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The impact of virtual images of coastal landscape features on stress recovery based on EEG

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Understanding how coastal landscape features influence stress recovery can provide valuable insights for designing healthier urban environments. This study aims to evaluate the psychological and physiological restorative effects of four types of coastal landscape features—coastal walkway, coastal mountain park, coastal plaza, and coastal beach—using immersive virtual reality simulations. 44 university students participated in a laboratory experiment involving subjective evaluations, heart rate variability, and electroencephalogram (EEG) measurements. The results demonstrated that virtual images of coastal landscape features alleviate mood disturbances and enhance perceived recovery. Specifically, autonomic nervous system (ANS) responses showed significant improvement: low-frequency to high-frequency ratio decreased by 8.47–20.20%, root mean square of successive differences increased by 8.41–27.83%, and the standard deviation of heart intervals increased by 13.05–25.07%. EEG findings further revealed reduced brain energy consumption, with total power decreasing by 0.83–9.10% and α relative power increasing by 2.76–28.51%. The virtual images of coastal walkway demonstrated the strongest restorative effect, especially in promoting optimal neural avalanche activity (12.70–18.17% improvement). Correlation analysis indicated a strong relationship between ANS and brain responses. Notably, this study innovatively introduced neural avalanche parameters to assess brain criticality states, offering a novel approach to evaluating environmental restoration. These findings contribute to environmental psychology by offering scientific evidence for optimizing coastal landscape design to support mental health and stress regulation.

Keywords Restorative environment, Virtual reality, Electroencephalogram, Coastal landscape features, Neural avalanche, Autonomic nervous system

Abbreviations

ANS	Autonomic nervous system
AD	Avalanche duration
EEG	Electroencephalogram
ICA	Independent component analysis
LF	Low frequency
PNS	Parasympathetic nervous system
Rα	Alpha relative power
RMSSD	Root mean square of successive differences
SRT	Stress recovery theory
VR	Virtual reality
ACI	Avalanche criticality index
AS	Avalanche size
HRV	Heart rate variability
IPQ	Igroup presence questionnaire
HF	High frequency
POMS	Profile of mood states
RCS	Restorative components scale
SDNN	Standard deviation of normal-to-normal intervals

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TMD	Total mood disturbance
VSV	Visual satisfaction vote

High-density and high-pressure living environments have increasingly contributed to psychological stress and emotional disorders among urban residents, especially university students[1]. According to the European Landscape Convention (2000)[2], "landscape is an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors." This widely accepted definition highlights the perceptual nature and formation mechanisms of landscapes, establishing a conceptual basis for exploring how environmental features influence human health. Coastal spaces, rich in blue and green elements, are considered to hold strong potential as restorative environments[3]. A deeper understanding of how the visual features of coastal landscapes influence stress levels can help improve their quality, enhance residents' well-being, and contribute to the development of healthy cities.

Extensive research has highlighted the beneficial impacts of urban natural environments on residents' well-being. For example, Liu et al.[4] emphasized the positive effects of urban greenways on perception and emotions, while Xu et al.[5] revealed the positive role of campus green spaces in stress recovery for college students. These studies confirm that natural environments help improve positive emotions and support stress recovery. However, previous research has primarily focused on green areas like city parks[6] and forests[7], with less attention given to other natural environments like water bodies. In recent decades, the distinctiveness and aesthetics of landscapes have become increasingly important in environmental and territorial management, either hindering or promoting economic development[8]. In coastal areas, the influence of landscapes on urban development is particularly evident. Coasts are among the most dynamic and valuable geomorphological environments on Earth[9]. Since the rise of seaside tourism and resorts, the appeal of coastal areas has been largely dependent on the aesthetics of their landscapes[10]. Coastal landscape features refer to the natural environments along coastal areas, including shorelines, beaches, cliffs, wetlands, and the coastal flora and ecosystems. High-quality coastal landscape features not only provide residents with opportunities to connect with nature but are also crucial for biodiversity conservation and ecosystem services. Previous studies have mainly focused on how coastal landscape features contribute to urban planning and maritime development[8], with limited research exploring human experiences of coastal spaces from a perceptual perspective. Jeon et al.[3] highlighted the role of waterscapes in promoting psychological and physiological recovery, and Gao et al.[11] analyzed the perceptual experience of waterfront-built environments. Human perceptual restoration is primarily driven by visual information. While many studies have focused on individual visual features, such as vegetation type or color[12], research on the combined visual features of water bodies and their surrounding environments is still relatively scarce. Therefore, there is still a gap in our understanding of the overall interaction between people and coastal landscape features.

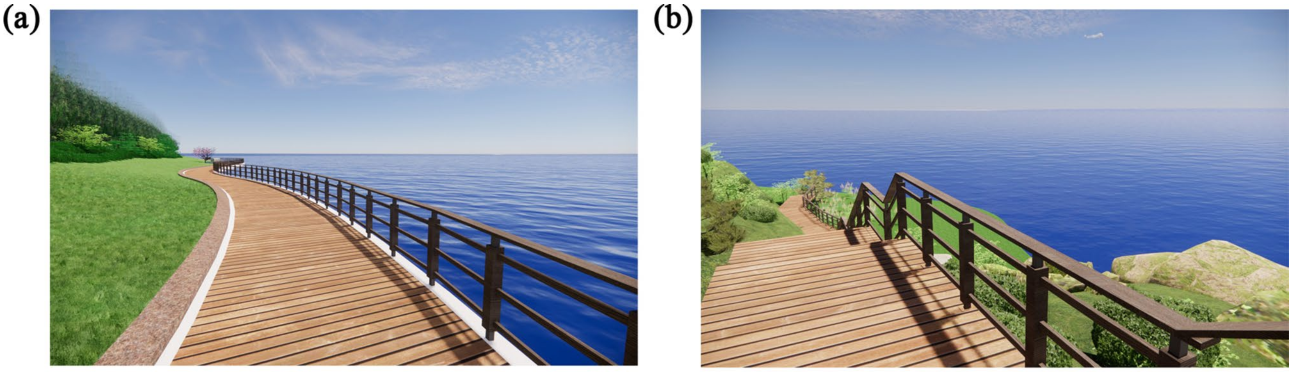
Comprehensive psychological and physiological measurements are effective tools in environmental research. The perceived quality of visual environments can be assessed through descriptive surveys, using terms like comfort and satisfaction[3]. Emotional responses are often measured using questionnaires such as the profile of mood states (POMS)[13] or the shortened stress assessment and treatment inventory (SATI)[14]. Some researchers also use the Restorative Components Scale (RCS)[15] to assess subjective perceptions of recovery. On the physiological side, common measurements include heart rate variability (HRV)[3], electroencephalogram (EEG)[3], skin temperature[16], and electrodermal activity[17]. When the brain encounters external stimuli, it rapidly activates the HPA axis, leading to cortisol secretion from the adrenal glands, which transmits stress signals to other organs and regulates emotions[18]. This process also triggers detectable alterations in the autonomic nervous system (ANS) and brain activity[19]. Both HRV and EEG are capable of accurately and quickly reflecting subtle nervous system changes induced by environmental stimuli. Jeon et al.[3] found that exposure to waterfront environments, compared to urban settings, increased the standard deviation of heart intervals (SDNN) by 13.9% and enhanced β oscillatory activity by 5–8%. Similarly, Liu et al.[20] reported that as emotional distress decreased, low-frequency to high-frequency ratio (LF/HF) declined and α oscillatory activity increased. Recently, virtual reality (VR) technology has offered an approach for environmental perception research. VR can faithfully replicate real-world settings and provide a controlled experimental environment, ensuring the reliability of experimental data[21]. This method is especially beneficial for studying the complex effects of visual characteristics on stress recovery, with previous research demonstrating VR's effectiveness in exploring the restorative properties of visual environments[22].

This study investigates the effects of virtual images of coastal landscape features on stress recovery, focusing on overall visual characteristics. The primary goals of the study are outlined as follows: (1) How do virtual images of coastal landscape features affect psychological responses? (2) What impact do virtual images of coastal landscape features have on physiological responses? (3) What are the mechanisms by which virtual images of coastal landscape features influence stress recovery? The aim of this study is to enhance comprehension of virtual images of coastal landscape features and offer residents more valuable chances to engage with natural environments, offering scientific insights for urban sustainable development and planning.

Methods

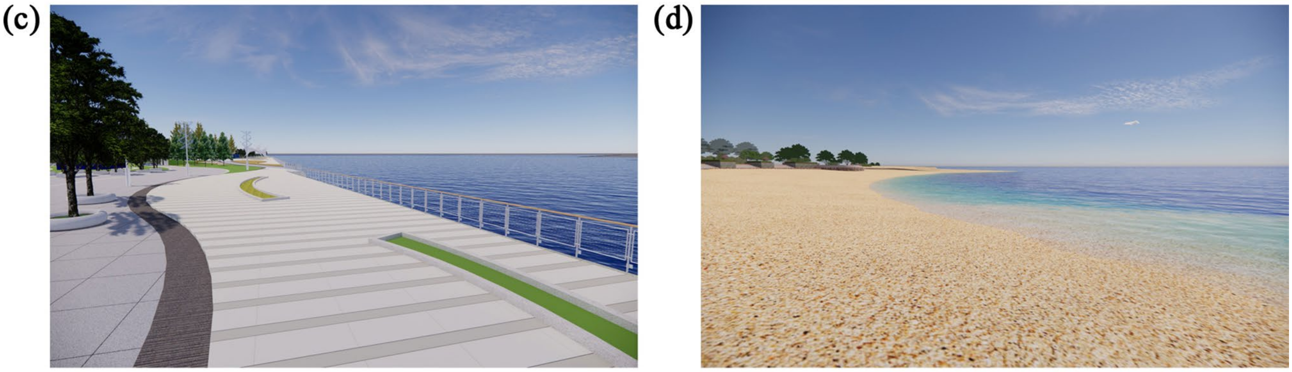
Virtual images of coastal landscape features

In this study, four representative coastal landscape features were selected and presented as virtual images using VR technology (see Fig. 1): (a) Coastal walkway: a linear, unobstructed path approximately 2.5 m wide, with open water on the right and greenery on the left. (b) Coastal mountain park: located on a gentle slope with an elevation difference of about 30 m, featuring a wooden platform and guardrails that provide a sea view, surrounded by dense vegetation. (c) Coastal plaza: a wide, hard-paved area approximately 12 m across, with low vegetation coverage and an open spatial layout. (d) Coastal beach: an open, nearly natural sandy beach approximately 30 m wide, characterized by spaciousness and minimal artificial intervention. To ensure the visual



Coastal walkway

Coastal mountain park



Coastal plaza

Coastal beach

Fig. 1. Visual stimuli.

		Age					
	No.	Max.	Min.	Mean ± SD	Height (cm)	Weight (kg)	Body Mass Index (kg/m^2)
Male	22	23	19	21.32 ± 1.17	179.14 ± 5.33	75.45 ± 5.40	23.53 ± 1.65
Female	22	24	18	20.18 ± 1.62	164.59 ± 3.35	51.82 ± 3.32	19.15 ± 1.42
Total	44	24	18	20.75 ± 1.51	171.86 ± 8.57	63.64 ± 12.75	21.34 ± 2.69

Table 1. The participants' information.

stimuli across different types of coastal landscape features were comparable, the proportions of the sea and sky were standardized during the modeling stage. Specifically, they were set to occupy approximately 70% of the field of view in each scene, minimizing the potential influence of varying degrees of blue space—widely recognized for its restorative qualities—on psychological and physiological responses. This approach enabled a more objective assessment of the restorative effects attributable to the spatial features of each scene type. To minimize interference from unrelated factors, an HTC VIVE VR headset (HTC Corporation, Taiwan; https://www.vive.com) was used to present the scenes. Previous research has shown that VR can effectively replicate real environments[23]. The models were created using Sketchup software (2021, https://www.sketchup.com) and rendered with Enscape software (3.5, https://enscape3d.com).

Participants

To minimize individual differences, this study recruited only undergraduate and graduate students from the iSMART who had lived in Qingdao for more than two years. All participants were architecture majors, ensuring a relatively uniform lifestyle and educational background. Thirty days before the experiment, the research team posted a volunteer recruitment notice in the iSMART WeChat group, specifying that participants must be physically healthy, without visual impairments, cardiovascular diseases, or brain injuries. To calculate the minimum necessary sample size, G*power software (3.0, https://www.psychologie.hhu.de/arbeitsgruppen/allgemeine-psychologie-und-arbeitspsychologie/gpow-er) was used, with $\alpha = 0.5$, $p = 0.05$, and power $(1 - \beta) = 0.8$, which indicated that at least 21 participants were needed. 44 participants were recruited, with an equal gender distribution and an average age of 20.75 years (SD: 1.51, see in Table 1). They were advised to refrain from smoking, drinking alcohol, or taking any medication 24 h before the experiment, maintain adequate sleep, and refrain from vigorous exercise two hours before the experiment to ensure normal physiological conditions.

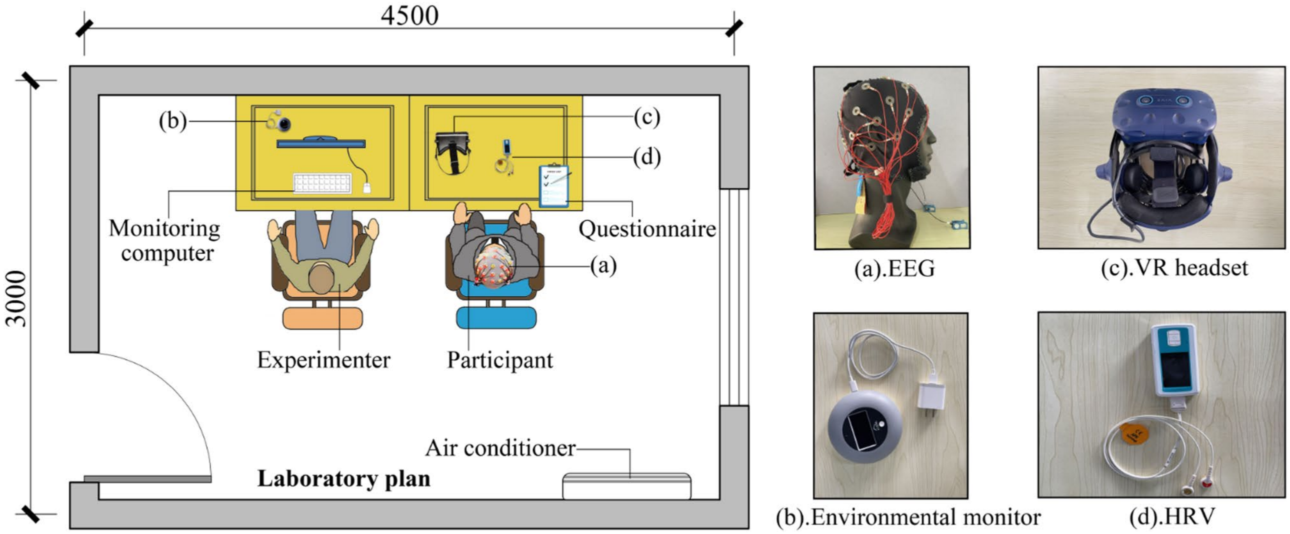


Fig. 2. Experiment site.

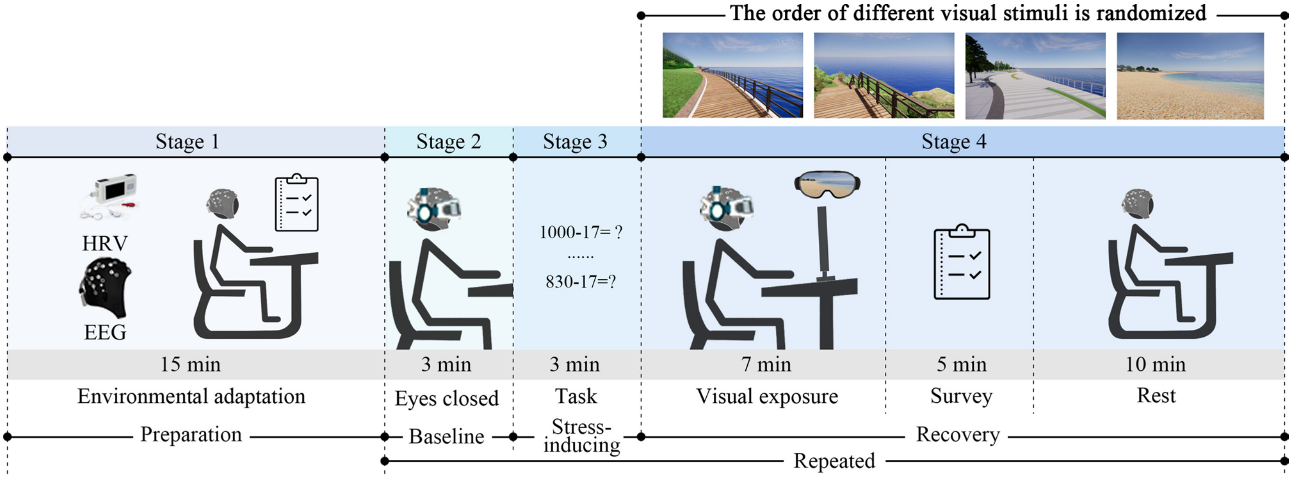


Fig. 3. Experiment procedure.

Additionally, participants were required to keep their scalp clean. All experimental procedures were strictly conducted in accordance with relevant regulations.

Procedure

The experiment was conducted daily between 9:00 AM and 12:00 PM. The experiment was conducted in a controlled room (3 m × 4.5 m × 4.2 m) located on the 4th floor of iSMART (see Fig. 2). During the experiment, the thermal condition was kept stable at 23 ± 0.5 °C and 50 ± 5% humidity, with ambient noise levels kept below 15 dBA and no sound stimuli were introduced.

As shown in Fig. 3, the experimental procedure was divided into four stages: (1) Adaptation stage: Upon arrival at the room, participants were given a brief explanation of the experimental process, including instructions on how to complete the questionnaires. After physiological equipment was fitted, participants sat quietly for 15 min to eliminate external environmental influences. (2) Baseline stage: Participants wore VR equipment and sat with their eyes closed while physiological data was collected for 3 min as baseline measurements[3]. (3) Stress-inducing stage: A stress task was used to induce a stress state. Participants were asked to repeatedly subtract a given number from 1000 orally, with each answer required within 3 s, and immediate feedback was given on correctness[24]. (4) Recovery stage: Participants viewed a coastal scene for 7 min, followed by completing a questionnaire. Following a 10-min break, participants proceeded to the next session of the experiment[25]. The presentation order of the scenes was randomized, and steps 2–4 were repeated four times. To confirm the accuracy of the virtual model, participants completed the Igroup presence questionnaire (IPQ) after all experiments[26]. The IPQ assessed four aspects (general presence (G), spatial presence (S), involvement (I), and experienced realism (E)) with a total of

14 items, scored from 20 to 100. The IPQ results indicated G = 65.21, S = 60.23, I = 56.48, and E = 57.67, suggesting a high degree of realism in the virtual model used in this study[27].

Psychological responses

The subjective questionnaires include four sections: (1) Personal information, including age, height, and weight. (2) Visual satisfaction vote (VSV), with the question "How satisfied are you with the current landscape?" Participants rated their satisfaction on a scale from − 3 (very dissatisfied) to 3 (very satisfied). (3) The POMS, for which the simplified Chinese version was used as all participants were Chinese university students[28]. This scale covers five negative emotion dimensions (confusion (C), anger (A), fatigue (F), depression (D), and tension (T)) and two positive emotion dimensions (vigor (V) and esteem (E)), with a total of 40 items. Participants evaluated each item on a 1 to 5 scale, ranging from 1 (not at all) to 5 (very much). The difference between negative and positive emotion scores represents the total mood disturbance (TMD), with the calculation method shown in Eq. (1). (4) Restorative perception assessment, for which the revised Chinese version of the Restorative Components Scale (RCS) was used[29]. This scale consists of 15 items based on the four aspects of restorative environments: being away, extent, fascination, and compatibility. Participants evaluated on a scale from − 3 (strongly disagree) to 3 (strongly agree), with higher RCS indicating stronger subjective restorative perception. Since all participants were Chinese university students, a bilingual version of the questionnaire (Chinese–English) was used to ensure clarity and ease of understanding (see Appendix A).

$$TMD = C + A + F + D + T - V - E + 100 \tag{1}$$

Physiological responses

The ANS and central nervous system are key systems that respond to external stimuli. HRV and EEG were used to reflect neural responses in this study.

HRV

The ANS is composed of the sympathetic (SNS) and parasympathetic nervous system (PNS). The SNS is primarily associated with stress responses, and its increased activity is typically accompanied by elevated low frequency (LF, 0.04–0.15 Hz) signals. In contrast, the PNS is related to relaxation, and increased high frequency (HF, 0.15–0.4 Hz) signals reflect higher PNS activity[30]. The balance between the SNS and PNS is often evaluated using the LF/HF, with a decrease in the LF/HF generally indicating a reduction in stress levels[31]. The RMSSD between adjacent R–R intervals is used to evaluate PNS activity, with higher RMSSD values indicating stronger PNS activation, reflecting a more relaxed state and greater short-term HRV[32]. The SDNN measures overall HRV, with higher SDNN associated with better cardiac health[3]. In this study, HRV were recorded using the Healink-R211B (Healink, China, 1000 Hz) and analyzed with Kubios HRV Standard (https://www.kubios.com).

EEG

EEG data quality can be easily affected by artifacts like eye movements and muscle tension during collection. Therefore, preprocessing is necessary to promote data reliability. After localization and re-referencing, band-pass filtering is applied to exclude frequencies outside the 1–45 Hz range. EEG data is then divided into overlapping 2 s epochs, with 1-s overlaps. Independent Component Analysis (ICA) is subsequently performed to enhance the data quality. The EEG data is manually reviewed to remove poor-quality segments. If more than 50% of a participant's data is contaminated, their data is invalid. After basic testing, data from all participants are valid. Above steps were carried out using the EEGLAB (2024, https://sccn.ucsd.edu/eeglab/index.php). The data was measured using the EPOC Flex Saline Sensor Kit (Emotiv Inc., USA), the electrodes layout shown in Fig. 4.

(1) Power

Power is a widely used parameter in EEG analysis that represents the strength of brain oscillations. Due to the often large values of power, a logarithmic transformation is usually applied, as outlined in Eqs. (2)–(3). When stress levels rise, neural activity intensifies, causing an increase in total power (Power $_{\text{total}}$). In contrast, when the body is in a relaxed state, brain activity requires less energy, leading to a reduction in Power$_{\text{total}}$[33,34].

$$Power' = \sum_{\mathrm{n}=\mathrm{i}}^{\mathrm{j}} \left| FFT_{\mathrm{n}}^{2} \right| \tag{2}$$

$$Power = \log_{10}\left(Power'\right) \tag{3}$$

Here, Power′ represents the absolute power, where *i* and *j* denote the lower and upper boundaries of the frequency band, respectively, and FFT_n refers to the frequency-domain sequence obtained via Fast Fourier Transform (FFT). The term Power indicates the value obtained after applying a logarithmic transformation to Power′.

(2) α relative power (Rα)

Because of the significant variations in power, relative power is often a more reliable measure of the intensity of oscillatory activity within specific frequency bands[35]. The α-band, commonly seen during relaxed states[36], is believed to be linked with stress recovery.

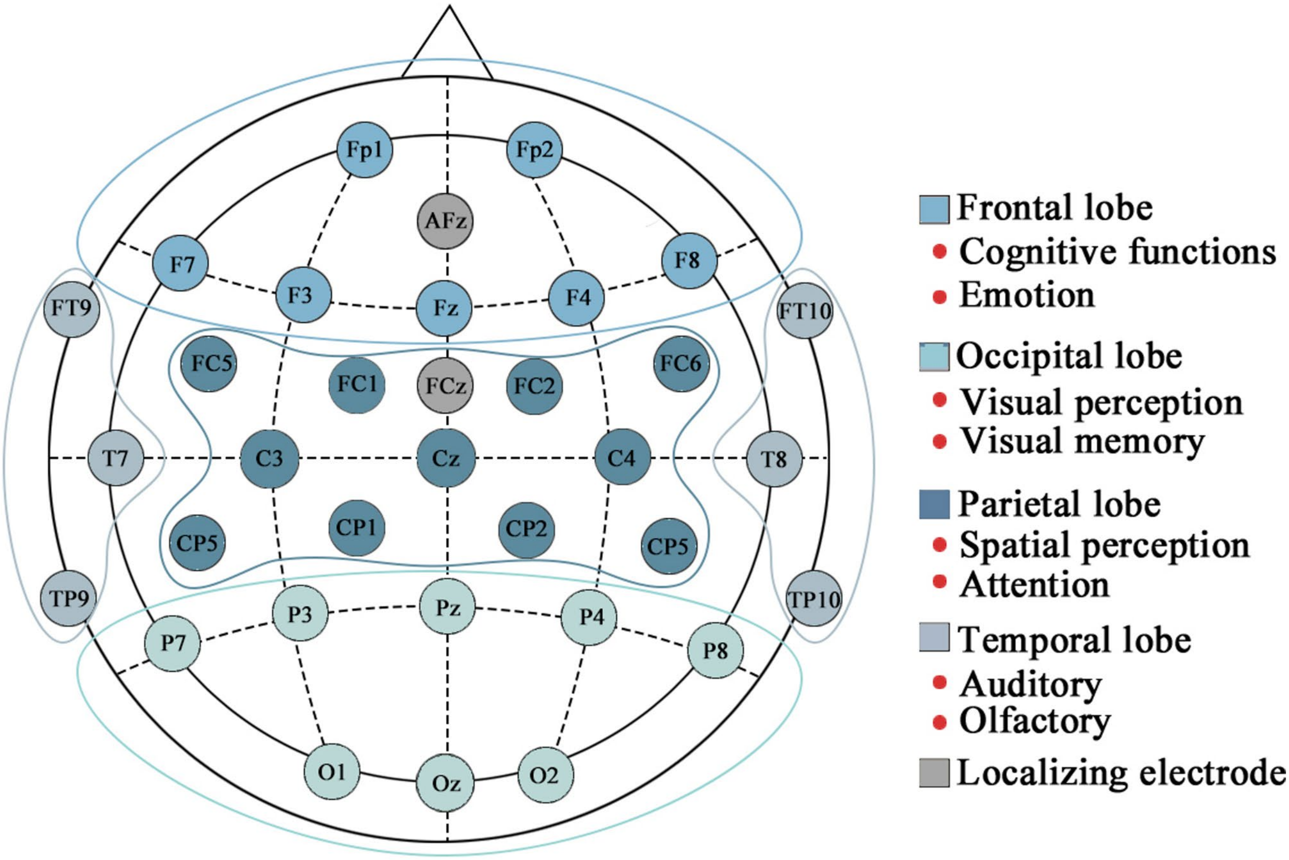


Fig. 4. The electrodes layout of this EEG device.

$$R\alpha = \frac{Power_{\alpha}}{Power_{total}} \tag{4}$$

In Eq. (4), Power$_{\alpha}$ is the power of the α band, while Power$_{total}$ refers to the sum of the powers of the δ (1–4 Hz), θ (4–8 Hz), α (8–14 Hz), and β (14–30 Hz) frequency bands.

(3) Neural avalanche parameters

In avalanche activity, both avalanche size (AS) and duration (AD) follow a power-law distribution, and brain neural avalanches exhibit similar characteristics. The power-law exponent can quantitatively describe the properties of such avalanche activity[37]. The specific steps are as follows: (1) Define time windows, with the window length typically set as a multiple of the sampling rate. In this study, a window length of 31.2 ms was used[38]. The mean amplitude of the data sequence for each channel was set as the threshold for that channel. (2) Perform binarization of the EEG sequence, marking data points exceeding the threshold as 1 and the rest as 0. (3) Group the time windows where 1 appears. A single or consecutive occurrence of 1 in these windows is considered a neural avalanche, with the count of data points in the window representing AS, and the window duration representing AD[39,40]. The power-law exponent is determined through the maximum likelihood estimation (MLE) method[41], with the calculation methods shown in Eqs. (5)–(7).

$$P\left(AS\right) \sim AS^{-\lambda_1} \tag{5}$$

$$P\left(AD\right) \sim AD^{-\lambda_2} \tag{6}$$

$$P\left(\overline{AS}\right) \sim \overline{AS}^{-\lambda_3} \tag{7}$$

where λ_1, λ_2, and λ_3 represent the power-law exponents for AS, AD, and the average avalanche size ($\overline{AS}$), respectively. Based on this, some scholars have proposed using the avalanche criticality index (ACI) to assess criticality (see in Eqs. 8–9)[37,42]. A smaller ACI indicates that avalanche activity is closer to the critical point, which suggests greater capacity for brain information integration and a more comfortable state[43].

$$\lambda_4 = \frac{\lambda_2 - 1}{\lambda_1 - 1} \tag{8}$$

$$ACI = |\lambda_4 - \lambda_3| = \left|\frac{\lambda_2 - 1}{\lambda_1 - 1} - \lambda_3\right| \tag{9}$$

Statistics analysis

All data were confirmed to follow a normal distribution using the Shapiro–Wilk test. Differences in physiological responses across different time periods were compared using paired t-tests (see Appendix B1). A one-way analysis of variance (ANOVA) with LSD post-hoc tests (refer to Appendix B2) was used to examine the differences between the visual stimuli. Spearman's rank correlation test was applied to assess the relationship between psychological and physiological responses. All statistical analyses were conducted using SPSS (26.0, https://www.ibm.com/products/spss-statistics).

Results

VSV

The virtual images of coastal landscape features were generally found to be satisfactory, with the mean VSV for all four scenes being greater than 0 (see Fig. 5). S1 had the highest VSV (2.45), which was 1.08, 3.59, and 1.68 times that of S2, S3, and S4, respectively. However, in S3, participants showed divergent responses, with 10 rating their VSV below 0 and 6 giving the highest score of 3, indicating varied perceptions of the virtual image of the coastal plaza. Overall, the visual characteristics of the coastal walkway and coastal mountain park were found to be more satisfying.

POMS

Virtual images of coastal landscape features elicited positive emotions. As shown in Fig. 6a, after visual exposure, the scores for the Vigor and Esteem items ranged from 17.09 to 20.77, while the scores for negative emotion items ranged from 7.18 to 11.27. In Fig. 6b, S1 had the lowest TMD at 96.59, while S2 and S3 had similar TMD of 102.86 and 102.50, respectively. These results suggest that the walkway space is more effective in alleviating mood disturbances.

RCS

All virtual images of coastal landscape features elicited positive subjective restorative perceptions, with RCS scores greater than 0 (see Fig. 7). S1 was subjectively perceived as most conducive to recovery, with the highest RCS (30.68), which was 1.10 to 1.83 times higher than the other scenes, followed by S2 (27.91). As shown in Fig. 8, S1 scored highest in the "being away" and "fascination" dimensions (2.10–2.20), while S2 had the highest score in the "compatibility" dimension (2.05). S1 and S2 had similar scores in the "extent" dimension (1.92). S3 consistently performed the worst across all four dimensions. Overall, the coastal plaza showed relatively weaker subjective restorative potential.

HRV

LF/HF

During the baseline and stress-inducing stages, LF/HF was similar across groups. However, in the recovery stage, exposure to different virtual images of coastal landscape features led to noticeable differences in LF/HF (see Fig. 9). From the baseline stage to the stress-inducing stage, LF/HF increased by 1.49–1.60, indicating a rise in stress levels. However, upon entering the recovery stage, LF/HF decreased by 1.73–1.81. Paired t-tests showed

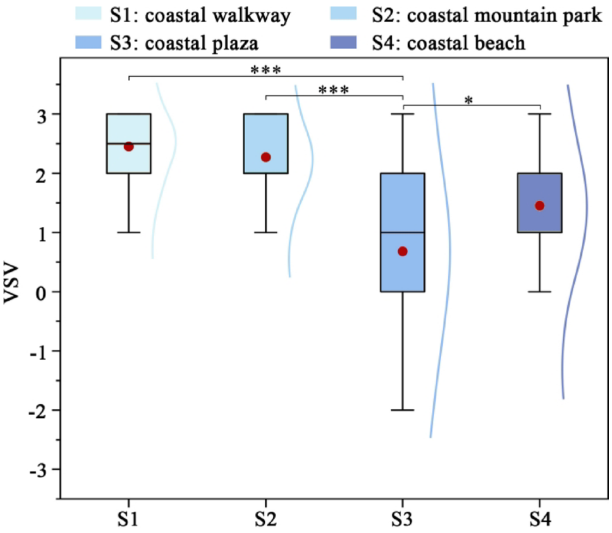


Fig. 5. VSV results for four virtual images of coastal landscape features (Each box shows the interquartile range (IQR), with the median marked by a horizontal line and the red dot indicating the mean value. Vertical whiskers represent 1.5 × IQR. The curves represent the normal distribution of the data. $^{***}p < 0.001$; $^{*}p < 0.05$).

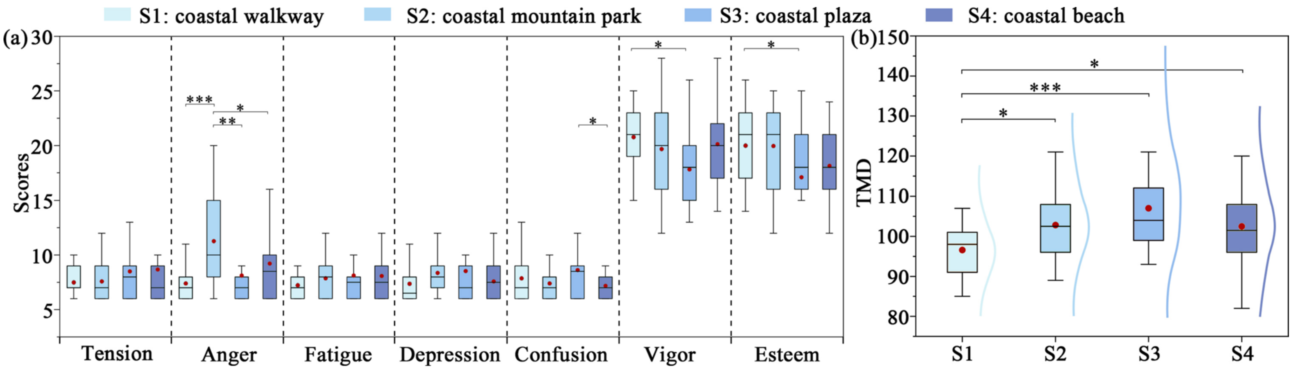


Fig. 6. (**a**) POMS subscale scores and (**b**) TMD scores under exposure to virtual images of coastal landscape features. (*$p<0.05$; **$p<0.01$; ***$p<0.001$).

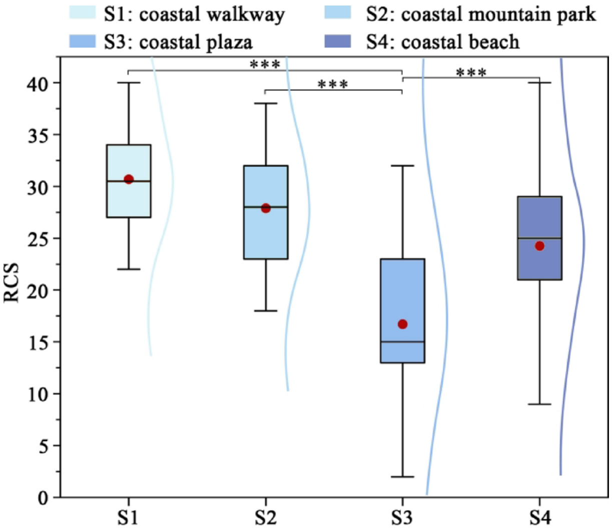


Fig. 7. Results of RCS under exposure to virtual images of coastal landscape features. (***$p<0.001$).

significant differences in LF/HF across the three stages ($p<0.001$), suggesting that stress levels significantly decreased under visual stimuli. Among the scenes, S1 had the lowest LF/HF (1.27), with S2 and S4 showing similar values (1.31–1.34). Compared to the stress-inducing stage, S1 had the largest reduction in LF/HF (58.85%), followed by S2 and S3, with decreases of 57.94% and 56.54%, respectively. The LF/HF after visual stimulation was significantly lower than in the baseline stage, with reductions of 20.20%, 15.87%, 8.47%, and 12.75% for S1, S2, S3, and S4, respectively. Overall, coastal spaces positively influenced ANS activity, with PNS dominance.

RMSSD

Higher RMSSD are associated with stronger PNS dominance. Exposure to different virtual images of coastal landscape features led to varying degrees of improvement in ANS activity (see Fig. 10). Participants' RMSSD ranged from 24.89 to 26.00 ms during the baseline stage, and after the stress stimulus, RMSSD significantly increased by 4.60–6.85 ms. Compared to the stress-inducing stage, RMSSD significantly increased after scene exposure, with S1 showing the highest RMSSD (31.81 ms), representing a 56.85% increase. S2 followed with an RMSSD increase of 59.52% (11.48 ms). Compared to the baseline stage, RMSSD increased by 8.41–27.83% during the recovery stage, indicating a shift in autonomic nervous activity towards a more relaxed state. Overall, the visual characteristics of coastal spaces helped promote PNS dominance in autonomic activity, increasing RMSSD and reducing stress levels.

SDNN

After exposure to different virtual images of coastal landscape features, SDNN was higher than those at baseline, indicating a reduction in stress levels (see Fig. 11). Similar to the changes in RMSSD, there were notable differences in SDNN across the three stages ($p<0.001$, as shown in Fig. 11). From the baseline stage to the stress-inducing stage, SDNN decreased by 8.85–16.29%, but it increased by 32.26–38.10% in the recovery stage. S1 had the highest SDNN (135.49 ms). Compared to the stress-inducing stage, SDNN in S1 and S2 showed the largest

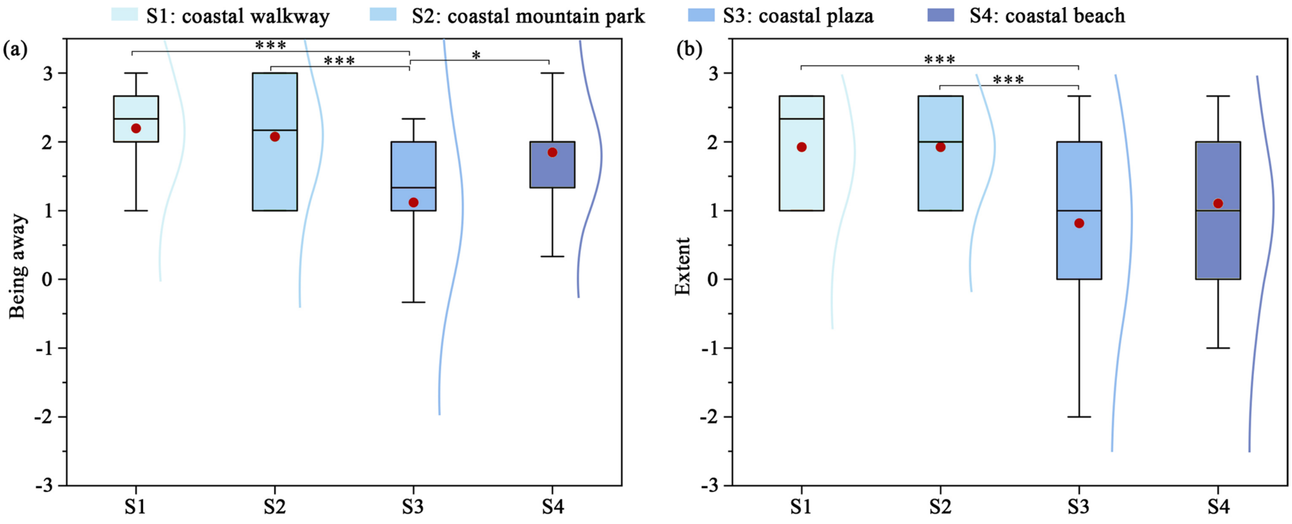


Fig. 8. RCS subscale scores under exposure to virtual images of coastal landscape features. (**a**) Being away, (**b**) Extent, (**c**) Fascination, and (**d**) Compatibility. (*$p < 0.05$; **$p < 0.01$; ***: $p < 0.001$).

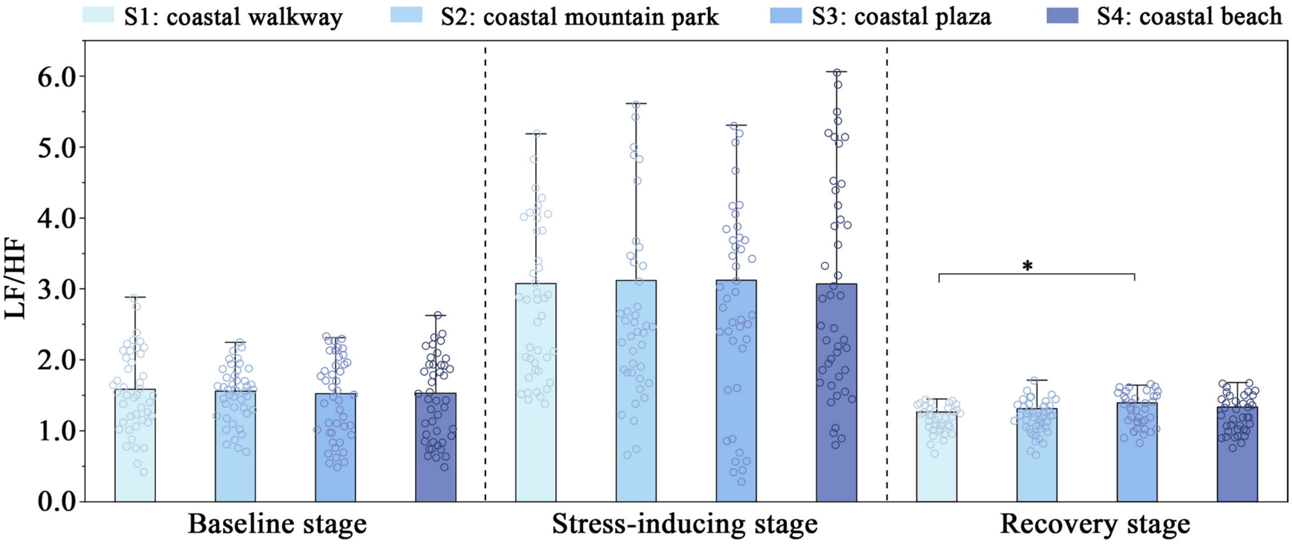


Fig. 9. Changes in LF/HF across three stages under exposure to virtual images of coastal landscape features. (Bars show means ± SD; dots represent individual participants. *$p < 0.05$.)

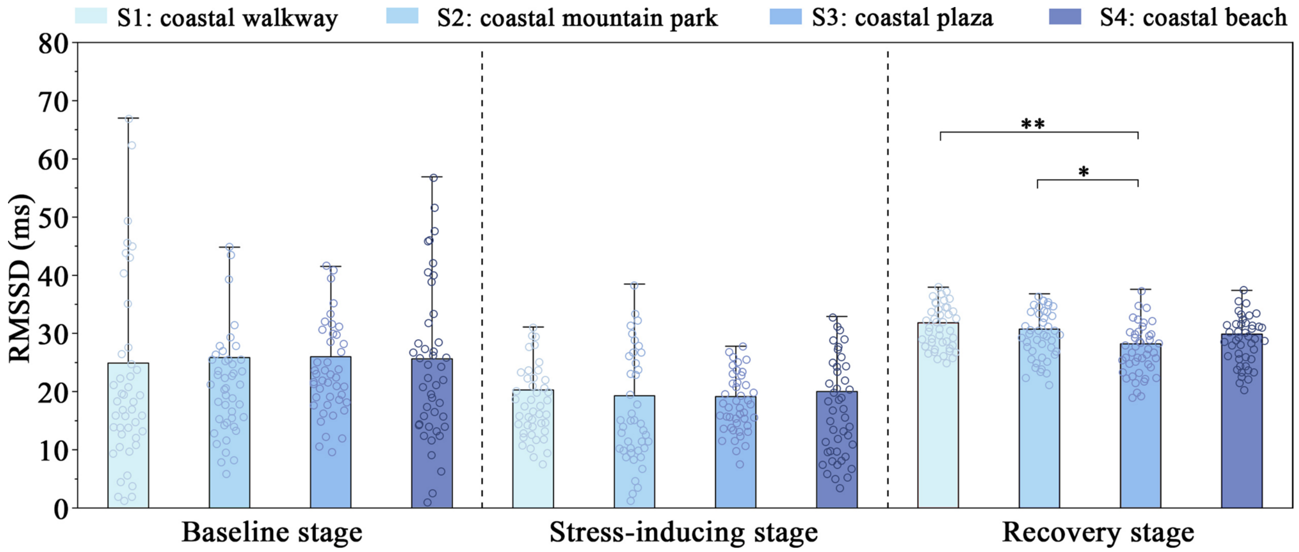


Fig. 10. Changes in RMSSD across three stages under exposure to virtual images of coastal landscape features. (*$p < 0.05$; **$p < 0.01$).

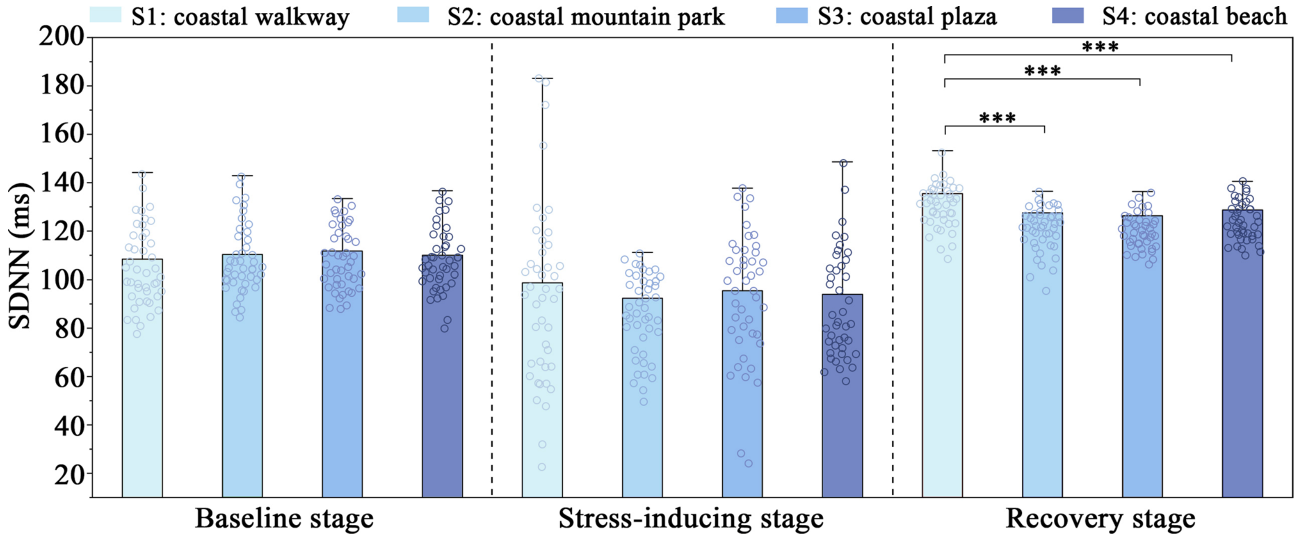


Fig. 11. Changes in SDNN across three stages under exposure to virtual images of coastal landscape features (***$p < 0.001$).

increases, with 37.21% and 38.10% respectively. Relative to the baseline stage, S1 had the greatest SDNN increase (25.07%), while S2 and S3 had similar increases (15.61–16.93%). Overall, visual stimulation from coastal spaces induced more active ANS responses, with the walkway space being particularly effective in supporting SDNN recovery.

EEG

Power$_{total}$

Figure 12 illustrates the changes in plots under different visual stimuli, with the color intensity representing the strength of energy. During the stress-inducing task, the plots show noticeably darker colors, indicating more intense brain oscillatory activity, particularly in the parietal region. However, after exposure to the virtual images of coastal landscape features, the color intensity lightens, suggesting reduced overall brain activity. Oscillatory activity remains slightly stronger in the prefrontal and parietal regions compared to the rest of the brain.

Exposure to different virtual images of coastal landscape features improved brain activity by reducing Power$_{total}$ (see Fig. 13). From the baseline stage to the stress-inducing stage, Power $_{total}$ significantly increased by 2.94–11.73%, indicating that as stress increased, the brain consumed more energy. In the recovery stage, Power$_{total}$ decreased significantly by 3.66–18.65%, reflecting a reduction in brain stress levels. Compared to the stress-inducing stage, S1 most effectively calmed the oscillatory activity of activated neurons (−18.65%),

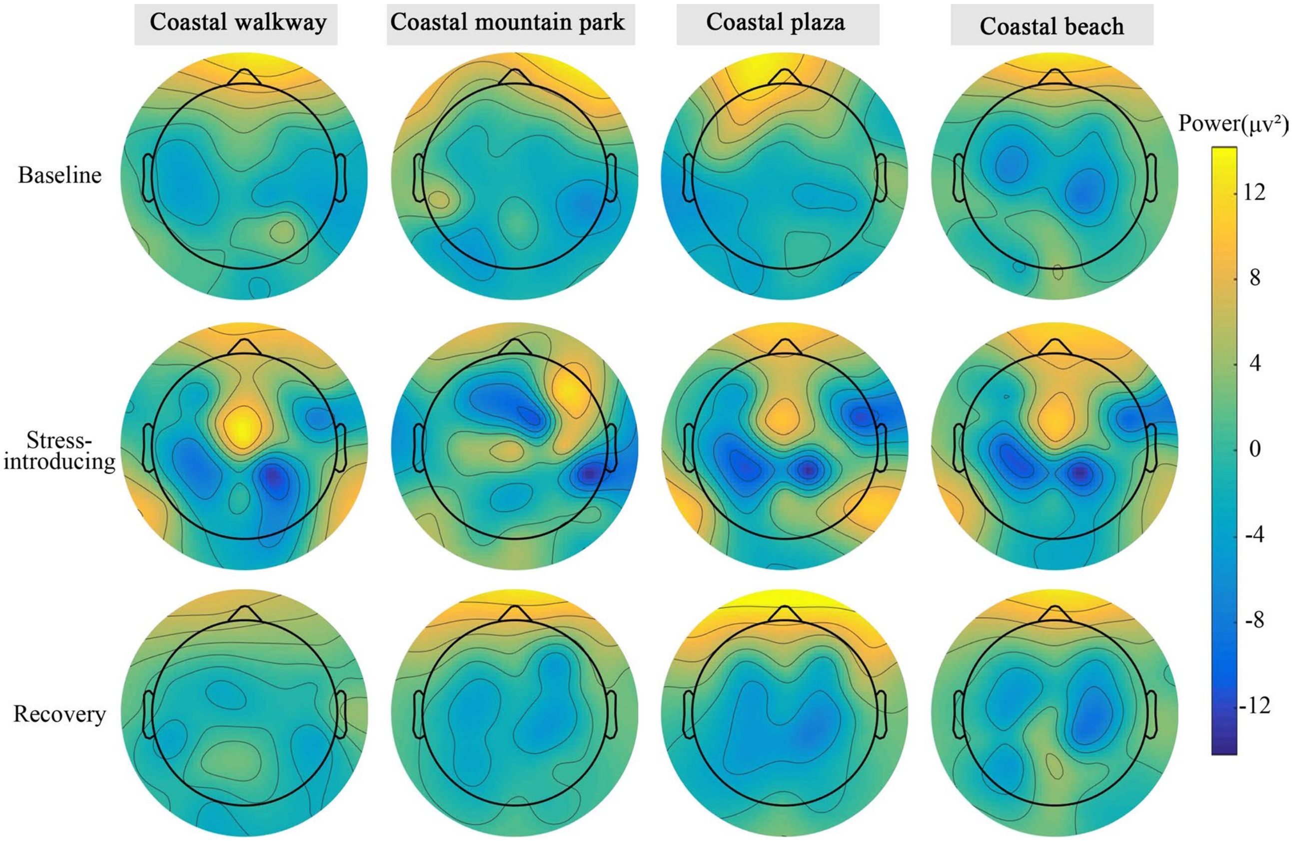


Fig. 12. The changes of plots across three stages under exposure to virtual images of coastal landscape features.

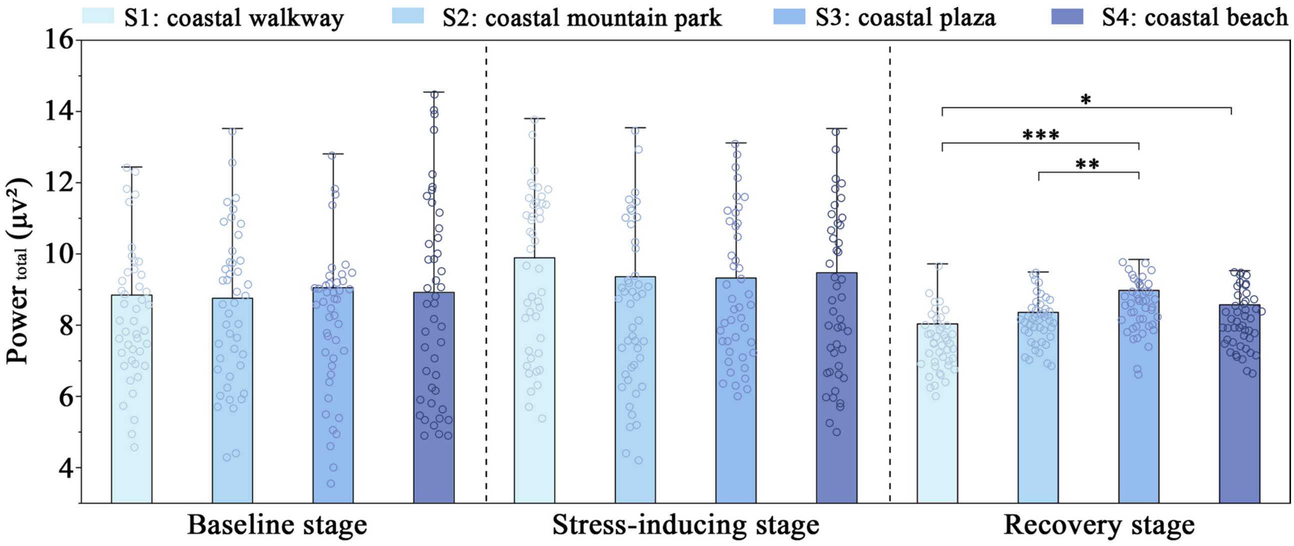


Fig. 13. Changes in Power total across three stages under exposure to virtual images of coastal landscape features. (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$).

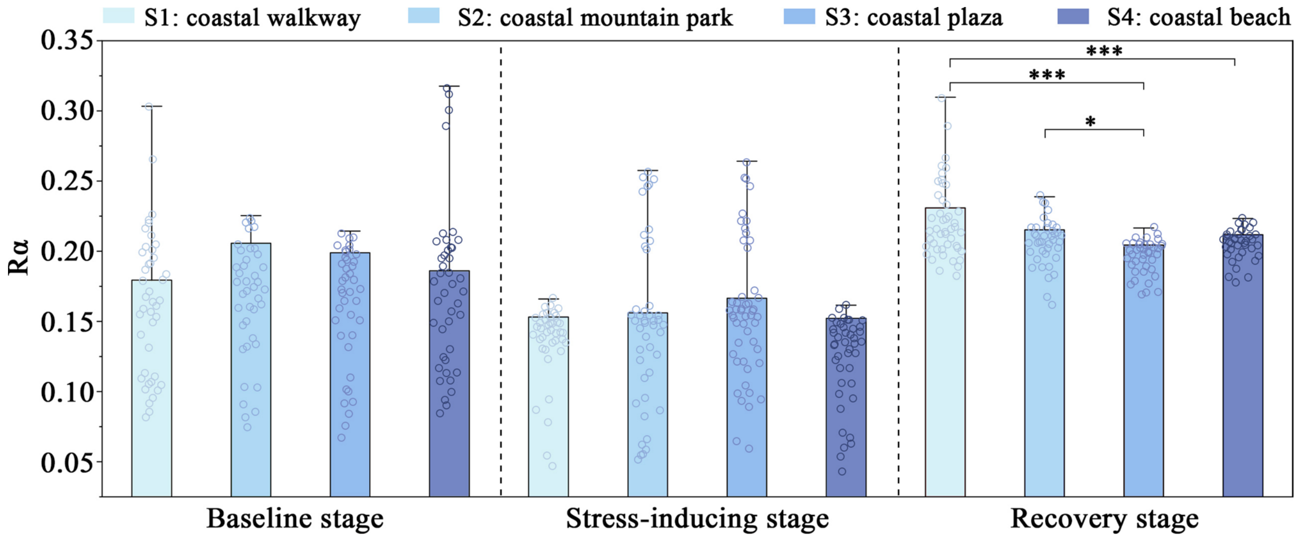


Fig. 14. Changes in Rα across three stages under exposure to virtual images of coastal landscape features. (*$p < 0.05$; ***$p < 0.001$).

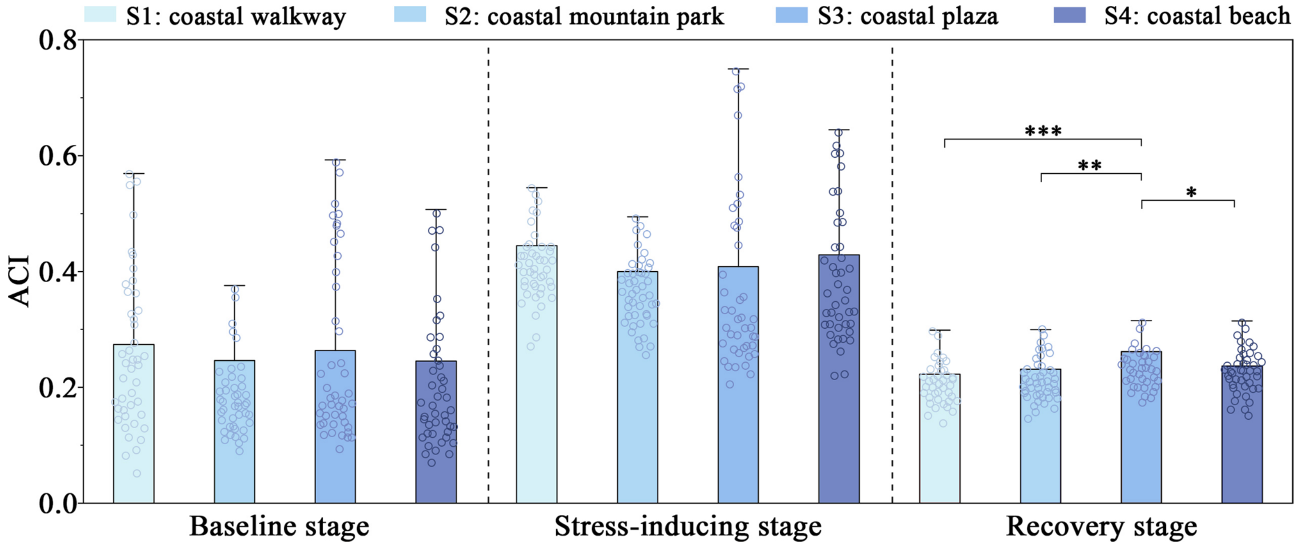


Fig. 15. Changes in ACI across three stages under exposure to virtual images of coastal landscape features. (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$).

followed by S2 (− 10.61%). After auditory and visual stimulation, brain oscillatory activity returned to a more relaxed state compared to the baseline stage, with Power $_{\text{total}}$ decreasing by 0.83–9.10%. Overall, coastal spaces, particularly the walkway, facilitated the recovery of brain oscillatory activity.

Rα

The virtual images of coastal landscape features activated α activity (see Fig. 14). Stress stimulus caused a reduction in Rα (− 0.03 to − 0.05), while exposure to coastal spaces promoted stress recovery, leading to a significant increase in Rα (0.04–0.08), making participants feel even more relaxed than during the baseline stage. In the recovery stage, S1 had the highest Rα (0.23). Compared to the stress-inducing stage, S1's Rα increased by 50.71%, and compared to the baseline stage, it increased by 28.51%. These results indicate that the coastal walkway significantly activated α oscillatory activity.

Neural avalanche parameters

The virtual images of coastal landscape features facilitated positive neural avalanche activity. As shown in Fig. 15, the recovery stage had the lowest ACI (0.15–0.22) across the three stages. Compared to the stress-inducing stage, ACI in the recovery stage significantly decreased by 35.87–49.96%, and compared to the baseline stage, it decreased by 0.62–18.80%. S1 consistently showed the largest reduction in ACI, while S3 had the smallest reduction. Overall, exposure to coastal spaces promoted positive neural avalanche activity, with the walkway space being particularly effective in shifting brain activity toward a critical state.

To further explore variation in visual restorative effects, λ1 and λ2 during the recovery stage were analyzed for each participant. The mean values of λ1 and λ2 from the baseline stage were used as a central reference point to divide the plane into four quadrants. In the lower-left quadrant, both λ1 and λ2 were lower than the baseline value, indicating large-scale, long-duration avalanche activity that requires higher energy consumption. In contrast, the upper-right quadrant reflects smaller, short-duration avalanches, suggesting reduced energy demand. Following exposure to different virtual coastal landscape features, most participants' λ1 and λ2 values shifted away from the lower-left quadrant, indicating reduced unnecessary brain activity (see Fig. 16). However, some participants did not exhibit this shift, suggesting that individual responses to visual recovery stimuli may vary.

Figure 17 shows the proportion of participants whose λ1 and λ2 values were distributed in the upper-right region. S1 was most effective in enhancing the balance of brain activity, with the highest proportion of participants in the upper-right region (63.64%). S2 and S4 followed, with 56.82% and 54.55%, respectively. While patterns of neural avalanche activity differed across individuals, the results demonstrate that coastal spaces are effective in driving brain activity toward criticality.

Correlation analysis

Significant correlations were observed between psychological and physiological responses under visual exposure to virtual images of coastal landscape features (see Fig. 18). VSV showed a strong negative correlation with LF/HF and Power $_{total}$, while it was significantly positively linked with RMSSD, SDNN, and Rα. RCS was significantly positively correlated with SDNN and Rα, and significantly negatively correlated with Power$_{total}$ and ACI. To further examine the relationship between psychological restoration and physiological responses, this study analyzed the correlations between psychological sub-indicators and physiological measures (see Appendix B3).

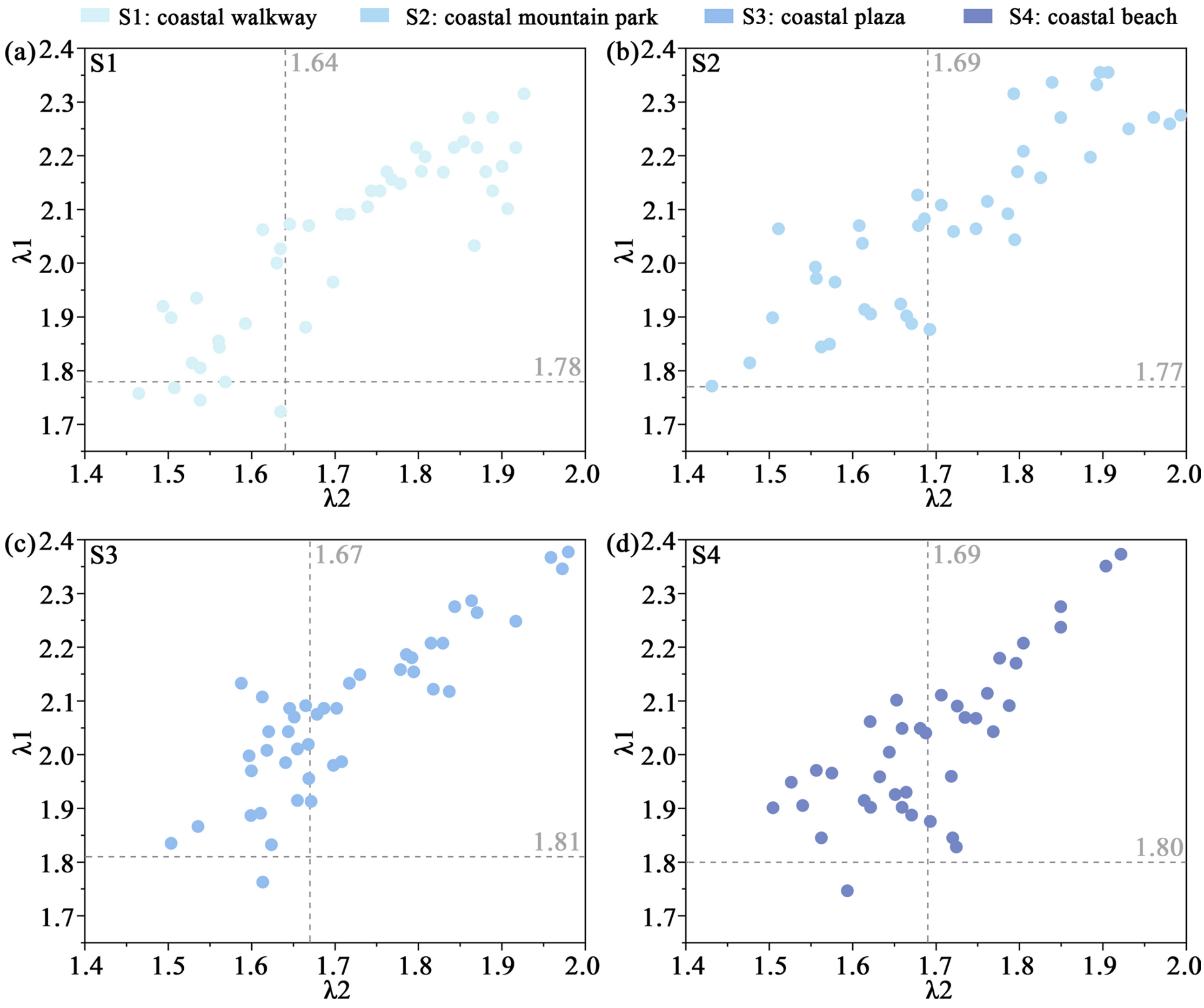


Fig. 16. Individual participants analysis of λ1 and λ2.

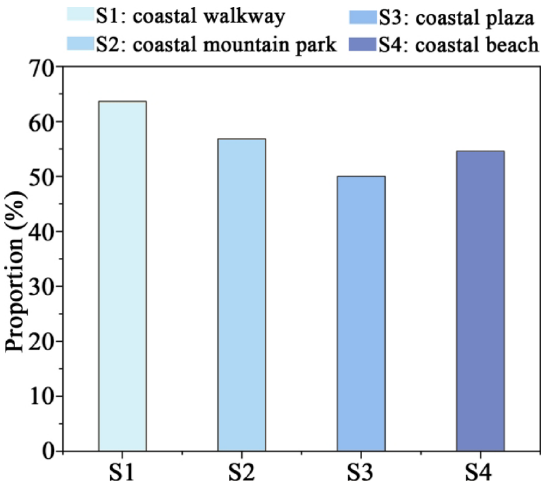


Fig. 17. Proportion of participants with λ1 and λ2 distributed in the upper right area.

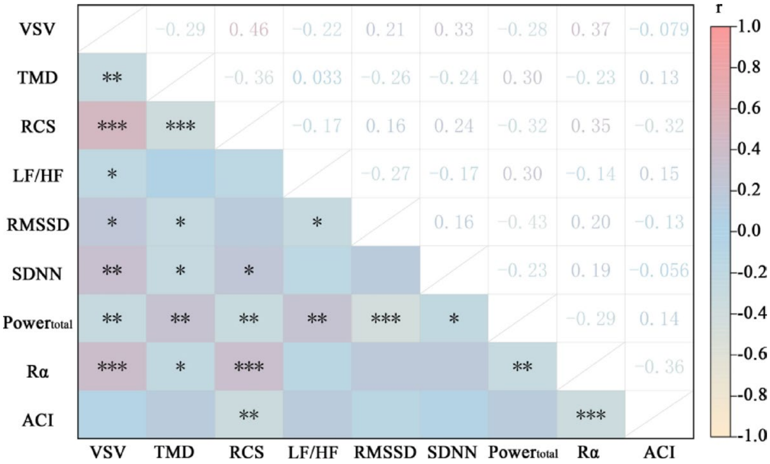


Fig. 18. Correlation analysis between psychological measures and physiological indicators under exposure to virtual images of coastal landscape features.

Among the results, Rα was strongly associated with positive emotional states. Specifically, Rα was significantly positively correlated with Vigor ($r = 0.37$, $p < 0.001$) and Fascination ($r = 0.26$, $p < 0.05$). Compatibility was positively correlated with RMSSD ($r = 0.26$, $p < 0.05$) and negatively correlated with LF/HF ($r = -0.25$, $p < 0.05$). Additionally, Tension was positively correlated with Power $_{total}$ ($r = 0.23$, $p < 0.05$) and negatively correlated with RMSSD ($r = -0.24$, $p < 0.05$). Interestingly, a strong positive correlation was found between LF/HF and Power$_{total}$, with $r = 0.30$ ($p < 0.01$), indicating that ANS and brain are related. Overall, virtual images of coastal landscape features trigger an interaction between psychological and physiological responses, jointly regulating stress recovery.

Discussion

Effects of virtual images of coastal landscape features on stress recovery

The positive impact of coastal landscapes on stress recovery is supported by three major theoretical frameworks. (1) The Attention Restoration Theory (ART) suggests that prolonged directed attention leads to mental fatigue, and natural environments help replenish attentional resources through "soft fascination"[44]. (2) The Stress Recovery Theory (SRT) posits that natural environments can reduce psychological stress by facilitating affective and cognitive restoration[45]. (3) The Biophilia Hypothesis proposes that humans have an innate affinity for nature, particularly for elements such as plants and water, which naturally draw attention and elicit positive emotional responses[46].

These results align with the aforementioned theoretical perspectives. Participants' VSV in response to virtual images of coastal landscape features ranged from 0.68 to 2.45, indicating that most participants found the scenes visually appealing. Previous studies have confirmed that the presence of water can enhance environmental pleasure and visual appeal[47], which aligns with our findings. Compared to traditional green landscapes—such as urban parks, greenways, or forests—coastal landscapes were perceived as offering higher visual quality and restorative potential[48]. For instance, forest environments, characterized by dense vegetation and low noise levels, have been shown to reduce heart rate and improve HRV, while urban green spaces have been linked to improved attention and subjective restoration[49]. In contrast, coastal landscapes combine greenery with open views of water and skyline, offering greater visual openness and spatial fluidity, which may account for their stronger restorative effects[50].

Furthermore, blue spaces have gained increasing attention for their ability to promote both emotion and cognitive recovery. Some studies have found that coastal settings may be more effective than urban green spaces or mountain environments in restoring depleted psychological resources[51]. In urban contexts, incorporating blue elements such as fountains or artificial waterways has also been shown to enhance perceived restorativeness[3].

Among the coastal landscape features examined, the virtual image of coastal walkway produced the most pronounced improvements in subjective restoration, with a 5.77–9.77% reduction in TMD and the highest RCS score (30.68). This may be attributed to its high visual coherence and spatial consistency—an integration of water, greenways, vegetation, and surrounding elements that creates a smooth and unified visual experience. Such continuity avoids abrupt attentional shifts, supports neural relaxation, and enhances both positive emotions and aesthetic pleasure[52]. These findings align with Liu et al., who reported that greenways can increase the attractiveness of waterfronts by offering more opportunities for visual and physical engagement[4,53].

From a physiological perspective, virtual images of coastal landscape features elicited positive ANS responses. Compared to baseline, LF/HF decreased by 8.47–20.20%, while RMSSD and SDNN increased by 8.41–27.83% and 13.05–25.07%, respectively, indicating parasympathetic dominance and reduced physiological stress. Relative to green environments, blue spaces may exert a more direct and substantial regulatory effect on HRV, as some studies have shown that the presence of water enhances physiological recovery more effectively[54].

In terms of neurophysiological activity, EEG results showed a decrease in total power (0.83–9.10%) and a significant increase in Rα (Rα 2.76–28.51%), suggesting lower brain energy consumption and a more relaxed state. These changes may be associated with the regulation of the HPA axis through the inhibition of amygdala hyperactivity by the dorsolateral and ventromedial prefrontal cortices[55]. In addition, coastal landscapes facilitated more efficient neural avalanche activity, with ACI decreasing by 0.62–18.80%. The coastal walkway again proved to be the most effective feature in guiding brain activity toward a critical state, reflecting a deeper neurological mechanism of restoration.

It is noteworthy that not all participants exhibited the same patterns of recovery. Across the four coastal features, only 50.00–63.64% of participants showed localized, short-duration neural avalanche activity during the recovery stage, suggesting individual variability in response to different visual exposures. Prior research has identified gender as an important factor in visual recovery, with some studies indicating that visual restoration effects may be more pronounced in women, who are generally more sensitive to visual stimuli[12,56].

Importantly, this study also revealed significant interactions between psychological and physiological recovery. Correlation analyses showed that $\text{Power}_{\text{total}}$ was significantly associated with HRV metrics including LF/HF, RMSSD, and SDNN ($p < 0.05$), indicating a close coupling between ANS activity and brain function. These interactions may be mediated by the vagus nerve, which plays a key role in emotional regulation. The vagus not only modulates HRV but also influences emotion-related brain regions such as the prefrontal cortex and limbic system. Meanwhile, the prefrontal cortex also regulates ascending vagal signals, forming a bidirectional feedback loop that helps maintain emotional balance and physiological homeostasis.

Practical implications for optimizing coastal landscape design

The importance of coastal spaces has been widely recognized, and many cities place significant emphasis on the design of these areas. Coastal spaces provide residents with diverse services and comfortable environments, enhancing their connection with nature, facilitating leisure activities, and offering a pleasant visual experience. This study's results underscore the importance of visual elements in influencing how coastal environments are perceived, providing practical recommendations for urban planning and designing healthier environments. Coastal walkways, integrated with green landscapes, are perceived as more restorative, while coastal plazas with larger hard-paved areas are relatively less effective. Increasing biodiversity by planting more native vegetation can help create a tranquil and pleasant environment. Improving the visual quality of coastal spaces is essential for maximizing their restorative potential. Measures such as increasing vegetation coverage and enhancing green visibility can significantly elevate both the aesthetic appeal and functional performance of these environments. Additionally, the implementation of dynamic monitoring and evaluation systems to assess the emotional impacts of coastal spaces on residents—and adjusting design strategies accordingly—can strengthen the integration of theoretical insights with practical applications. The findings of this study offer valuable guidance for designers and planners, emphasizing the importance of visual features in coastal landscapes and their synergy with surrounding environments to optimize health-promoting effects. This study opens up new avenues for future research to explore how different environmental factors in coastal spaces interact to alter human perception and well-being. In the context of rapid urbanization, understanding these underlying mechanisms will help promote public health and the development of sustainable environments.

Limitations and future work

This study innovatively integrated VR technology with multimodal physiological measurements to evaluate the impact of virtual images of typical coastal landscape features on stress recovery. The findings expand our understanding of environmental restoration mechanisms and provide empirical support for health-oriented coastal landscape design. Notably, this study was the first to introduce neural avalanche indicators (e.g., ACI) in the context of coastal landscape research, exploring their associations with subjective restoration and ANS activity. This offers a novel perspective on how brain activity approaches a critical state during recovery. Future studies could build upon this experimental framework to develop more portable or field-adaptable VR and physiological monitoring systems, promoting broader applications of multisensory restorative environment research in real-world contexts.

However, several limitations should be acknowledged. First, the experiment was conducted in a controlled laboratory setting, where only visual stimuli were presented and other environmental variables (e.g., lighting, temperature, sound, and smell) were held constant. In real-world scenarios, environmental perception is influenced by multiple factors such as visual pollution (e.g., litter, debris), the presence of others, aesthetic quality, and common auditory and olfactory disturbances in coastal areas (e.g., loud music, port activity, humidity, or fishy odors). Future research should incorporate auditory and olfactory stimuli to simulate more immersive or semi-natural environments, thereby enhancing ecological validity and the practical relevance of findings for design.

Second, although four representative types of coastal landscape features were selected, the visual models did not systematically control key spatial design variables that influence perception, such as walkway width, vegetation density, topographical variation, and spatial enclosure. Future studies may introduce these micro-scale spatial attributes as independent variables while keeping the main scene type constant, in order to investigate their modulatory effects on restorative outcomes and provide more operational design guidance for urban coastal environments.

Third, all participants were young university students in China, leading to a relatively homogeneous sample that may limit the generalizability of the findings. Given that environmental perception is also shaped by factors such as cultural background, social experience, and individual traits, future studies should recruit more diverse participant groups to enhance external validity.

Finally, social context—such as the presence of companions—is known to significantly affect environmental perception and the restorative experience. Future research could further incorporate social interaction variables to provide a more comprehensive understanding of the restorative mechanisms of coastal environments.

Conclusion

This study explored the impact of various virtual images of coastal landscape features (coastal walkway, coastal mountain park, coastal plaza, and coastal beach) on stress recovery, utilizing VR technology to provide an immersive experience. The subjective evaluations, HRV, and EEG signals of 44 young university students were measured, revealing that virtual images of coastal landscape features facilitate stress recovery. This research offers a new method for evaluating urban landscape quality from a health perspective and provides a reference for coastal landscape design. The detailed conclusions are outlined below:

(1) Virtual images of coastal landscape features are generally satisfying but show individual differences, especially in the coastal plaza. The coastal walkway is more effective in alleviating mood disturbances, with a total mood disturbance reduction of 5.77–9.77% compared to other landscapes. It also better supports subjective recovery, with the highest Restorative Components Scale (30.68), 1.10 to 1.83 times that of the other settings.

(2) Exposure to virtual images of coastal landscape features enhances positive autonomic nervous system activity. Compared to baseline, LF/HF decreased by 8.47–20.20%, RMSSD increased by 8.41–27.83%, and SDNN increased by 13.05–25.07%, indicating a reduction in stress levels. The coastal walkway performed best, with LF/HF decreasing by 3.26–8.85%, RMSSD increasing by 3.42–12.84%, and SDNN increasing by 5.29–7.27% compared to other landscapes, which further activated parasympathetic nervous activity related to relaxation.

(3) The virtual images of coastal landscape features aid brain stress recovery. Compared to baseline, $\text{Power}_{\text{total}}$ decreased by 0.83–9.10%, while Rα significantly increased by 2.76–28.51%, indicating a higher relaxation level of brain oscillatory activity. Virtual images of coastal landscape features also promoted positive neural avalanche activity, with avalanche criticality index (ACI) significantly decreasing by 0.62–18.80%, with the coastal walkway being the most effective in shifting brain activity towards a critical state. However, not all participants experienced recovery—only 63.64%, 56.82%, 50.00%, and 54.55% of participants exposed to the coastal walkway, coastal mountain park, coastal plaza, and coastal beach, respectively, exhibited small-scale, short-duration avalanche activity.

(4) Mental and neural recovery are correlated under exposure to virtual images of coastal landscape features. $\text{Power}_{\text{total}}$ was significantly correlated with LF/HF, RMSSD, and SDNN ($p < 0.05$), indicating that autonomic nervous system activity and brain activity jointly contribute to stress recovery.

This study integrated VR technology with multimodal physiological indicators to systematically evaluate the effects of typical coastal landscape feature images on stress recovery. It revealed the coupling mechanisms between subjective and physiological restoration and provided quantitative evidence to support health-oriented coastal space design. Coastal landscape design should prioritize walkway spaces and strategically combine blue and green elements while avoiding large areas of hard paving.

Data availability

The data presented in this study are available on request from the corresponding author.

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Author contributions

Conceptualization, J.S. and N.Z.; methodology, J.S. and N.Z.; investigation, J.J. and H.D.; software, J.J. ; visualization, Y.S.; formal analysis, Y.S.; resources, W.G.; writing—original draft, J.S. and N.Z.; writing—review and editing, J.S.; supervision, W.G.; All authors have read and agreed to the published version of the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Ethical approval

This study was approved by the Ethics Committee of Qingdao University (Approval No. QDU-HEC-2022150). All participants provided informed consent prior to the experiment.

Additional information

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