http://www.press.ierek.com

ISSN (Print: 2357-0849, online: 2357-0857)

Environmental Science and Sustainable Development

Research Paper

Received:09 December 2025, Accepted: 26 February 2026, Published online: 30 June 2026

DOI: 10.21625/essd.v11i1.1264

The Effect of Natural Sounds on Stress Recovery: A Study of Heart Rate Variability

Xiaotong Jing [1], Chao Liu [2], Hiroatsu Fukuda [3 *]

[1]*Doctoral student, Faculty of Environmental Engineering, The University of Kitakyushu, Japan*

[2] *Lecturer of the Innovation Institute for Sustainable Maritime Architecture Research and Technology, Qingdao University of Technology, China*

[3] *Professor, Faculty of Environmental Engineering, The University of Kitakyushu, Japan*

Abstract

Psychological stress is widespread in urban populations, and soundscape-based interventions may offer a low-cost way to support recovery. This study presented a controlled dataset linking perceived restorativeness with cardiac autonomic responses during post-stress recovery under different natural sound exposures. Using a within-subject design, 26 participants completed four laboratory sessions in a balanced random order: silence, water sound, birdsong, and wind sound. Natural sound stimuli were author-recorded and presented as 5-min segments. The headphone-equivalent sound pressure level for natural sound conditions was standardized to 50 dB (A). Acute stress was induced using the Maastricht Acute Stress Test (MAST), followed by a recovery phase with continuous electrocardiogram (ECG) recording. Subjective responses were assessed using the Perceived Restorativeness Scale (PRS), and physiological recovery was evaluated using heart rate variability indicators derived from ECG (including LF/HF ratio and a stress index). Compared with silence, natural sounds were associated with improved recovery, with higher PRS ratings for water sound and birdsong and lower LF/HF ratios and stress index values, particularly under birdsong. This data provided a reproducible basis for comparing sound-type-specific recovery profiles and supports evidence-informed design of restorative acoustic environments.

Keywords

Natural sounds; soundscape; stress recovery; electrocardiogram; HRV

1. Introduction

The rapid development of urbanization has changed the urban living environment and people's lifestyles. The accelerating pace of life and immense competitive pressures are gradually robbing people of inner peace, leading to a rise in negative emotions, a decline in spiritual well-being, and an increased susceptibility to stress reactions. Stress responses occur frequently in our daily lives. If stress cannot be restored in time, it will disrupt the homeostasis of the human body's functions and cause disorders in the nervous and endocrine systems. This leads to non-steady-state loads, which have a serious negative impact on the physical and mental health of individuals. (McEwen, 2007). In response to this growing public health challenge, research exploring restorative environments has expanded significantly, with particular attention to the potential therapeutic benefits of natural settings.

At present, research on the restorative benefits of the environment mainly focuses on visual-spatial experience, using visual stimuli such as photos, videos, and slides for stress recovery. However, environmental perception is not limited to vision alone. In recent years, some scholars have begun to focus their research on restorative environments on the auditory aspect. (Iyendo, 2016; Aletta and Kang, 2019; Sona et al., 2019). Research suggests that natural sounds, such as the sound of flowing water and bird chirping, are pleasant sounds that make people feel relaxed and have certain potential restorative effects.(Grahn & Stigsdotter, 2010; Payne, 2013). Even some studies have pointed out that soundscapes play a more significant role in environmental restoration: Jabben et al. (2015) found that the average noise level has a considerable impact on the restoration of urban parks and noted that soundscapes play a crucial role in environmental restoration. Ma et al. (2021) found that compared with visual scene stimulation, sound has a more significant impact on psychological recovery. Meanwhile, Kang and Zhang (2010) argued that a high-quality acoustic environment would also have a positive impact on the recovery from physiological stress. Liu et al. (2024) discovered that the sounds of birds chirping and flowing water can help alleviate mental stress. This indicates that the restorative effect of sound in the overall environmental restoration cannot be ignored.

In the past, scholars' research methods on the impact of soundscape on stress resilience mainly relied on subjective evaluation. Although subjective evaluation could reflect the influence of the environment on volunteers in consciousness, most of the time, the influence of the environment on people was unconscious. (Winkielman et al., 2007; Reinerman-Jones et al., 2010). Therefore, it is necessary to incorporate the measurement of neurophysiological parameters into the experiment to comprehensively and effectively evaluate the impact of the acoustic environment on stress recovery. A systematic review and meta-analysis by Zhu et al. (2024) Synthesized evidence from 15 studies involving 1,285 participants found that natural sound exposure significantly reduced anxiety levels (as measured by the Visual Analogue Scale and State Anxiety Inventory), decreased heart rate, lowered systolic and diastolic blood pressure, and reduced respiratory rate. These findings suggest that natural sounds elicit a parasympathetic response consistent with the relaxation response theorized to support stress recovery.

Cardiac autonomic function, particularly as measured through heart rate variability (HRV), has emerged as a particularly sensitive indicator of stress recovery responses. HRV reflects the dynamic interplay between sympathetic and parasympathetic branches of the autonomic nervous system, with higher variability generally indicating greater adaptive capacity and physiological resilience. Studies have shown that natural sound exposure can increase HRV, suggesting improved autonomic regulation. (Brown et al., 2013). These studies are consistent with the assumption of Ulrich's stress recovery theory. (Ulrich, 1981) that activating the PSNS helps promote stress recovery (Gladwell et al., 2012). In conclusion, these literatures indicate that entering and approaching restorative environments has positive impacts on short-term stress recovery and long-term cardiovascular health.

Despite growing evidence that natural sounds may support stress recovery, three limitations remain prominent in the current literature. First, many studies treat “natural sound” as a broad category, which makes it difficult to isolate and compare the effects of specific sound types under controlled and acoustically standardized exposure conditions. Second, findings are often based on subjective evaluations alone, whereas stress recovery also involves largely unconscious physiological regulation; therefore, datasets that simultaneously report perceived restorativeness and objective cardiac autonomic markers remain comparatively limited. Third, reproducibility is frequently constrained by incomplete reporting of key procedural details (stress induction protocol, stimulus calibration, and HRV preprocessing), which reduces the potential for cross-study comparison and secondary analyses. To address these gaps, the present study provides a controlled, within-subject laboratory dataset in which 26 participants underwent stress induction via the Maastricht Acute Stress Test (MAST) (Smeets et al., 2012) and then completed four recovery conditions (silence, water sound, birdsong, and wind sound) presented in a balanced random sequence. All natural sound stimuli were standardized to a headphone equivalent level of 50 dB(A), and recovery was assessed using both the Perceived Restorativeness Scale (PRS) (Payne, 2013) and electrocardiogram-derived heart rate variability (HRV) indices (SDNN, HF power, LF/HF ratio, and stress index) acquired at 1000 Hz with clearly specified artefact screening and correction procedures. By combining standardized acoustic exposure with transparent physiological processing, this work aims to strengthen the evidence base for soundscape design and to facilitate future reuse of the dataset for replication and comparative soundscape research.

2. Method

To examine how various natural sounds influence stress recovery in students, this research adopted a multimodal methodology combining perceptual assessments with objective biometric data. Psychological and physiological stress was elicited using the Maastricht Acute Stress Test (MAST). Following the stress induction, participants were randomly assigned to experience one of four types of sound environments. Subjective feedback and heart rate variability (HRV) measurements were collected and analyzed throughout the recovery phase.

2.1. Participants

The participants of the experiment were mainly recruited through the public recruitment plan for experimental volunteers at Qingdao University of Technology. The recruitment targets were college students and postgraduate students currently enrolled. Students sign up voluntarily. The main reason for choosing college students as the research group is that young people at this stage are generally healthier. They are more sensitive to sounds and have a stronger understanding of the acoustic environment. The study was conducted in accordance with the Declaration of Helsinki and approved by the University Ethics Committee (IRB number: QUT-HEC-2024023). All participants received written and verbal information about the study and provided written informed consent before data collection. Participants were informed of their right to withdraw at any time without penalty, and all data were anonymized prior to analysis. We calculated the sample size through G.Power software (Araujo et al., 2016). Under the condition that the effect size was 0.5(medium), a=0.05, and the power was 0.8, the sample size was at least 24. Therefore, 26 participants were recruited for the experiment. The participants' information is shown in Table 1.

Table 1. Participants Information.

Participants Information		Number
Gender	Male	12
	Female	14
Age	18-21 years old	12
	22-25 years old	14
Health and hearing condition	Normal years old	26
Do you often listen to music?	Yes	14
	No	16

2.2. Acoustic stimuli

All sound stimuli used in the experiment were recorded by the authors using professional audio recording equipment. The recorder was positioned approximately 1.5 m above ground level, and a representative 5-min segment was selected from each recording for use as a restorative sound stimulus. To maximize the purity of the natural sound sources, recordings were conducted at sparsely populated natural sites with minimal anthropogenic noise. Because recordings were obtained under different environmental conditions, the original sound pressure levels (SPLs) varied across stimuli. To minimize potential confounding effects of SPL on the experimental outcomes, all sound-type stimuli were presented at a standardized SPL. Table 2 summarizes the sound stimuli and reports the preset and measured SPL values for each condition.

Table 2. Detailed information on the sound source and preset and measured values of the sound pressure level.

Sound	Details	Monitor the equivalent sound pressure level in the headphones.		
		Preset value	**Measured value**	**Sensitivity**
Silence	Turn on the noise-cancelling mode of the headphones to reduce ambient noise.	＜38 dB(A)	＜38 dB(A)	±1.3 dB(A)
Water sound	The water sound was recorded in the Beijiushui Scenic Area of Laoshan Mountain, Qingdao.	50 dB(A)	49.6 dB(A)	
Birdsong	The birdsong was recorded in the woods of Zhongshan Park in Qingdao.	50 dB(A)	48.7 dB(A)	
Wind sound	The sound of the wind was recorded on the playground of Qingdao Technological University.	50 dB(A)	50.3 dB(A)	

2.3. Physiological and psychological evaluation methods

The subjective assessment in this study was conducted using the Perceived Restorativeness Scale (PRS). Each item was rated on a 5-point Likert scale. To reduce participant fatigue, four representative items were selected for each PRS subscale. Details of the selected items are provided in Appendix A.1.

Physiological responses were assessed using electrocardiogram (ECG) recordings. ECG reflects the periodic bioelectrical activity generated over each cardiac cycle, primarily resulting from sequential excitation of the sinoatrial node, atria, and ventricles. ECG-based analyses are commonly performed in both the time and frequency domains. In the time domain, key indices include heart rate and heart rate variability (HRV). Heart rate is typically derived from the R–R interval, defined as the time between two consecutive R-wave peaks, which represents one complete cardiac excitation cycle. HRV characterizes the temporal variability between successive heartbeats and is computed from fluctuations in consecutive R–R intervals. A widely used time-domain metric is the standard deviation of normal-to-normal intervals (SDNN) over a defined period. Higher SDNN values indicate greater overall autonomic regulation and have been associated with better stress recovery and cardiovascular health.

Frequency-domain analysis provides complementary information on autonomic function. Using a Fourier transform, the time-series ECG signal is decomposed into its frequency components, and the power spectral density is calculated within predefined bands, typically including high frequency (HF), low frequency (LF), very low frequency (VLF), and ultra-low frequency (ULF). Among these, LF and HF power, as well as the LF/HF ratio, are often used as indicators of autonomic modulation and are sensitive to environmental and affective influences. HF power predominantly reflects parasympathetic (vagal) activity; higher HF values are generally interpreted as indicating a more relaxed physiological state. (Sinha et al., 1992; Murakami & Ohira, 2007). The LF/HF ratio is frequently used to describe sympathovagal balance: higher values are commonly interpreted as relatively greater sympathetic dominance and/or reduced vagal influence on sinoatrial node regulation. An LF/HF ratio close to 1 suggests comparable contributions of sympathetic and parasympathetic activity, whereas values >1 are often interpreted as reflecting heightened arousal and values <1 as reflecting parasympathetic predominance.

2.4. Experimental process

Figure 1 shows the detailed experimental process. The experiment comprised four conditions and followed a within-subject design, such that each participant completed all four acoustic conditions. Each condition consisted of two phases: a stimulation phase and a recovery phase. Upon arrival, participants were fitted with HRV monitoring equipment and rested quietly for 5 min to acclimatize to the laboratory environment. During the stimulation phase, participants completed the Maastricht Acute Stress Test (MAST) twice. The MAST is a well-established standardized paradigm for stress induction that is simple and cost-effective to administer and elicits physiological and psychological responses comparable to real-world stress reactions (Quaedflieg et al., 2015). It comprises two consecutive tasks: a cold pressor test (physiological stressor) and a mental arithmetic task (psychological stressor). In the cold pressor test, participants immersed both palms fully in ice-cold water for 30 s to induce pain-related physiological stress, followed immediately by a 90-s mental arithmetic task requiring serial subtraction from four-digit numbers, with responses reported verbally. During the recovery phase, participants were exposed to one of four auditory stimuli while HRV was recorded continuously. To minimize order effects, the four conditions were presented in a counterbalanced randomized sequence. A 10-min washout period was implemented between conditions, during which participants remained in a neutral, silent environment to reduce potential carry-over effects.

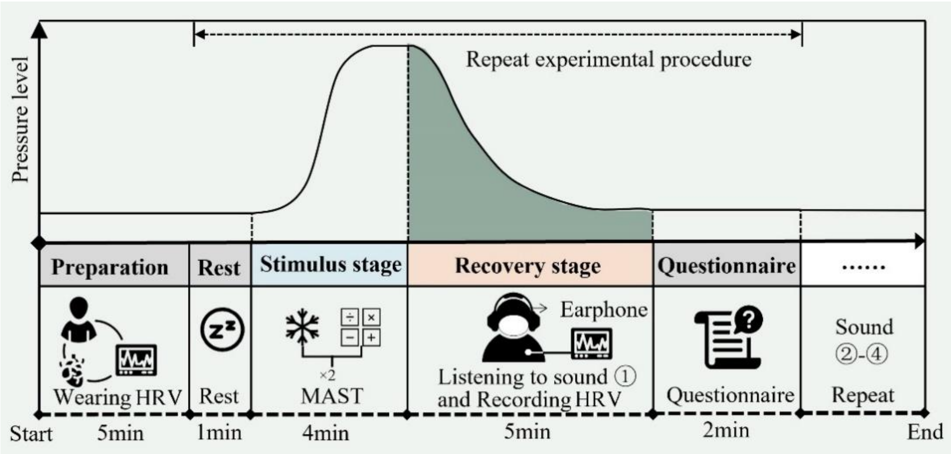

Figure 1. Experimental process.

2.5. Data collection and Statistical analysis

ECG signals were acquired using the HeaLing-R211B system at a sampling rate of 1000 Hz. A single-lead configuration was applied, with electrodes placed at the right infraclavicular region and the left lower thorax. Participants remained seated throughout the recording. Before analysis, HRV data were preprocessed. R–R intervals were screened for artifacts and ectopic beats using a threshold criterion (R–R intervals outside 300–2000 ms). Identified artifacts were corrected using the automatic correction algorithm implemented in Kubios. (Lipponen & Tarvainen, 2019).

All statistical analyses were performed using IBM SPSS Statistics (Version 28.0). Subjective outcomes (Perceived Restorativeness Scale, PRS) and physiological indices (SDNN, HF power, LF/HF ratio, and stress index) were analyzed to evaluate differences in stress recovery across the four auditory conditions. A one-way repeated-measures analysis of variance (ANOVA) was used as the primary inferential approach. Figures were generated using OriginPro 2021 and further refined for publication using Adobe Photoshop 2024.

3. Results

3.1. PRS result

The subjective evaluation of the restorative potential of different sound environments was conducted using PRS, which encompassed four key dimensions: being-away, fascination, compatibility, and an overall PRS score. The results are visually presented in **Figure 2**, **Figure 3**, **Figure 4**, & **Figure 5.** Overall, the pattern of results was clear and consistent: compared with silence and wind sound, the two natural sound conditions (water sound and birdsong) received significantly higher ratings across all PRS dimensions. For the being-away dimension (**Figure 2**), water sound (mean = 1.91) and birdsong (mean = 2.14) were both significantly higher than silence (mean = 0.07; $p < 0.01$). Birdsong was also significantly higher than wind sound ($p < 0.01$), whereas wind sound remained close to baseline and below the two natural sound conditions. The distributional patterns further indicate higher medians for water sound and birdsong, with relatively narrower interquartile ranges, suggesting greater agreement among participants regarding their perceived sense of "being away."

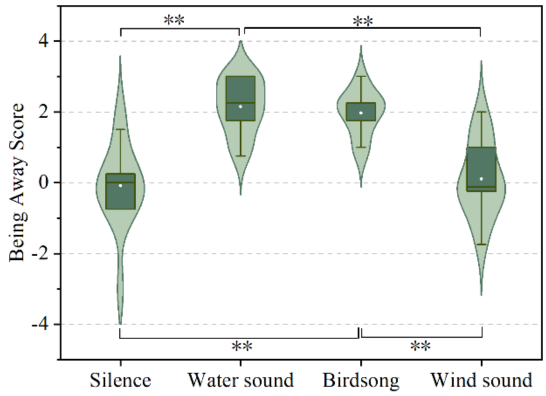

Figure 2. Being away score (**, p < 0.01).

A similar pattern was observed for fascination (**Figure 3**). Water sound and birdsong again yielded relatively high ratings (means = 1.45 and 1.66, respectively), exceeding the silent control condition (mean = −0.28). In contrast, wind sound ratings clustered around zero to slightly negative values, indicating a comparatively limited capacity to capture attention relative to water sound and birdsong.

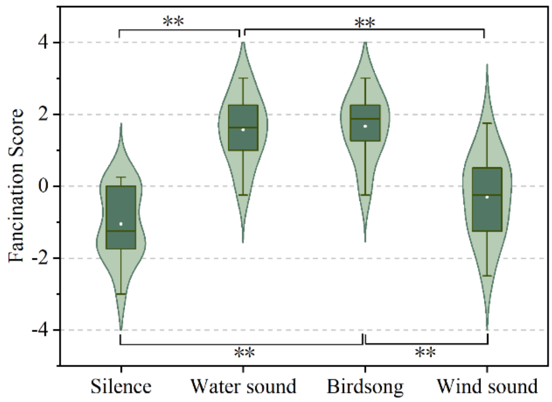

Figure 3. Fascination score (**, p < 0.01).

For compatibility (**Figure 4**), water sound and birdsong maintained high scores (means = 1.86 and 2.20, respectively). Wind sound produced the lowest compatibility rating (mean = −0.13), which was lower than the silent condition (mean = 0.47), suggesting that participants perceived the windy sound environment as less compatible with their preferred recovery experience.

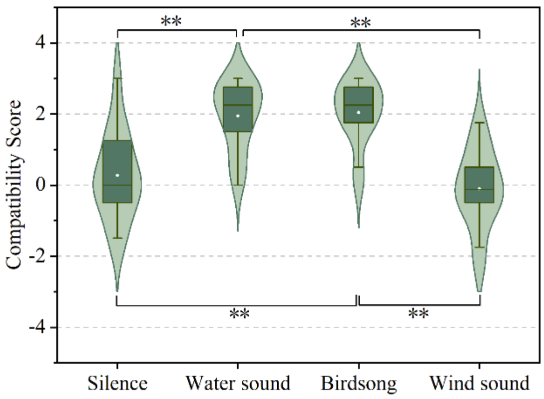

Figure 4. Compatibility score (**, p < 0.01).

When these dimensions were aggregated, the overall PRS under underwater sound and birdsong was significantly higher than under silence ($p < 0.01$; **Figure 5**). Specifically, the overall PRS under flowing water and birdsong was approximately 2.11 and 2.27 times that of the silent control condition, respectively, whereas the wind sound condition remained near baseline. Taken together, these subjective findings indicate that water sound and birdsong were perceived as the most restorative auditory environments, substantially outperforming both silence and wind sound. This provides a psychological basis for examining whether these perceived restorative benefits are accompanied by enhanced physiological stress recovery, as assessed via HRV in the following section.

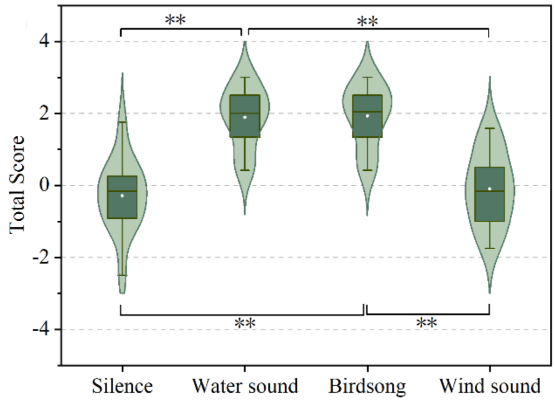

Figure 5. Total score (**, p < 0.01).

3.2. HRV result

Figure 6 presents the evaluation results of SDNN under four working conditions. The analysis of SDNN data revealed obvious physiological trends corresponding to subjective restorative perception. A repeated-measures ANOVA revealed a significant main effect of acoustic condition on SDNN, $F(3, 90) = 4.62$, $p = 0.005$, $\eta p^2 = 0.13$, indicating a moderate effect size. As shown in the figure, the average SDNN value of water sound was the highest (34.9 ms±9.8), indicating that among all conditions, the enhancement of overall autonomous regulation and stress recovery was the most significant. Secondly, Birdsong (33.3 ms±9.3) and Wind Sound (32.2 ms±10.8). The average SDNN value under the silent condition was the lowest (31.6 ms±12.5), indicating a relatively low level of physiological recovery. In conclusion, the SDNN results indicated that exposure to natural sounds, especially water sounds, leads to a significant increase in SDNN compared with silence. This provided objective physiological evidence that natural sounds, especially water sounds, could enhance the function of the autonomic nervous system, promote stress recovery, and effectively confirm the subjective perceptual restorative discovery.

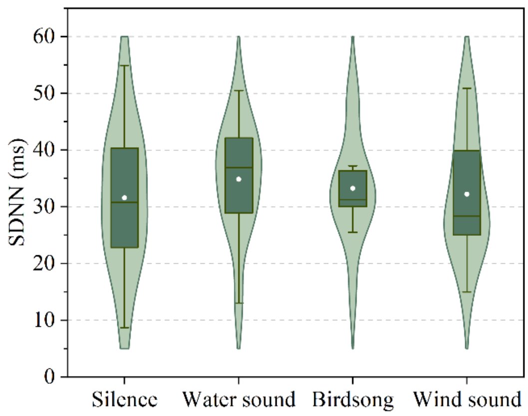

Figure 6. The SDNN results of the subjects under four sound conditions.

The frequency domain analysis of HRV provided deeper insights into the autonomic nervous system (ANS) dynamics during exposure to different sound environments. HF power, a marker of parasympathetic (vagal) activity and respiratory sinus arrhythmia, and the LF/HF ratio, an indicator of the sympathovagal balance, were analyzed in **Figure 7** and **Figure 8.** As shown in **Figure 7**, repeated-measures ANOVA indicated a significant effect of acoustic condition on HF power, $F(2.41, 72.30) = 8.57$, $p < 0.001$, $\eta p^2 = 0.22$. The high-frequency power data analysis indicates that the average high-frequency power caused by water sound was up to 57.2 ms^2, suggesting that the activity of the parasympathetic nervous system is significantly increased compared to other conditions. Although the average values of the still sound, birdsong, and wind sound were similar, being 52.0 ms^2, 52.8 ms^2, and 52.2 ms^2, respectively.

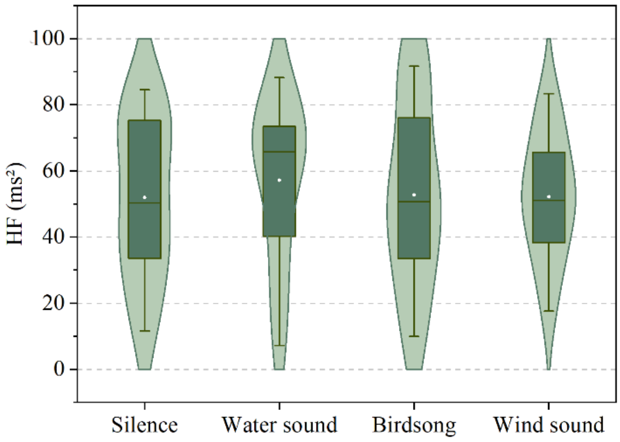

Figure 7. The HF results.

However, the increase in the average value of water sounds indicates a stronger vagus nerve-mediated relaxation response. The most striking result comes from the analysis of the LF/HF ratio (**Figure 8**). The average LF/HF ratio under water sound was the lowest (0.39±0.15), followed by birdsong (0.59±0.48), indicating a shift from autonomic nerve balance to parasympathetic nerve dominance. The LF/HF ratios of the silence group (0.71±0.52) and the wind sound group (0.82±0.58) were significantly higher than those of the water sound, reflecting a relatively higher sympathetic tone or a less relaxed state. In conclusion, the frequency-domain analysis of HRV provides compelling physiological evidence that the sounds of water and birds uniquely promote stress recovery by significantly enhancing parasympathetic nerve activity and shifting autonomic nerve balance towards a resting and digestive state. This effect is obvious and much stronger than that of silence and the sound of the wind. These results, in synergy with the subjective PRS scores and SDNN results, construct a coherent narrative. That is, the sound of water is the most effective auditory stimulus for triggering psychological and physiological recovery.

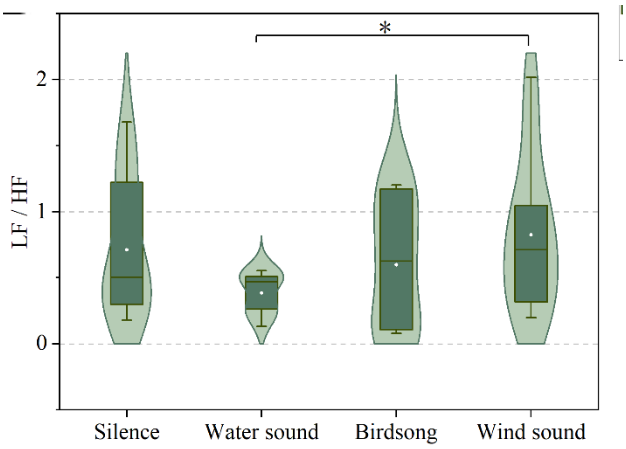

Figure 8. The LF/HF results (*, $p < 0.05$).

The stress index, a derived HRV parameter that reflects the level of sympathetic activation and overall stress load on the autonomic nervous system, was analyzed across the four experimental conditions. Lower values indicate reduced stress and a more relaxed physiological state. **Figure 9** shows the results of the pressure index under the four working conditions. As shown in **Figure 9**, repeated-measures ANOVA demonstrated a significant effect of acoustic condition on stress index, $F(3, 90) = 5.73$, $p = 0.001$, $\eta p^2 = 0.16$. The average stress index under the birdsong condition was the lowest (10.54±2.39), which was 14.48% lower than that under the silent condition. It indicates that among the four conditions, the reduction in sympathetic nervous system activity and overall physiological stress is the greatest. Secondly, there are wind sounds and water sounds, which are 10.54 and 11.09, respectively, 11.44% and 9.9% lower than the silent conditions. In conclusion, the results of the stress index provide convergent physiological evidence that exposure to natural sounds effectively reduces sympathetic nerve activation and promotes a less stressful physiological state compared to silence.

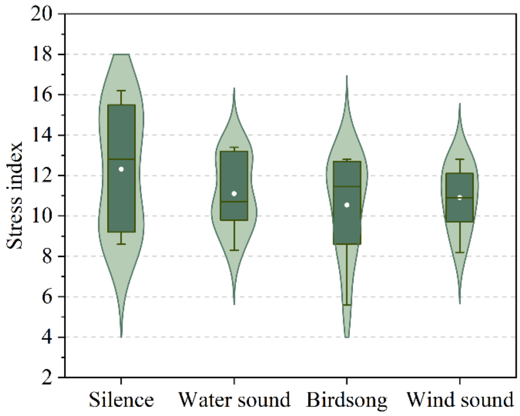

Figure 9. The Stress index results of the subjects under four sound conditions.

4. Discussion

This study integrates psychological and physiological evidence on the restorative effects of natural soundscapes by combining PRS ratings with high-resolution HRV indices. Overall, the results suggest convergence between subjective restorative appraisals and objective autonomic recovery: conditions associated with higher perceived restorativeness also tended to show more favorable HRV profiles. This pattern is consistent with broader syntheses indicating that exposure to natural environments and natural sounds is linked to stress reduction and improved well-being. (Buxton et al., 2021).

Among the tested sound types, water sound and birdsong yielded the highest PRS scores, and this subjective advantage aligned with enhanced autonomic regulation, particularly higher SDNN values, during the corresponding recovery periods. Such agreement between perceived restoration and physiological regulation is compatible with Attention Restoration Theory, which proposes that environments with softly fascinating qualities can facilitate restoration by reducing demands on directed attention. Notably, the median PRS scores for birdsong and water sound were more than twice those observed under the silent control condition, underscoring their psychological strength in promoting a sense of being-away and perceived compatibility with recovery needs.

Physiological analysis indicates that underwater sound is the most effective stimulus for triggering the dominance of the parasympathetic nervous system and for restoring the balance of the autonomic nervous system to its normal state. Unlike the quiet state that leads to relatively high sympathetic nerve tension, underwater sound can effectively activate the parasympathetic nervous system, facilitating rapid internal balance restoration after acute stress. This physiological transformation provides a mechanistic explanation for the "attractive" and "appealing" qualities that underwater sound exhibits in subjective charm evaluations. Furthermore, recent controlled studies comparing multiple natural soundscapes also report that water sounds often show strong relaxation-related signatures in physiological measures, supporting the plausibility of water sound as a robust restorative stimulus (Bai & Zhang, 2024). Although water sounds can effectively activate the parasympathetic nervous system, birdsong seems to have unique advantages in inhibiting the activity of the sympathetic nervous system and reducing the overall physiological stress load. Birdsong in our dataset appears to show particular advantages in reducing overall physiological stress load. The stress index under the bird call condition was the lowest, 14.48% lower than that in the silent condition, indicating that the physiological cost brought by stress was significantly reduced. However, it is important to interpret birdsong effects cautiously because the literature includes mixed findings depending on experimental context, co-occurring sounds, and stressor type. For example, controlled work has reported limited incremental effects of birdsong on physiological stress recovery under some conditions (Hedblom et al., 2019). Taken together, these comparisons reinforce that “nature” as a category does not guarantee restorative outcomes; rather, sound type, acoustic quality, and contextual framing are likely decisive for both perceived and physiological restoration (Buxton et al., 2021; Ratcliffe, 2021).

Several limitations should be noted. First, high-frequency (HF) power is sensitive to respiratory rate and tidal volume; without concurrent respiration measurement, changes in HF cannot be unambiguously attributed to vagal modulation alone. Future studies should therefore incorporate respiratory monitoring or paced-breathing protocols to disentangle autonomic from respiratory contributions. Second, the laboratory headphone paradigm enhances control but may differ from real-world restorative experiences in urban parks, where multisensory context and meaning attribution can amplify or attenuate restoration processes. From an architectural and urban planning perspective, these results support the deliberate integration of high-quality restorative acoustic elements into public and healthcare-related environments, while also emphasizing that not all natural sounds are equally beneficial and that design decisions should consider sound composition and user context.

5. Conclusion

This study demonstrates that exposure to specific types of natural sounds—particularly water sounds and birdsong—significantly enhances both psychological and physiological recovery from acute stress among college students. The results clearly indicate that these sounds are far more effective than silence in promoting restorative outcomes. Subjective assessments using the Perceived Restorativeness Scale showed that water sounds and birdsong were perceived as substantially more restorative than the silent control condition. These subjective benefits were strongly supported by objective heart rate variability metrics: a marked reduction in the LF/HF ratio under natural sound conditions reflects a shift toward parasympathetic dominance, indicating a calmer autonomic state. Furthermore, a consistent decrease in stress index values provided additional evidence of reduced sympathetic activation. By integrating subjective self-reports with high-resolution physiological monitoring, this research offers a holistic understanding of how natural auditory stimuli facilitate stress recovery. These findings hold practical value for the design of therapeutic soundscapes and restorative environments in settings such as hospitals, offices, and urban public spaces. Future studies could explore the effects of longer exposure durations, individual differences in sound preference, and the potential synergies when combining natural sounds with visual natural elements.

Acknowledgments
A part of this paper was presented at a conference named Urban Planning & Architectural Design for Sustainable Development (UPADSD).
Funding
This work was supported by JST SPRING, Japan Grant Number JPMJSP2149.
Ethics approval
The study was conducted in accordance with the Declaration of Helsinki and approved by the University Ethics Committee (IRB number: QUT-HEC-2024023).
Conflict of interest
The author(s) declare(s) that there is no competing interest.

References

Aletta, F. & Kang, J. (2019). Promoting Healthy and Supportive Acoustic Environments: Going beyond the Quietness. *International Journal of Environmental Research and Public Health* 16(24), 4988. doi: https://doi.org/10.3390/ijerph16244988.

Araujo, T. K. de, Secolin, R., Félix, T. M., Souza, L. T. de, Fontes, M. Í. B., Monlleó, I. L., Souza, J. de, Fett-Conte, A. C., Ribeiro, E. M., Xavier, A. C., Rezende, A. A. de, Simioni, M., Ribeiro-dos-Santos, Â. K. C., Santos, S. E. B. dos, & Gil-da-Silva-Lopes, V. L. (2016). A multicentric association study between 39 genes and nonsyndromic cleft lip and palate in a Brazilian population. Journal of Cranio-Maxillofacial Surgery, 44(1), 16–20. https://doi.org/10.1016/j.jcms.2015.07.026

Bai, Z. & Zhang, S. (2024). Effects of different natural soundscapes on human psychophysiology in a national forest park. *Scientific Reports* 14(1), 17462. doi: 10.1038/s41598-024-67812-1.

Brown, D.K., Barton, J.L., & Gladwell, V.F. (2013). Viewing Nature Scenes Positively Affects Recovery of Autonomic Function Following Acute Mental Stress. *Environmental Science & Technology* 47, 5562 - 5569. doi: https://doi.org/10.1021/es305019p.

Buxton, R., Pearson, A., Allou, C., Fristrup, K., & Wittemyer, G. (2021). A synthesis of health benefits of natural sounds and their distribution in national parks. *Proceedings of the National Academy of Sciences* 118, e2013097118. doi: 10.1073/pnas.2013097118.

Gladwell, V. F., Brown, D. K., Barton, J. L., Tarvainen, M. P., Kuoppa, P., Pretty, J., Suddaby, J. M., & Sandercock, G. R. H. (2012). The effects of views of nature on autonomic control. *European Journal of Applied Physiology, 112*(9), 3379–3386. https://doi.org/10.1007/s00421-012-2318-8

Grahn, P., & Stigsdotter, U.K. (2010). The relation between perceived sensory dimensions of urban green space and stress restoration. *Landscape and Urban Planning* 94(3)**,** 264-275. doi: https://doi.org/10.1016/j.landurbplan.2009.10.012.

Hedblom, M.A.-O., Gunnarsson, B., Schaefer, M.A.-O., Knez, I., Thorsson, P., & Lundström, J.N. (2019). Sounds of Nature in the City: No Evidence of Bird Song Improving Stress Recovery. *International Journal of Environmental Research and Public Health* 16(8)**,** 1390. doi: https://doi.org/10.3390/ijerph16081390.

Iyendo, T.O. (2016). Exploring the effect of sound and music on health in hospital settings: A narrative review. *International Journal of Nursing Studies* 63**,** 82-100. doi: https://doi.org/10.1016/j.ijnurstu.2016.08.008.

Jabben, J., Weber, M., & Verheijen, E. (2015). A framework for rating the environmental value of urban parks. *Science of The Total Environment* 508**,** 395-401. doi: https://doi.org/10.1016/j.scitotenv.2014.12.007.

Kang, J., & Zhang, M. (2010). Semantic differential analysis of the soundscape in urban open public spaces. *Building and Environment* 45(1)**,** 150-157. doi: https://doi.org/10.1016/j.buildenv.2009.05.014.

Lipponen, J.A.-O., & Tarvainen, M.A.-O. (2019). A robust algorithm for heart rate variability time series artefact correction using novel beat classification. *J Med Eng Technol.* 43(3)(1464-522X (Electronic))**,** 173-181. doi: 10.1080/03091902.2019.

Liu, C., Jing, X., Shi, J., Li, J., Zhang, Y., & Gao, W. (2024). Effects of natural sound on human stress recovery based on EEG techniques. *Journal of Environmental Psychology* 97**,** 102365. doi: https://doi.org/10.1016/j.jenvp.2024.102365.

Ma, K.W., Mak, C.M., & Wong, H.M. (2021). Effects of environmental sound quality on soundscape preference in a public urban space. *Applied Acoustics* 171**,** 107570. doi: https://doi.org/10.1016/j.apacoust.2020.107570.

McEwen, B.S. (2007). Physiology and neurobiology of stress and adaptation: central role of the brain. *Physiological Reviews* 87(3)(0031-9333 (Print))**,** 873-904. doi: 10.1152/physrev.00041.2006.

Murakami, H., & Ohira, H. (2007). Influence of Attention Manipulation on Emotion and Autonomic Responses. *Perceptual and motor skills* 105**,** 299-308. doi: 10.2466/PMS.105.5.299-308.

Payne, S.R. (2013). The production of a Perceived Restorativeness Soundscape Scale. *Applied Acoustics* 74(2)**,** 255-263. doi: https://doi.org/10.1016/j.apacoust.2011.11.005.

Quaedflieg, C.W.E.M., Meyer, T., Smulders, F.T.Y., & Smeets, T. (2015). The functional role of individual-alpha based frontal asymmetry in stress responding. *Biological Psychology* 104**,** 75-81. doi: https://doi.org/10.1016/j.biopsycho.2014.11.014.

Ratcliffe, E. (2021). Sound and Soundscape in Restorative Natural Environments: A Narrative Literature Review. *Frontiers in Psychology* 12. doi: 10.3389/fpsyg.2021.570563.

Reinerman-Jones, L., Cosenzo, K.A., & Nicholson, D.M. (2010). *Subjective and Objective Measures of Operator State in Automated Systems.*

Sinha, R., Lovallo, W.R., & Parsons, O.A. (1992). Cardiovascular differentiation of emotions. *Psychosomatic Medicine* 54**,** 422–435. doi: 10.1097/00006842-199207000-00005.

Smeets, T., Cornelisse, S., Quaedflieg, C. W. E. M., Meyer, T., Jelicic, M., & Merckelbach, H. (2012). Introducing the Maastricht Acute Stress Test (MAST): A quick and non-invasive approach to elicit robust autonomic and glucocorticoid stress responses. Psychoneuroendocrinology, 37(12), 1998–2008. https://doi.org/10.1016/j.psyneuen.2012.04.012

Sona, B., Dietl, E., & Steidle, A. (2019). Recovery in sensory-enriched break environments: integrating vision, sound, and scent into simulated indoor and outdoor environments. *Ergonomics* 62(4)(1366-5847 (Electronic))**,** 521-536. doi: 10.1080/00140139.2018.

Ulrich, R. (1981). Natural Versus Urban Scenes: Some Psychophysiological Effects. *Environment and Behavior* 13**,** 523-556. doi: 10.1177/0013916581135001.

Winkielman, P., Berntson, G., & Cacioppo, J. (2007). "The Psychophysiological Perspective on the Social Mind." 89-108.

Zhu, R., Yuan, L., Pan, Y., Wang, Y., Xiu, D. & Liu, W. (2024). Effects of natural sound exposure on health recovery: A systematic review and meta-analysis. *Science of The Total Environment* 921**,** 171052. doi: https://doi.org/10.1016/j.scitotenv.2024.171052.

Appendices

Appendix A. Perceived Restorativeness Scale (PRS)

PRS	Score
	Totally disagree (-3), Disagree (-2), Slightly disagree (-1), Neutral (0), Slightly agree (1), Agree (2), Totally agree (3),
Being-Away	1. The sound makes me feel free.
	2. The sound gives me a break from my daily routine.
	3. The sound allows me to temporarily escape from the stress of daily study life.
	4. The sound makes me relax.
Fascination	5. This sound has attractive qualities.
	6. I wish I knew more about this sound.
	7. There's a lot to explore and discover in this sound.
	8. This sound is charming.
Compatibility	9. I can do what I want in this sound.
	10. The sound suits me.
	11. I feel like I'm in tune with this sound.
	12. I can feel happiness in this sound.