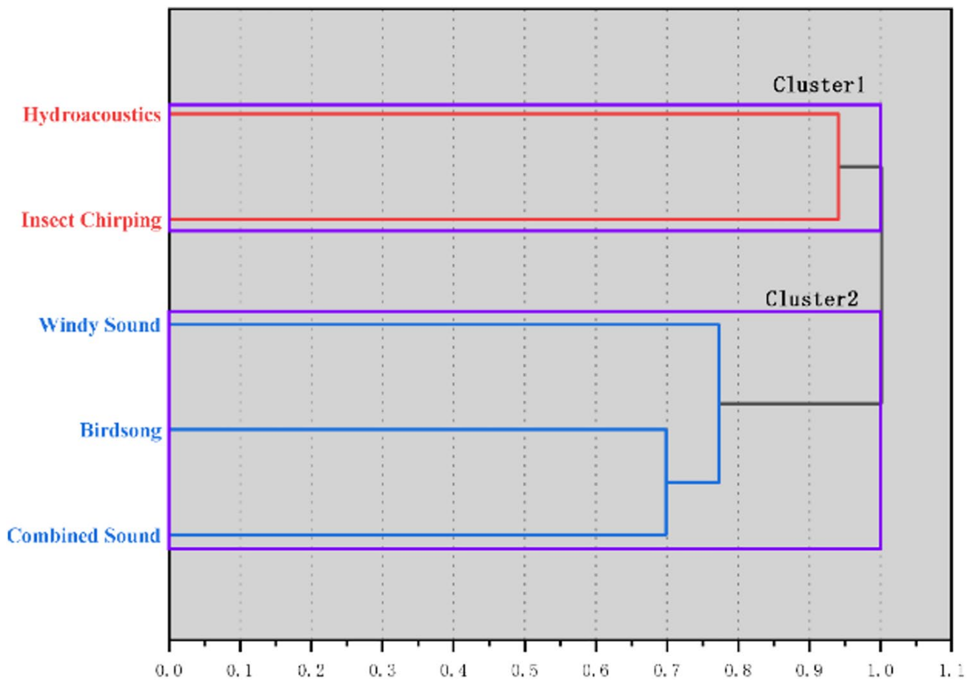

Figure 9. Cluster analysis based on Pa data.

From Table 6, the results of ridge regression indicate that the significance level based on the F-test is 0.000***, demonstrating significance at a high level. This suggests a regression relationship between the five natural soundscapes from the national forest park and Pa. Additionally, the goodness of fit for the model, represented by R^2, is 0.96, indicating excellent model performance. The formula for the Pa model is:

$$\begin{aligned} Pa = \ & 3.842+0.157 \times \text{ Hydroacoustics} + 0.118 \\ & \times \text{ Windy Sound} + 0.291 \times \text{ Birdsong} + 0.088 \\ & \times \text{ Insect Chirping} + 0.365 \times \text{ Combined Sound.} \end{aligned}$$

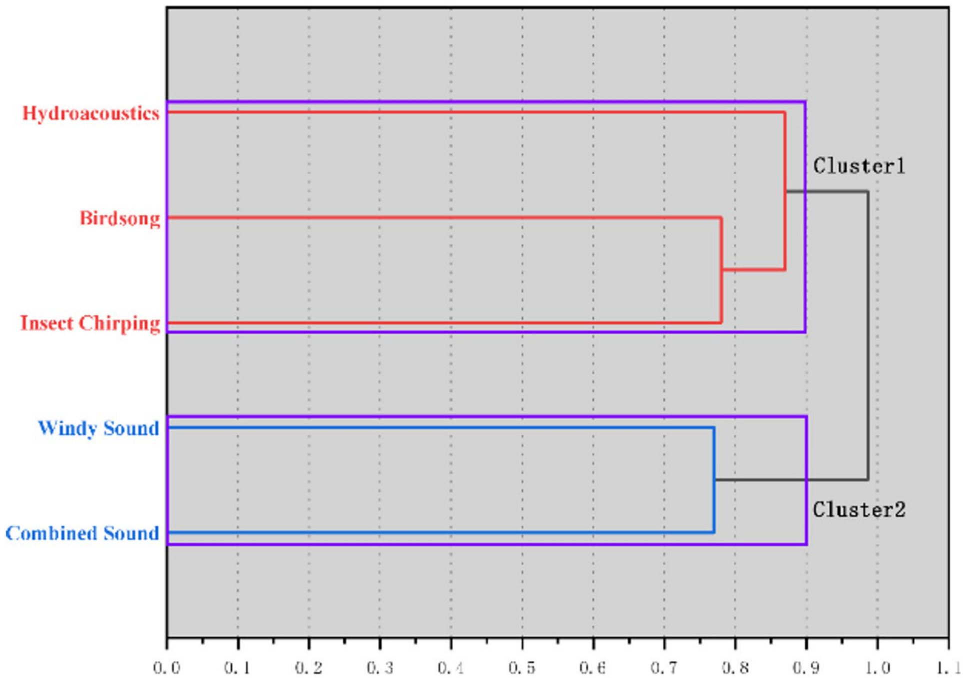

Figure 10. Cluster analysis based on PA data.

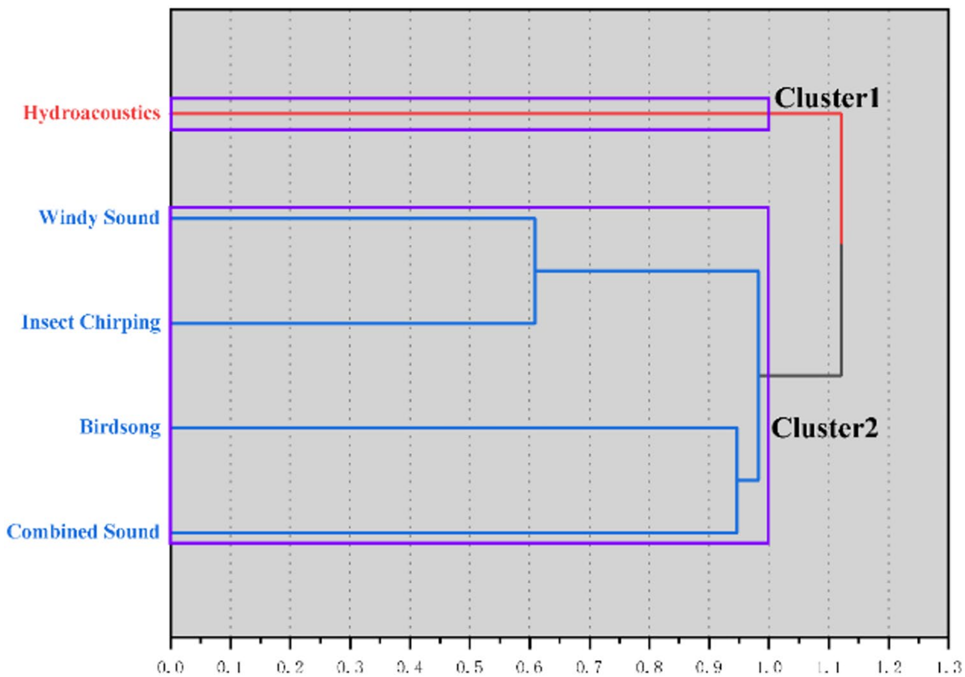

Figure 11. Cluster analysis based on NA data.

From Table 7, The results of Ridge regression show that: based on the F-test, the significance P value is 0.000***, indicating that there is a regression relationship between the natural soundscapes and the recovery of negative emotion (NA). At the same time, the goodness of fit R^2 of the model is 0.965, and the model performance is relatively excellent. Formula of NA model:

$$\begin{aligned} NA = \ & 1.055 + 0.16 \times \text{Hydroacoustics} \\ & + 0.09 \times \text{Windy Sound} + 0.275 \times \text{Birdsong} \\ & + 0.086 \times \text{InsectChirping} + 0.345 \times \text{Combined Sound}. \end{aligned}$$

K = 0.155	Nonnormalized coefficient		Normalized coefficient					
	B	Standard error	Beta	*t*	*P*	R^2	Adjusted R^2	*F*
Constant	6.448	2.256	–	2.858	0.006***	0.973	0.97	333.656(0.000***)
Windy sound	0.402	0.018	0.382	22.114	0.000***			
Birdsong	0.132	0.046	0.065	2.866	0.006***			
Hydroacoustics	0.151	0.031	0.13	4.898	0.000***			
Insect chirping	0.089	0.027	0.078	3.342	0.002***			
Combined sound	0.399	0.017	0.412	23.721	0.000***			

Table 5. Ridge regression results on Pm. 1. Dependent variable: Pm 2. ***, ** and * represent significance levels of 1, 5 and 10% respectively.

K = 0.185	Nonnormalized coefficient		Normalized coefficient					
	B	Standard error	Beta	*t*	*P*	R^2	Adjusted R^2	*F*
Constant	3.842	3.119	–	1.232	0.224	0.96	0.956	220.931(0.000***)
Hydroacoustics	0.157	0.029	0.156	5.493	0.000***			
Windy sound	0.118	0.037	0.081	3.187	0.003***			
Birdsong	0.291	0.024	0.298	12.047	0.000***			
Insect chirping	0.088	0.031	0.085	2.881	0.006***			
Combined sound	0.365	0.021	0.397	17.507	0.000***			

Table 6. Ridge regression results on Pa. 1. Dependent variable: Pa 2. ***, ** and * represent significance levels of 1, 5 and 10% respectively.

K = 0.185	Nonnormalized coefficient		Normalized coefficient					
	B	Standard error	Beta	*t*	*P*	R^2	Adjusted R^2	*F*
Constant	1.055	2.788	–	0.379	0.707	0.965	0.961	251.753(0.000***)
Hydroacoustics	0.16	0.025	0.168	6.295	0.000***			
Windy sound	0.09	0.033	0.065	2.718	0.009***			
Birdsong	0.275	0.022	0.296	12.765	0.000***			
Insect chirping	0.086	0.027	0.087	3.126	0.003***			
Combined sound	0.345	0.019	0.394	18.507	0.000***			

Table 7. Ridge regression results on NA. 1. Dependent variable: NA 2. ***, ** and * represent significance levels of 1%, 5% and 10% respectively.

K = 0.155	Nonnormalized coefficient		Normalized coefficient					
	B	Standard error	Beta	*t*	*P*	R^2	Adjusted R^2	*F*
Constant	− 2.981	1.654	–	− 1.803	0.078*	0.971	0.968	310.949(0.000***)
Windy Sound	0.272	0.013	0.287	20.214	0.000***			
Birdsong	0.226	0.021	0.225	10.65	0.000***			
Hydroacoustics	0.123	0.025	0.119	5.002	0.000***			
Insect Chirping	0.048	0.026	0.045	1.809	0.077*			
Combined Sound	0.306	0.019	0.288	16.241	0.000***			

Table 8. Ridge regression results on PA. 1. Dependent variable: PA 2. ***, ** and * represent significance levels of 1, 5 and 10% respectively.

From Table 8, The results of Ridge regression show that: based on the F-test, the significance P value is 0.000***, indicating that there is a regression relationship between the natural soundscapes and the recovery of positive emotion (PA). At the same time, the goodness of fit R^2 of the model is 0.965, and the model performance is relatively excellent. Formula of PA model:

$$\begin{aligned} PA = & -2.981 + 0.123 \times \text{Hydroacoustics} + 0.272 \times \text{Windy Sound} \\ & + 0.226 \times \text{Birdsong} + 0.048 \times \text{Insect Chirping} + 0.306 \times \text{Combined Sound}. \end{aligned}$$

Discussion

The natural soundscape of the National Forest has physiologically restorative capacity

It was found that after exposure to the natural soundscape in Zhangjiajie National Forest Park, the brain wave values of the participants changed significantly ($p < 0.001$). This includes specific bands, such as α, β, γ, and indices derived from these bands, including the eSence Relaxation Index (Pm) and the eSence Attention Index (Pa). Specifically, the vast majority of participants had a significant rise in Pm and Pa after listening to these five natural acoustic landscapes.

The elevation in Pm values suggests an enhancement in the participants' relaxation levels. Zhang and Tan utilized the Pm index to explore the relaxation levels of 70 university students after virtual tourism, stating, "After visiting virtual tourist spots, participants exhibited a significant increase in relaxation levels, manifested by a noticeable rise in the Pm index"[79]. In our experiment, we found that all five common natural acoustic landscapes led to a significant increase in Pm. Windy Sound demonstrated the largest effect size on Pm, with a Cohen's d value of 4.873, surpassing even the Cohen's d value of Combined Sound. This may be attributed to the fact that the chosen sound collection site in Zhangjiajie National Forest Park is near water, where a narrow pathway creates a "canyon effect," accelerating wind speed. Additionally, the water's abundance of leaves generates a pleasant rustling sound as the wind passes through, contributing to Windy Sound's pronounced relaxation effect. Wang and He conducted soundscape research in the trial area of Qianjiangyuan National Park in China, focusing on the restorative impact of soundscape on participants using heart rate, respiratory rate, and skin conductance levels. Their results indicated that water sound had the greatest impact on participants' heart rate and respiratory rate, suggesting the highest level of relaxation in water sound[1]. Differences in experimental results may stem from two factors: (1) They proposed that the multitude of water bodies in Qianjiangyuan National Park might be a contributing factor, while Zhangjiajie National Forest Park predominantly features mountainous terrain, with Windy Sound being most significant in the selected soundscape location. This may be one reason for the disparate conclusions. (2) Their study included only Insect Chirping, Birdsong, Hydroacoustics, and Combined Sound in the natural sounds, excluding Windy Sound present in our experiment. This discrepancy may be due to variations in soundscape locations. While our study confirms a substantial impact of Windy Sound on relaxation, the conclusions are somewhat limited by the different positioning of national forest parks.

The significant increase in Pa indicates that the participants' concentration levels were restored after listening to the natural sounds. This is consistent with Kaplan's Theory of Restoration, which posits that individuals experiencing directed attention fatigue recover more quickly through soft fascination[39,80]. In our Pa study, we similarly observed significant effects on Pa enhancement across all five natural acoustic landscapes, with Cohen's d being greatest before and after listening to the combined sounds. This means that, compared to the other four natural acoustic landscapes, the combined sounds were outstanding in increasing the level of individual attention. Ding used the Pa index in his research on plant feature preferences, proving that external stimuli can cause significant changes in the Pa index[81]. Our study is consistent with Ding's EEG signal research method, verifying the intuitive response of Pa signals to changes in participants' EEG.

In summary, the natural soundscape of national forest park has a significant positive impact on EEG signals, which is manifested as a significant increase in Pa and Pm, partially confirming Hypothesis 1.

The natural soundscape of the national forest has psychological restorative capacity

This study discovered noticeable changes in participants' pre- and post-evaluations on the Profile of Mood States (POMS) scale after listening to the five natural soundscapes in Zhangjiajie National Forest Park. The seven indicators of the abbreviated POMS scale can be categorized into positive emotions (including Vigor and Self-esteem) and negative emotions (including Tension, Anger, Anxiety, Depression, and Fatigue). Specifically, after experiencing the natural soundscapes, three participants showed a decrease in positive emotions (PA), while 49 participants exhibited an increase. Additionally, 44 participants showed a decrease in negative emotions (NA), while 8 participants displayed an increase.

The increase in PA directly indicates that participants subjectively perceived gaining energy and vitality from the natural soundscapes. The decrease in negative emotions (NA) suggests that participants subjectively felt recovery from negative emotional states. Regarding psychological indicators, the change in Fatigue was the most significant ($p < 0.001$), while the change in Anger was the least significant ($p > 0.05$). This implies that the restoration impact of national forest parks' natural soundscapes on Fatigue is the most pronounced, while the influence on Anger is relatively weak. In summary, national forest parks' natural soundscapes also exhibit significant positive effects on psychological aspects, thereby providing additional support for the partial correctness of Hypothesis 1. Therefore,1.2 and 1.1 collectively validate the accuracy of Hypothesis 1.

Combined sound has a better psychophysical restorative effect than single-element sound.

This study responded to the restorative differences of the different elements of the natural soundscape by comparing the difference in Cohen's d between before and after listening to them; in other words, those with a large

Cohen's d were more restorative, and vice versa for those with a small Cohen's d. In the comparison of Pm, Hydroacoustics had the largest difference in Pm for Windy Sound, followed by Combined Sound, Birdsong, and Insect Chirping. In the comparison of Pm, the largest Cohen's d difference is Windy Sound, followed by Combined Sound, Birdsong, and Insect Chirping. Hydroacoustics has the worst restorative effect on Pm; in the comparison of Pa, the largest Cohen's d difference is Combined Sound, followed by Birdsong, Insect Chirping, and Hydroacoustics, and Windy Sound had the worst restorative effect on Pa. In the evaluation of psychology, Combined Sound had the highest subjective psychological score. Taken together, Combined Sound has the highest average ranking, so it can be assumed that Combined Sound has the best restorative effect compared to the other four single-element sounds, which also proves that hypothesis H2 is correct.

The effect of gender on restorative sexual effects

In the realm of psychological and physiological restoration, this study found that gender is not a highly significant influencing factor, except for Windy Sound, which exhibits relatively noticeable gender characteristics. This observation might indirectly suggest that the natural soundscapes in national forest parks have a pronounced restorative effect across all genders. Specifically, concerning Pm, the recovery effects of Hydroacoustics, Birdsong, Insect Chirping, and Combined Sound are not significantly influenced by gender ($p > 0.1$). However, it is noteworthy that Windy Sound shows a notable gender difference ($p < 0.0001$). Experimental data reveals that females exhibit a greater preference for Windy Sound (21.80 ± 2.85) compared to males (16.04 ± 2.31). Similarly, in terms of Pa values, the one-way analysis of variance for gender indicates that Hydroacoustics, Birdsong, and Insect Chirping do not exhibit significant gender differences in Pa recovery ($p > 0.1$). Nevertheless, Windy Sound also demonstrates gender differences in Pa, with the experimental data showing a greater reduction in concentration among females (13.84 ± 14.3). This may suggest that females have a stronger preference for Windy Sound among these five natural soundscapes. Zhao when discussing the relationship between demographic characteristics and the restorative effects of birdsong, found that gender ($p > 0.05$) and occupation ($p > 0.05$) did not exhibit significant differences in restorative effects[82]. Liu and Xu (2021), in a study on people's preferences for sound space in urban public landscapes during the post-pandemic era, discovered that the impact of gender on soundscape preferences could be neglected[83]. Similarly, Yu and Kang, in a statistical analysis across 19 case study points, systematically investigated factors affecting preferences for soundscapes in terms of social, demographic, physical, behavioral, and psychological aspects. Their data revealed that gender, occupation, and living conditions typically do not significantly influence sound preference assessments[84]. The results of this study align with the conclusions drawn by Zhao, Liu, and Yu regarding the relationship between gender and the restoration of natural soundscapes. However, the study is to some extent not comprehensive, primarily because Windy Sound still exhibits some gender differences, which may be related to the unique Windy Sound formed by the topography of Zhangjiajie. In general, gender usually does not have a significant impact on restoration effects, although specific cases, such as Windy Sound, may exhibit gender differences. Overall, gender indicators do not significantly influence the restorative effects of natural soundscapes, confirming the inaccuracy of Hypothesis 3.

Research methods (cluster analysis and ridge regression equations)

The stratified clustering of 52 participants based on different indicators was performed to provide precise "treatment plans" for specific purposes. For example, if the primary goal is physiological recovery, simultaneous consideration of clustering analyses based on Pa and Pm is necessary, taking their intersection into account. The clustering analysis proceeded in two steps: first, an overall clustering based on both psychological and physiological indicators, and then four separate clusterings based on psychological indicators (PA and NA) and physiological indicators (Pa and Pm).

In the PA clustering, Hydroacoustics, Insect Chirping, and Birdsong formed one cluster, while Combined Sound and Windy Sound constituted a separate category. This suggests that Hydroacoustics, Insect Chirping, and Birdsong exhibit consistent effects on PA. In the NA clustering, Hydroacoustics was placed in a separate cluster, while the remaining four natural soundscapes were grouped together. This implies that, except for Hydroacoustics, the other four sounds exhibit similar effects on NA. In the Pa clustering, Hydroacoustics and Insect Chirping were grouped together, while Windy Sound, Birdsong, and Combined Sound formed a distinct category. In the Pm clustering, Hydroacoustics, Insect Chirping, and Combined Sound were grouped together, while Windy Sound and Birdsong constituted a separate category. This indicates that Hydroacoustics, Insect Chirping, and Combined Sound exhibit similar effects on Pm.

In the final phase of the study, ridge regression was employed to construct predictive models for the restoration of Pm, Pa, NA, and PA based on the common natural soundscapes in the summer national forest park. Specifically:

(1) $Pm = 6.448 + 0.382 \times \text{Windy Sound} + 0.065 \times \text{Birdsong} + 0.13 \times \text{Hydroacoustics} + 0.078 \times \text{Insect Chirping} + 0.412 \times \text{Combined Sound}$.
(2) $Pa = 3.842 + 0.157 \times \text{Hydroacoustics} + 0.118 \times \text{Windy Sound} + 0.291 \times \text{Birdsong} + 0.088 \times \text{Insect Chirping} + 0.365 \times \text{Combined Sound}$.
(3) $NA = 1.055 + 0.16 \times \text{Hydroacoustics} + 0.09 \times \text{Windy Sound} + 0.275 \times \text{Birdsong} + 0.086 \times \text{Insect Chirping} + 0.345 \times \text{Combined Sound}$.
(4) $PA = -2.981 + 0.123 \times \text{Hydroacoustics} + 0.272 \times \text{Windy Sound} + 0.226 \times \text{Birdsong} + 0.048 \times \text{Insect Chirping} + 0.306 \times \text{Combined Sound}$.

The numerical models highlight that Combined Sound carries a significant weight in both psychological and physiological aspects. This supports the correctness of Hypothesis 2. Such numerical models offer a more intuitive understanding of the weight coefficients for the five natural soundscapes in Pm, Pa, NA, and PA, providing a more rational perception of restoration.

Deficiencies and prospects

Few systematic studies have focused on the comparison of the psychophysiological recovery effects of combined sound and single-element sound. In this study, we analysed the natural soundscape of Zhangjiajie National Forest Park through experimental data, and demonstrated that the recovery effect of multi-element combined natural soundscape is indeed greater than that of single-element natural soundscape. During the experimental process, this study required the subjects to put on eye masks for auditory analysis, in order to reveal the comparison of the subjects' responses to hearing different natural soundscapes without the interference of other factors such as vision and touch. However, there are some limitations to such an approach.

Due to the constraints of the objective experimental conditions, the limitations of this study also exist in these areas. (1) Capacity bias of the population sample. The subjects selected for this study were mainly undergraduates aged 19–22 years old, which has a certain statistical significance but undeniably does not cover other demographic demographics, such as age, income, and education level. In the future, we will continue to invite a wider range of subjects of different ages, occupations, and education levels to participate in our natural soundscape study. (2) Too few natural soundscape elements. The single element of this experiment was limited to Hydroacoustics, Windy Sound, Birdsong and Insert Chirping, which are common in summer, but there are thousands of other animals in Zhangjiajie National Forest Park, and the sounds of the same animals but different species of animals (e.g., the sounds of different birds, the sounds of different species of monkeys) are not available for our record the experiment. In the future, we will include a variety of animal sounds in our experiments, because Ratcliffe's experiments indicated that 50 different bird calls did not bring the same recovery effect. (3) In the future, our group will continue to collaborate with sports scientists and psychologists to study the restorative effects of the natural soundscape of the National Forest Park on more special groups, such as people with disabilities and depression, as well as to study the audio-visual perception of the National Forest Park in conjunction with virtual reality techniques.

Conclusions

In this study, using Zhangjiajie National Forest Park as the study site, we preliminarily investigated the differences between single-element natural soundscapes and natural soundscapes with multi-element combinations in terms of their effects on human psychophysiological recovery. We drew the following conclusions: (1) Psychological Restoration in National Forest Park: The psychological restoration capacity of natural soundscapes in the national forest park was confirmed. Significant changes ($p = 0.001$) were observed in psychological and physiological indicators after participants listened to each segment of the natural soundscapes. Relaxation index increased, attention index decreased, positive emotions significantly increased, and negative emotions significantly decreased. (2) Effectiveness Ranking of Soundscapes: Combined Sound ranked first in the average restoration effectiveness, indicating that the combination of multiple natural sounds indeed provides better restorative effects compared to single-element sounds. (3) Gender Influence on Restoration: Generally, gender does not significantly impact restoration effects. However, Windy Sound exhibited notable gender differences in restoration effects ($p = 0.001$). Despite this, in general, the impact of gender on the restoration effects of natural soundscapes is not significant.

The study sheds light on the comparative analysis of the psychological and physiological restorative effects of different elemental natural soundscapes in national forest parks. It contrasts the restorative effects of combined natural sounds with those of single-element natural sounds. Utilizing ridge regression, a mathematical model for the restoration of psychology and physiology by natural soundscapes was constructed, quantifying specific weight coefficients for the five common natural soundscapes.Based on the research findings, the study proposes the following recommendations: (1) Leveraging Soundscape Advantages: National forest parks should fully explore their acoustic advantages, providing free psychological restoration spaces for an increasing number of visitors. (2) Selection of Soundscape Therapy Locations: Locations for soundscape therapy should be chosen in areas with a variety of natural soundscape elements, such as waterfront trails with Hydroacoustics, Birdsong, and Windy Sound, avoiding sites with only one or two natural sounds. (3) Windy Sound as a Restoration Asset: The effectiveness of Windy Sound for restoration has been confirmed. The study recommends developing dedicated wind-themed soundscape restoration locations within national forest parks, capitalizing on the outstanding restoration capabilities of Windy Sound.

This study not only reveals the positive effects of natural soundscapes in national forest parks on human psychophysiological recovery, but also highlights the importance of such research for public health and wildlife conservation management. First of all, by understanding the impact of different natural soundscape elements on people's psychological states, we can better plan and design the soundscape of forest parks to provide a more healthy and restorative leisure environment for the public. This not only contributes to the quality of the visitor experience, but also to their mental health and well-being. Second, recognizing the value of natural soundscapes can encourage conservation managers to take a more scientific approach to protecting and enhancing these natural soundscapes, thereby maintaining biodiversity and ecosystem health. For example, by protecting water sources and vegetation, we preserve not only the habitat of animals, but also the source of their natural sound, which is crucial to maintaining the overall ecological balance of the forest park. Finally, this study encourages future research exploring the effects of different animal sounds on human psychology and physiology, as well as the interaction of audiovisual perception in national parks. This will help us better understand the links between people and nature and provide a scientific basis for more comprehensive conservation and resource management strategies.

Through these efforts, we hope to promote a more harmonious relationship between man and nature and protect our precious natural heritage for current and future generations.

Data availability

Data is provided within the manuscript or supplementary information files.

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Author contributions
Conceptualization, Z.B. and S.Z.; methodology, Z.B. and S.Z; software, Z.B. and S.Z.; validation, Z.B., S.Z.; formal analysis, Z.B.; investigation, Z.B. and S.Z; resources, Z.B. and S.Z.; data curation, Z.B. and S.Z.; writing—original draft preparation, Z.B. and S.Z.; writing—review and editing, Z.B. and S.Z.; visualization, Z.B.; supervision, S.Z.; project administration, S.Z.; funding acquisition, S.Z. All authors have read and agreed to the published version of the manuscript.

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Competing interests
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