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Harmonizing with nature: Unpacking the neurophysiological impacts of biophilic sound in virtual classroom design

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Abstract: This paper presents the results of an experiment on the effects of biophilic sound on electroencephalography (EEG) activations by comparing two virtual classroom designs: one non-biophilic and one biophilic. The results reveal significant interhemispheric interactions in theta, alpha, and gamma frequency bands. The presence of biophilic sound in conjunction with other biophilic elements decreases beta power, compared to its absence. These findings underscore the influence of auditory biophilic experiences on neurophysiological responses, providing insights for evidence-based design strategies to enhance biophilic environments.

Keywords: Biophilic Sound; Design Neurocognition; Electroencephalography (EEG); Virtual Reality (VR)

1. Introduction

Biophilia refers to the natural human connection to nature and living systems. According to biophilia theory, human well-being is intricately linked to nature, and exposure to natural elements can enhance human health and behaviors (Kellert et al., 2011). The objective of biophilic design is to integrate natural elements and patterns into constructed environments to improve human well-being and productivity (St-Jean et al., 2022). While most previous studies have focused on environmental variables that pose disadvantages to human health, such as toxic materials and indoor air quality, far less research has concentrated on the benefits, such as the incorporation of natural elements into indoor settings through biophilic design (Yin & Spengler, 2019).

There have been numerous studies exploring the relationship between nature and the built or virtual environment. Research suggests that exposure to natural elements can effectively reduce anxiety and improve attention restoration (Hartig et al., 2003; St-Jean et al., 2022). According to Attention Restoration Theory (ART), such exposure may lead to enhanced cognitive performance (Ohly et al., 2016; Stevenson et al., 2018). In the context of hospital patients, views of nature have been demonstrated to expedite healing and reduce the need for pain treatment (Ulrich, 1984). In a recent experiment utilizing VR and EEG to study patient rooms, the incorporation of features like plant walls and digital representations of nature significantly influenced alpha power in the frontal region, reducing tension and inducing positive emotional changes (Jung et al., 2023).

The integration of design elements inspired by nature in workplace environments has shown notable health benefits, including reductions in physiological stress and improvements in cognitive function (Yin et al., 2019). Previous studies have also reported that biophilic design can foster creativity, with factors such as views of nature and the use of natural materials predicting greater creativity (McCoy & Evans, 2022). Previous studies have indicated that exposing students to natural components in both built and virtual environments, such as greenery or outdoor vistas, may lead to improvements in cognitive performance, attention, and psychological comfort (Determan et al., 2019; Yin et al., 2019). Despite the potential for applying these principles in virtual learning spaces, there has been a lack of research examining neurocognitive functions within the metaverse virtual classroom setting.

To measure brain responses, researchers widely employ EEG, a method that captures electrical signals from the scalp resulting from brain activity below. These signals are analyzed across five principal frequency bands: delta, theta, alpha, beta, and gamma (Jatupaiboon et al., 2013; Liang et al., 2017). Alpha waves, indicative of relaxed alertness, predominantly appear over the parietal and occipital regions. Beta waves, associated with higher arousal levels, becomes more pronounced during intense mental tasks, especially in the frontal areas (Kuribayashi & Nittono, 2017; Muller & Cunningham, 2020). The frontal cortex plays a crucial role in visuo-spatial processing (Waberski et al., 2008) and visual attention (Liang et al., 2017). Opening the eyes decreases alpha activity while increasing beta activity.

Recent research (e.g., Jung et al., 2023; Kim and Gero, 2023) has explored the impact of biophilic design in virtual environments. However, the specific role of biophilic sounds within indoor learning spaces remains unexplored. Biophilic sounds can be incorporated into classroom settings during break times, as background music, or before examinations to alleviate stress and anxiety, thereby potentially improving mental health. As the popularity of online learning and metaverse virtual classrooms continues to rise, understanding how to create virtual classroom environment that provide a multisensory experience—merging visual and auditory stimuli—is increasingly important. Such environments can encourage positive student engagement and enhance learning outcomes.

This study aims to explore the effect of biophilic sound on neurophysiological activation in a metaverse virtual classroom using VR and EEG measures to assess brain electrical activity, which can provide insights into cognitive performance and attention. We investigate the following research questions (RQs):

RQ1. What is the effect of biophilic sound on EEG activation in two distinct virtual classrooms?

RQ2. Are there significant differences in EEG frequency bands between virtual classrooms designed with and without biophilic elements?

2. Neurocognition in VR measured using EEG

The study of neurocognition using EEG and VR has gained increasing interest in recent years due to its potential to create a more realistic and immersive environment for studying neurocognitive processes. EEG measures the electrical activity of the brain, while VR generates an artificial environment that simulates real-world scenarios. VR enables the creation of simulated environments suitable for the study of cognitive and emotional processes in a controlled setting (Tauscher et al.,2019).

By combining these two technologies, researchers can investigate brain activity in response to various stimuli presented in a more naturalistic and ecologically valid setting. EEG signal recording during VR exposure has proven effective in capturing levels of alertness, calmness, and engagement, providing insights into both physical and mental states and enabling personalized treatment approaches. One of the key advantages of using EEG and VR is the ability to manipulate and control visual and auditory stimuli, eliciting specific cognitive and behavioral responses from participants (Jung et al.,2023; Kober et al.,2012).

Previous studies have investigated the visual impact of nature on brain activation. Mostajeran et al. (2023) examined the effects of virtual nature settings on immersion, presence, and emotion regulation using EEG data. The results indicated that participants in the virtual nature setting exhibited increased alpha and theta activity, suggestive of a state of relaxation and heightened attentional focus. Kim and Gero (2023) conducted research on the effects of biophilic design on university students' neurophysiological responses within virtual classrooms, presenting seven different biophilic design cases as visual stimuli in two display conditions (monitor display and VR Head-Mounted display). The findings indicated significant main effects of condition and hemisphere in alpha power, as well as an interaction effect between case and education major. Additionally, an interaction effect emerged among condition, case, hemisphere, and education major in beta power (Kim & Gero, 2023).

The utilization of auditory effects, particularly nature sounds, has been explored for their potential therapeutic benefits in treating mental health conditions and enhancing learning environments. Höller et al. (2012) investigated whether common effects exist when individuals listen to music. Participants brought their favorite relaxing and stimulating music and were exposed to both tactile stimulation and a resting condition. The results revealed significant responses in the alpha range in parietal and occipital regions for most subjects during both relaxing and stimulating music, as well as during tactile stimulation. Beta activity increased in most subjects while listening to stimulating music and during tactile stimulation.

You et al. (2020) studied the effects of auditory stimulation using nature sounds on EEG signals. EEG recordings were obtained while participants were exposed to two different auditory stimuli: white noise and nature sounds. The nature sounds included various elements like birdsong, flowing water, and rustling leaves. The results indicated that exposure to natural sounds led to significant changes in EEG signals, including increased alpha and theta activity and decreased beta and gamma activity compared to exposure to white noise. These findings suggest the potential benefits of using nature sounds in various therapeutic applications, such as stress reduction and sleep improvement.

A study by Li et al. (2021) collected EEG data from participants exposed to sounds from parks dominated by birdsong and traffic noise, in both audio-only and audio-visual conditions. The findings indicated that EEG alpha power, indicative of a relaxed state, was significantly stronger at the birdsong-dominant site compared to the traffic-noise-dominant site, under both audio-only and audio-visual conditions. Conversely, beta power, reflecting a stressed state, was higher at the traffic-noise-dominant site than at the birdsong-dominant site (Li et al., 2021).

A recent study by Almed et al. (2023) has demonstrated that multisensory integration is significantly enhanced when our selective attention targets align with audiovisual stimuli. This interaction occurs at multiple levels of processing in the brain, emphasizing the critical role of biophilic soundscapes and multisensory integration in advancing our comprehension of sensory experiences.

3.Methods

The current study utilized an EEG headset and a VR Head Mounted Display (HMD) device to measure neurophysiological responses to biophilic sounds in a virtual classroom setting. Employing a between-subjects design, participants were randomly divided into four groups, with two groups exposed to the natural flow of a river as biophilic sound.

The study investigated EEG frequency bands in virtual classroom settings through multisensory integration of visual and auditory stimuli, specifically comparing the neurophysiological effects of biophilic versus non-biophilic designs, as well as environments with and without sound. Through statistical analysis, we aimed to identify significant differences in EEG responses to biophilic sounds across two classroom designs: one standard (non-biophilic) environment serving as the control, and another enhanced with biophilic elements.

3.1 Participants

In the study, 77 healthy undergraduate students were recruited through an online system from April 1 to April 30, 2022, on a university campus in Seoul, South Korea. As actual users of the classrooms, these participants were engaged in the experiment. Ten participants were unable to complete the experiment due to transmission errors with the EEG software or technical difficulties with VR devices. The valid data from the remaining 67 participants (27 males, 40 females in their 20s) who successfully completed the experiment were used in the study's analysis. The study received approval from the Institutional Review Board, and all participants provided their informed consent before participating in the experiment.

3.2 VR Simulation

A metaverse virtual classroom was simulated for the experiment stimuli. The dimensions of the classroom used as the stimulus were 7.6m (W) x 11.5m (D) x 2.7m (H), and the layout and 3D model are illustrated in Figure 1. Two room models were utilized: Room 1 served as a control setting, while Room 2 featured a biophilic design. The design elements and attributes were inspired by and applied based on the theory of biophilic design (Kellert et al., 2011). Apart from the biophilic interventions, both rooms were identical, sharing the same room size, layout, and furniture, facilitating comparisons between Room 1 and Room 2. The biophilic design elements were applied to specific areas of the walls and floor, as depicted in Figure 1.

The VR dynamics consist of walkthroughs that begin from a public corridor leading to the two rooms. The stimuli were pre-modeled in VR using Rhino (version 6.0) and then simulated in real-time using Unity software (version 2022). These simulations were presented through the HTC Vive Pro head-mounted display.

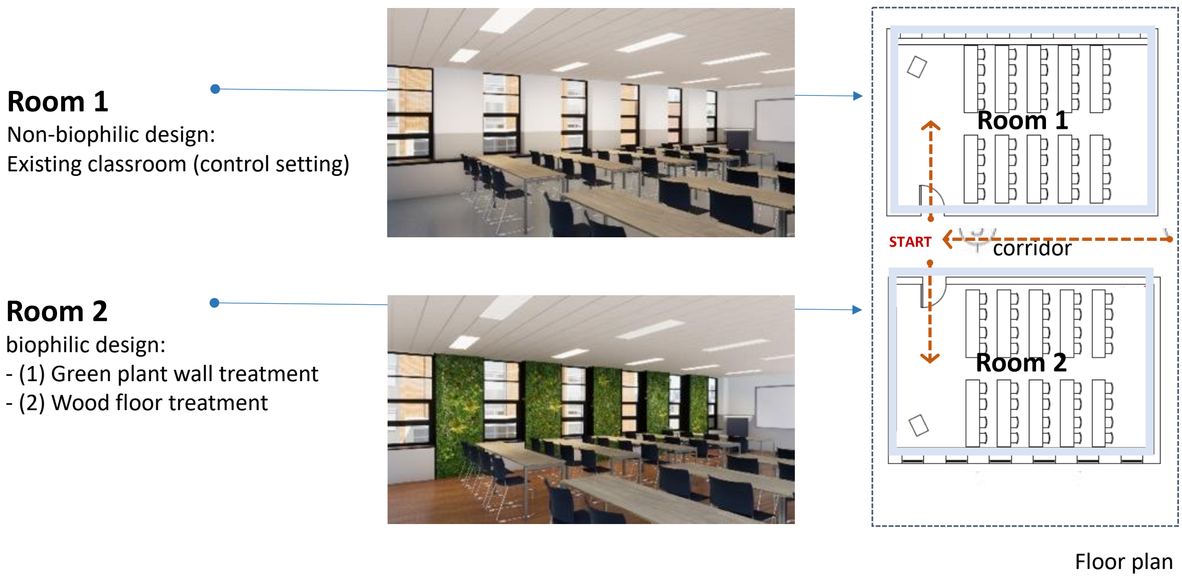

Figure 1 Virtual classrooms (Room 1 and Room 2)

3.3 Hardware and software

The HTC Vive Pro HMD features a dual-OLED display with a combined resolution of 2880 x 1600 pixels and a pixel density of 615 ppi. We employed a Gigabyte RP75 laptop equipped with an Intel Core i7 CPU and an NVIDIA GeForce RTX 3070 graphics card to connect the HMD and share the VR experience, We utilized the Emotiv Epoc X wireless headset to measure EEG signals, and data collection was performed using Emotiv Pro. This equipment features 14 saline-based electrodes, positioned on both the left and right sides, at AF3, AF4, F7, F8, FC5, FC6 , T7,T8 , P7, P8 , O1, and O2 (AF: Anterior Frontal, F: Frontal, FC: Frontocentral, T: Temporal, P: Parietal, O: Occipital) in accordance with the 10-20 EEG electrode placement system.

The headset operates at a sampling rate of 2,048 Hertz, which is internally down sampled to 128 Hertz. It offers a resolution of LSB = 0.51μV in 14-bit mode or 0.1275μV in 16-bit mode. The bandwidth spans from 0.16 to 43Hz, and it includes digital notch filters at 50Hz and 60Hz to reduce interference. Figure 2 illustrates a VR headset and an EEG headset, indicating 14 electrode locations according to the International 10-20 system for EEG.

Figure 2 HTC Vive VR headset (left) and Emotiv Epoc X EEG headset with 14 electrode locations (right)

3.4 Experiment Procedure

Each experiment was conducted individually with a researcher present, and each session lasted approximately one hour. Prior to the experiment, all participants signed the consent form approved by IRB.

Participants received a step-by-step introduction to the experiment and were informed of safety precautions. They were seated comfortably in a laboratory setting and fitted with the EEG equipment, with a researcher ensuring that each electrode was correctly attached to their scalp.

The experiment consisted of two sequential settings: participants experienced VR-walkthrough content using the HMD. They were guided to first arrive at the public corridor, open the door to the 1st room, and spend two minutes experiencing the classroom. After the virtual tour of the 1st room, participants exited and returned to the corridor, then opened the door to the 2nd room and stayed for two minutes.

Participants were randomly assigned to one of four groups. Groups 1 and 3 received no sound intervention, while Groups 2 and 4 were exposed to biophilic sound intervention in the form of the sound of a flowing river, delivered through the HTC Vive Pro headset. If necessary, extra time was provided to participants before presenting the next stimulus.

Upon completing the sequence of two settings, participants completed a survey. They received compensation for their participation before exiting the laboratory. The timeline of the procedure is presented in Figure 3.

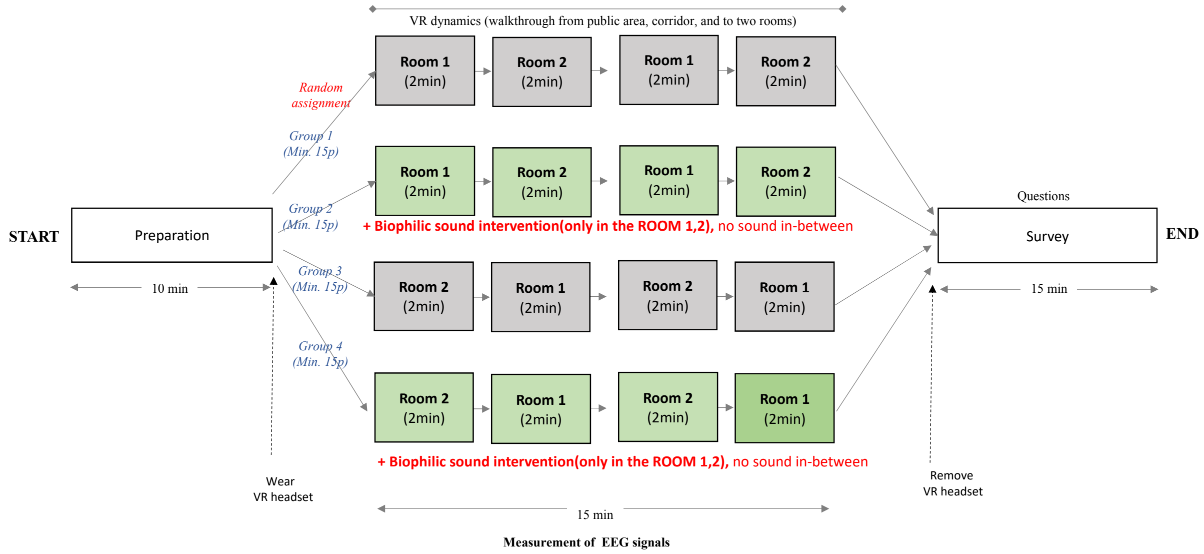

Figure 3 Experiment Procedure

3.5 Data collection and EEG analysis method

Data collection took place from May 1 to May 30, 2022, at a university laboratory in South Korea. The experiments were conducted on weekdays between 10:00 am and 5:00 pm in a laboratory room equipped with the necessary conditions for EEG experiments, including controlled lighting, temperature, and humidity.

For EEG data processing, EEGLAB (Delorme & Makeig, 2004), an open-source MATLAB toolbox, was employed. The data were subjected to band-pass filtering, with a range from 4 to 50 Hz. Continuous resting-state EEG data were segmented into epochs of 1-second length. An epoch refers to a specific time segment of the EEG signal. Epochs containing deliberate signal noise were systematically removed. Independent Component Analysis (ICA) was utilized to eliminate signal noise sources, such as eye movements, eye blinks, and muscle activity.

For detailed data analysis, EEG data from individual conditions containing fewer than 18 epochs, which accounted for 20% of the total EEG data, were excluded from the statistical analysis. After de-noising and removing participants with insufficient data, each group ended up with varying participant numbers. Specifically, Group 1 had 12, 14, 13, and 11 participants for the 1st, 2nd, 3rd, and 4th measurements, respectively. Similarly, Group 2 had 13, 12, 14, and 13 participants for the same measurements. Group 3 had 13, 11, 11, and 14 participants, while Group 4 had 13, 14, 15, and 15 participants for each respective measurement.

EEG frequency power analysis was conducted using a Fast Fourier Transform (FFT). For each epoch, the power within the theta (4-8Hz), alpha (9-12Hz), beta (13-30Hz), and gamma (31-

50Hz) frequency bands was calculated by averaging their power. This was followed by an averaging across all epochs. The "relative power" of EEG frequency bands refers to the proportion of signal power within a specific frequency band range (e.g., delta, theta, alpha, beta, gamma) compared to the total power across all measured frequency bands. To mitigate individual differences among subjects, the EEG frequency power data were transformed into Z-scores. A Gaussian distribution was applied to the normative EEG data, and a threshold of -1.96 to 1.96 Z-scores was employed, corresponding to a 95% confidence level, based on previous research (Thatcher et al., 2003).

The statistical analysis was carried out using *SPSS* version 23.0 on the final frequency band power of the EEG data. A significance level of p <.05 was applied to establish statistical significance.

4.Results

A repeated measures analysis of variance (ANOVA) was employed to investigate the neurophysiological impacts of biophilic sound effects. The results revealed a significant interaction of brain regions, except for those in the second Room 1 of Group 3 and Group 4. In the results of theta, alpha, and gamma power, significant inter-hemispheric interactions were observed between the left and right hemispheres, suggesting that communication and coordination between the two hemispheres of the brain play a role in these experiment conditions.

In the 1st Room 2 and 2nd Room 1, the results of beta power indicated a significant interaction effect between brain regions and groups in the context of sound effects. This suggests that differences in brain activity between regions depend on the presence or absence of sound effects. Table 1 presents only the significant results of the ANOVA analysis, where 'Gi' represents Group i.

Table 1 Statistically Significant Results of ANOVA for Groups, Regions and Left-Right Hemispheres

		1st Room1		**1st Room2**		**2nd Room1**		**2nd Room2**	
		G1-G2	G3-G4	G1-G2	G3-G4	G1-G2	G3-G4	G1-G2	G3-G4
Theta	Region	< .001	< .05	< .001	< .001	< .001		< .05	< .05
	L/R				< .001	< .001	< .05		< .05
	Region ✻ L/R		< .05						
Alpha	Region	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001
	L/R	< .05	< .05					< .05	
	Region ✻ L/R	< .05	< .05						

Beta	Region	< .001	0.001	< .001	< .001	< .001		< .001	< .05
	Region ※ Group			< .05		< .05	< .05		
	Group			< .05	< .05	< .05	< .05		
Gamma	Region	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001
	L/R	< .05							
	Region ※ L/R	< .05							

Heat maps depicting beta power activations for all conditions are shown in Figure 4. The colors in the heat map correspond to the intensity of beta power in EEG activations, with red areas indicating higher beta power—suggesting increased activity or arousal in those brain regions during the tasks. Conversely, blue areas signify lower beta power, implying reduced activity or arousal.

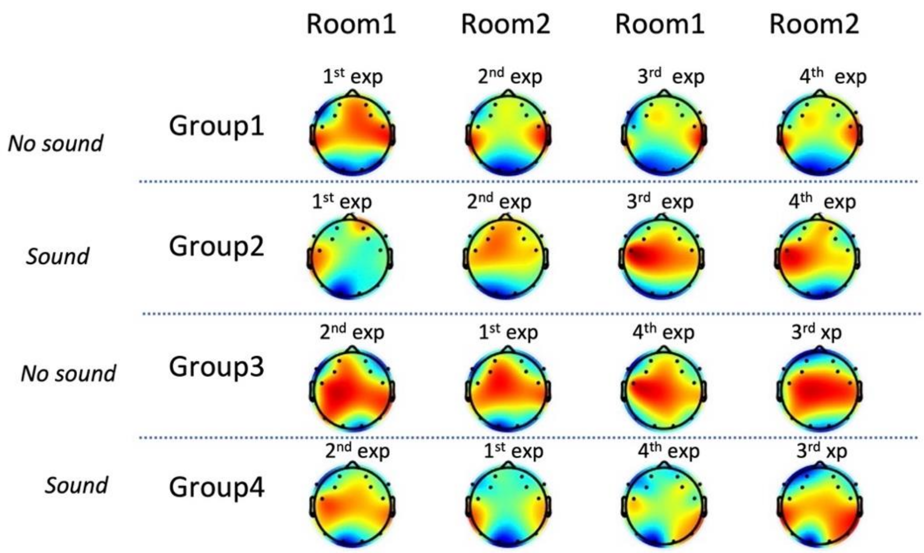

Figure 4 Heat map of beta power in EEG activations

ANOVA results showed group differences only in Beta, and there were no group differences in theta, alpha, and gamma. Therefore, a paired t-test for post-hoc analysis was conducted to compare beta power between the two groups. This analysis included comparisons of beta power between groups G1 and G2, as well as G3 and G4, across multiple brain regions (see Table 2). When comparing G1 and G2, it was found that beta power for G1 over T8 in the 1st Room 2 and over F8 in the 2nd Room 2 were significantly higher than those for G2 (T8: $t(11) = 2.61$, $p = 0.02$; F8: $t(8) = 3.47$, $p = 0.01$). Conversely, beta power for G1 over FC5 was lower than that for G2 in the 2nd Room 1 (FC5: $t(9) = -2.59$, $p = 0.03$). These results indicate that the combination of biophilic design with biophilic sound resulted in decreased beta power.

However, when biophilic design was presented without biophilic sound, there was an increase in beta power. This suggests that the addition of biophilic sound to biophilic design led to a decrease in beta power.

However, no similar effects were observed in the comparison between G3 and G4. In the first experimental condition, beta power for G3 was significantly higher than that for G4 in the same condition over AF3 in the 1st Room 1 (t(11) = 2.63, *p* = 0.02) and over F3 in the 1st Room 2 (t(9) = 2.58, *p* = 0.03). Conversely, beta power for G3 was significantly lower than that for G4 in the same condition over T7 in the 2nd Room 2 (t(9) = -2.70, *p* = 0.02) and over P8 in the 2nd Room 2 (t(10) = -2.95, *p* = 0.01). As both G3 and G4 were exposed to biophilic design in the first experiment and no biophilic design in the second experiment, it is possible that this exposure or order may have had additional effects on beta power beyond the presence or absence of biophilic sound.

Table 2 Statistical results of post-hoc analysis of beta relative power for channels

	Paired Differences					t	df	Sig (2-tailed)	Cohen's d
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference					
				Lower	Upper				
G1_Beta_1_r2_T8 - G2_Beta_1_r2_T8	0.81	1.07	0.31	0.13	1.49	2.61	11.00	0.02	0.75
G1_Beta_2_r1_FC5 - G2_Beta_2_r1_FC5	-1.23	1.50	0.47	-2.30	-0.16	-2.59	9.00	0.03	-0.82
G1_Beta_2_r2_F8 - G2_Beta_2_r2_F8	0.77	0.67	0.22	0.26	1.29	3.47	8.00	0.01	1.16
G3_Beta_1_r1_AF3 - G4_Beta_1_r1_AF3	0.51	0.68	0.20	0.08	0.95	2.63	11.00	0.02	0.76
G3_Beta_1_r2_F3 - G4_Beta_1_r2_F3	0.67	0.82	0.26	0.08	1.26	2.58	9.00	0.03	0.82
G3_Beta_2_r2_T7 - G4_Beta_2_r2_T7	-1.29	1.52	0.48	-2.38	-0.21	-2.70	9.00	0.02	-0.85
G3_Beta_2_r2_P8 - G4_Beta_2_r2_P8	-0.84	0.94	0.28	-1.47	-0.21	-2.95	10.00	0.01	-0.89

4.Discussion

This study revealed that the presence of biophilic sound, specifically the sound of a flowing river, led to a reduction in beta power. Given that beta power has been associated with higher levels of arousal, it is plausible that the biophilic sound had a calming effect on the participants. Conversely, when biophilic design was presented without biophilic sound, there was an increase in beta power. This increase in beta power could be attributed to the stimulating and engaging properties of the biophilic design itself. These findings suggest that biophilic design has the potential to increase arousal and cognitive engagement, even in the absence of biophilic sound. Overall, this study underscores the importance of considering multisensory integration and the combined effects of biophilic design and sound on cognitive and physiological responses.

The increase in beta power observed in this study is in line with previous research that has linked beta power to higher levels of arousal and cognitive engagement, suggesting that biophilic sound may have a calming effect on individuals. These results align with other studies that have reported significant effects on beta power in EEG signals in response to emotional biophilic sound (Li et al., 2021; Wilkins et al., 2020). Additionally, Höller et al. (2012) have reported significant effects in the beta range of EEG signals in response to emotional sound stimuli and music, indicating that the beta frequency range may be particularly sensitive to auditory stimulation (Höller et al., 2012). The observed interaction effect in this study extends these previous findings by demonstrating that differences in brain activity between regions are modulated by the specific sound effect presented. This highlights the intricate neural mechanisms involved in sound processing.

Beta power is generally produced when a subject is mentally active and is often dominant in the frontal region of the brain during mental activity (Kuribayashi & Nittono, 2017; Muller & Cunningham, 2020). In this study, higher beta power in the frontal cortex was observed when participants visually experienced biophilic design in a classroom setting, which included a green plant wall and wood flooring. The frontal cortex is associated with visuo-spatial information processing (Waberski et al., 2008) and visual attention (Liang et al., 2017), suggesting that biophilic design may enhance these cognitive processes. Additionally, a decrease in beta power was found in the temporal region, associated with sound, and the parietal region, associated with sensory processing (Damiani et al., 2020), when participants listened to biophilic sound. This suggests that biophilic sound may have a calming effect on the brain, potentially reducing mental workload and promoting relaxation.

5. Conclusion

This paper investigated the impact of biophilic sound in neurocognition through the use of EEG and VR. The experiment measured EEG activations in response to biophilic sound in two different classrooms (one non-biophilic and the other biophilic) and examined differences in brain regions using EEG frequency bands. The results revealed significant interaction among brain regions. Specifically, there were notable inter-hemispheric interactions in the theta, alpha, and gamma power bands, emphasizing the influence of biophilic design and sound on neurophysiological responses.

The combination of biophilic design and sound led to a decrease in beta power compared to biophilic design alone. This suggests that biophilic design, when combined with a multisensory experience, can have a substantial impact on neurophysiological responses and holds potential implications for evidence-based design strategies aimed at enhancing multisensory virtual classrooms.

However, this study had certain limitations. First, it only measured EEG signals during exposure to biophilic-designed stimuli, not during other tasks or activities. Future research could explore the effects of biophilic soundscapes on EEG activity in various contexts and tasks. Second, the sample size was relatively small per group, limiting the generalizability of the findings. Larger sample sizes should be considered in future studies. Third, the relatively subtle architectural design differences between Room 1 and Room 2 will be recognized as a limitation. Future studies could explore additional design elements, potentially by amplifying the differences. Lastly, while this study compared no sound and biophilic sound, future research could explore the impact of different classroom sounds or facility background noise.

This paper is part of a larger research project aimed at measuring neurophysiological, cognitive, emotional, and behavioral responses in biophilic environments. The integration of VR, EEG, and multimodal biosensors offers the potential to quantify the human experience comprehensively (Kim & Kim 2022). With a multi-sensory approach, this research brings natural elements into virtual classrooms, examining biophilia's effects on cognitive performance, creativity, mental health, and well-being.

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